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A METHOD FOR DETERMINING THE TOTAL STORAGE REQUIREMENTS IN A HIGH-RISE AUTOMATED WAREHOUSE

A THESIS

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A METHOD FOR DETERMINING THE TOTAL STORAGE
REQUIREMENTS IN A HIGH-RISE AUTOMATED WAREHOUSE

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SUMMARY

In 1971, a discrete-event simulator was developed by Dr. Kailash M. Bafna to evaluate the alternative designs of high-rise warehouse systems. It made possible the resolution of problems associated with rack configuration and operating policy. Such a simulator is an effective tool for the designer of automated warehouses.

An essential input to the high-rise warehouse simulator is the total storage slot requirement of the system. At present, no analytical technique is used to find this input. The research proposes a method for determining the optimum number of storage slots in the system that will minimize the sum of all warehouse costs.

The research concerns itself with two modes of storage: automated and conventional. The problem is one of finding the optimum item mix between the two modes. The criteria used to assemble each mix are either item throughput or volume per item. Item mixes will vary from all items in conventional storage to all items in automated storage. All variable costs for each mode are calculated and summed for every possible blend. The item mix that produces the minimum total storage cost is the optimum blend. Considering only those items of the optimum blend assigned to automated storage, the required number of storage slots may be found.

Variable costs consist of facilities, equipment, and manpower. Costs are a function of the number of slots and equipment capacity.

To utilize the method, certain information must be gathered from past inventory records. The data is then altered by forecasting to

reflect future demand.

The objective of the study is to develop a method for determining the total storage slot requirement of an automated warehouse. This method should provide accurate input data for use in high-rise warehouse simulation, resulting in better warehouse designs.

CHAPTER I

INTRODUCTION

Objective

The objective of this study is to develop a method for determining the total storage slot requirement of an automated high-rise warehouse from available inventory records. This method should provide accurate input data for use in high-rise warehouse simulation, resulting in better warehouse designs.

Reasons for the Study

In 1971, a discrete-event simulator of high-rise warehouse systems was developed by Kailash M. Bafna at Purdue University (1).[1] BASS, as it is called, evaluates alternative warehouse designs and resolves problems associated with rack configuration and operating policy. It is an effective tool for the designer of automated warehouses.

BASS was developed in three stages. First, all warehouse costs were exposed and expressed as elemental equations in a total cost model. Second, a simulator was designed to represent a high-rise warehouse in operation. Finally, the cost model and simulator were combined with a search technique to produce BASS which determines the optimum blend of warehouse parameters to meet the required storage and throughput capacities.

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[1] Numbers in parentheses refer to citations in the References.

A primary input to BASS is the total storage slot requirement of the system. Unless an accurate figure is initially available, the simulator will take longer to arrive at the final design of the warehouse. Consequently, a method to determine the optimum number of storage slots is preferred.

In some cases, BASS may not be used to aid in the design of an automated warehouse, since running such a complex simulator requires time, money, and programming expertise. Certain building or equipment constraints may hamper its effectiveness or the designer may not know of its existence. In any of these situations, the designer must depend on his own experience and judgement. After gathering the necessary information, he will attempt to design the system. As essential bit of information needed by him is the total storage slot requirement. He may contact a consultant or a storage machine manufacturer for help in designing the system. They will seek from him certain information such as the type of installation he desires, travel speed, hoist speed, etc., and also the total storage slot requirement. Clearly, a technique is needed to determine the optimum number of storage slots in the system.

Having realized the importance of the total storage slot requirement to the BASS simulator and the warehouse designer, an attempt was made to uncover a method for its development. A review of the literature revealed a few techniques that simply found the slot requirement from a forecast of the stock distribution. They did not, however, consider the prime criterion of cost.

A discussion with the representative of a leading storage machine manufacturer revealed that quantitative techniques are not presently used to determine the number of storage slots in automated warehouses. Most designers estimate the storage slot requirement by making an educated guess from inventory records.

As a result of these findings, it was decided to donduct the proposed study. It is felt that the method resulting from the research will provide the designer with accurate information necessary to effectively utilize the BASS simulator or manually design the system.

Importance of the Study

Automated high-rise storage is an area of materials handling that has drawn much attention in recent years. It is a discipline that consists of the handling and storage of unit loads in an orderly and defined manner using specialized equipment housed in a high-rise building. Such a system can provide significant savings in the following areas: improved materials flow, accurate inventory control, space savings, labor savings, reduced damage, improved safety, reduced pilferage, and a fast write-off (2).

High-rise storage stands as the fastest growing area of materials handling. It boasts an annual growth rate of 25 to 35 per cent with an anticipated annual sales of $200 million by 1975. Today, almost 1000 automated storage machines are operating in high-rise systems across the country. "Automated warehousing is a fascinating field that has come far in a short time, and yet has just begun to realize its potential" (3).

From the foregoing discussion, it is obvious that high-rise warehousing is more than just a fad. It is also more than a small investment with the average system of today costing over $1 million. By 1975, an average system will cost from $4 to $5 million (4).

An error in the size of the system can have a substantial effect on profits. If the size is overestimated, there will be more storage slots than necessary and slot utilization will be low. This reduces profits by an amount proportional to the initial cost plus the sum of the annual costs of the unused slots over the life of the system. The average cost of a storage slot in an automated high-rise system is about $120 to $150 and the annual cost is about $10 (5). In the case of underestimation, too few storage slots are available and additional storage space will have to be rented. Profits are decreased by all the costs associated with renting and transporting goods to and from the added storage area.

The choice of items to be stored in the automated warehouse can also affect profits. For example, if the average annual cost of a storage slot if $10 and the utilization is 85 per cent, the actual annual cost will be $11.50. Therefore, the actual monthly cost is about $1. Every month an item stays in storage adds $1 to its final cost. Consequently, only rapid turnover items should be put in automated storage. There are a few exceptions to this rule; for example, rapid turnover items with high volume per item. It is important to carefully consider each item chosen to be put in automated storage.

The importance of choosing the right storage slot requirement for the system cannot be overemphasized. Since the storage slot requirement depends on the choice of items to be stored in the warehouse, many combinations of items and numbers of slots will have to be considered in order to maximize profits. A method to determine the optimum number of storage slots should consider all relevant information and weigh all the possible alternatives. One such method has been developed in this research.

Review of the Literature

Recently, high-rise warehousing was called "the glamour boy of material handling" (6). The large volume of articles and write-ups in this area substantiates this statement. At least one book has been written on the subject (7) and an annual publication is available (8). Many articles have been published describing successful installations (9,10,11, 12). Some articles have attempted to answer questions or solve problems in the area of automated warehousing (13,14,15,16). Still other articles have tried to give guidelines on why and when to consider automated warehousing (17,18,19,20,21). However, although many articles were found on high-rise warehousing, few were of an analytical nature. The researcher did not find even one article that addressed itself directly to the problem of determining the total storage slot requirement of a system.

A review of thesis abstracts revealed that no academic research has been done to develop a method for determining the storage slot requirements.

Some light can be shed on the problem from the associated area of conventional warehousing. In 1966, Edward Zebrowski presented a paper on the development and control of conventional warehousing (22). Work on the paper was initially directed towards determination of long-range storage space requirements. Historical sales and inventory data were examined to determine the future inventory position. For each product, inventory levels and trends were projected into future time periods by mathematically fitting a straight-line trend or a semi-logarithmic straight-line trend to past inventory level data. Next, these predicted inventory levels were subjected to the human judgement of plant supervision who either accepted or modified the forecasts. From this came the best estimates of future inventory levels and storage space requirements.

It is a simple matter to translate the ideas of Zebrowski's paper into the language of automated warehousing. The results, however, would probably be far from optimum due to the fact that all items are not suitable for automated storage. Only items of rapid turnover and high throughput should be considered (23).

Another approach, also from the area of conventional warehousing, is that proposed by David Einbinder (24). Two methods were tested with identical source data to determine the space needs for a new warehouse. Using a method similar to Zebrowski's, sales forecasts were converted to quantities of a given product which were transformed into space requirements. The second method consisted of finding the actual maximum quantity of an item for any one day of the year. This figure was taken as the predicted storage space requirement for that item. The total space requirement was simply the sum of the item requirements. Either of Einbinder's techniques can be used to predict the storage slot requirement of a high-rise warehouse. However, no consideration was made for the throughput of each item.

It is clear that the techniques proposed previously should be based on a prior knowledge of the items best suited to automated storage. Only by analyzing the warehouse storage costs can such a determination be made.

In a recent article, Robert Reynolds presented a method of determining total comparative and resultant costs for selected conditions of storage (25). The study covered a variety of handling systems and applied to one product in a constant-volume inventory. Various values of items and turnover were selected. The study consisted of three parts. First, arbitrary product specifications were set based on typical warehouse unit loads. Handling and storage equipment were selected to represent the full range available and inventories of varying characteristics were designed to represent typical conditions. Second, cost data for each component were developed and analyzed in relation to the handling and storage of the product. Finally, all components were combined into complete systems and compared. The intent of the study was to show the relative costs of various storage methods and item characteristics. Although the article did provide definite guidelines, it was too general to be of use to the warehouse designer.

To be useful, warehouse costs must be identified specifically and accurately. A rigorous procedure for developing automated warehouse costs was given by Dr. K. M. Bafna (26). He listed the variable costs in a stacker crane system as cost of floor space, building, racks, stacker cranes, transfer cars, and fire protection. Each of these was analyzed and represented by an elemental cost equation. The elemental cost equations were summed to produce the total cost model for the system.

To make a valid comparison of storage systems, a method must be available to determine conventional warehousing costs. Such a technique was developed by E. Kay (27). Although less rigorous than Bafna's approach, Kay's method listed several variable cost factors. They were the cost of floor area, roof area, wall area, and handling. Each variable cost was identified and summed in the total cost equation.

Thus, we find that several interrelated studies have been made in the warehousing field which, if combined, could produce an effective tool for determining the total storage slot requirement of the system.

Outline of the Study

Chapter II gives the characteristics of the warehouse system compared in the method and explains the necessary assumptions. The handling and use of inventory records are discussed in Chapter III. In Chapter IV, mathematical models are developed for the cost elements and throughput capacities. A computer program is developed and the results of the sample runs are discussed in Chapter V. Chapter VI concludes this study with some observations and recommendations for further study.

CHAPTER II

WAREHOUSE DESIGN ASSUMPTIONS

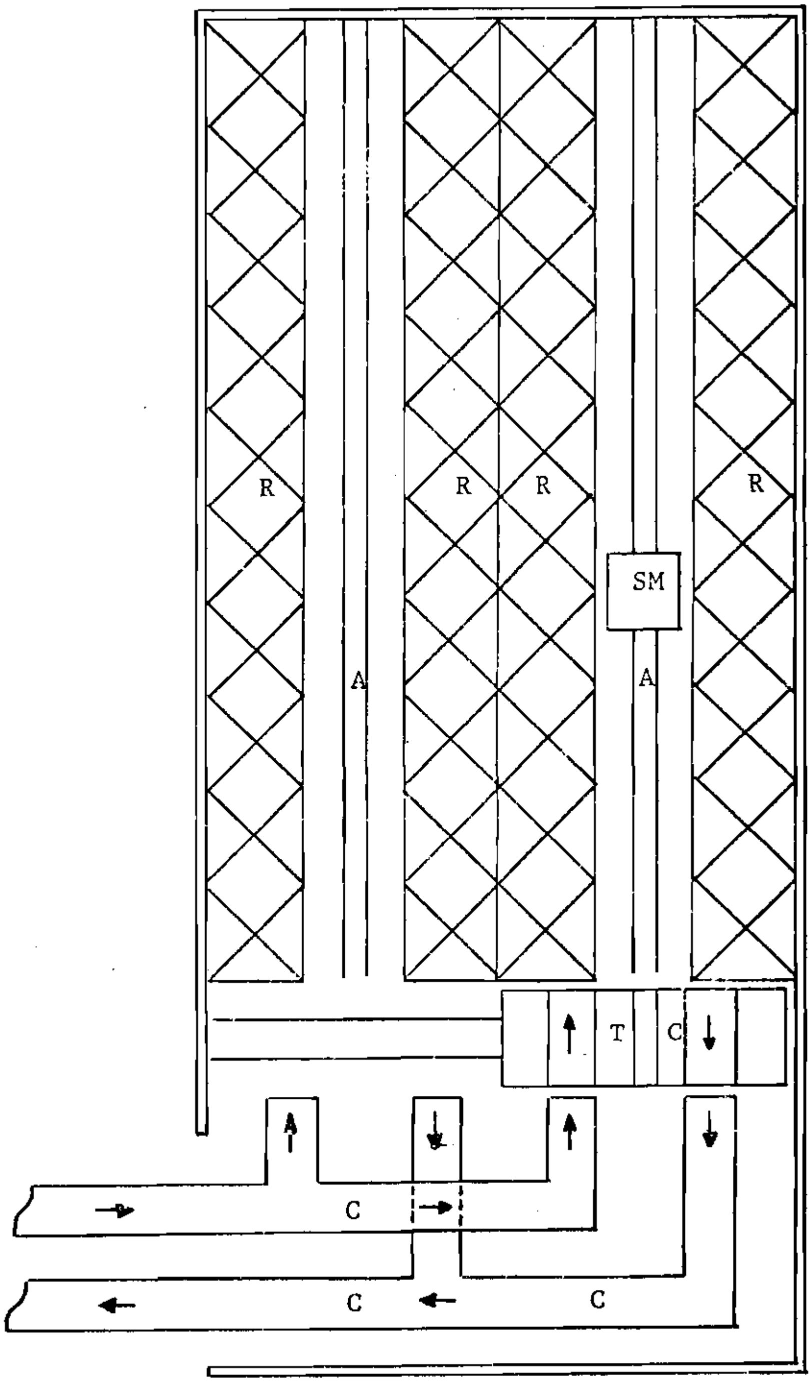
Automated Warehouse

An automated warehouse in its truest form, as used in this study, is defined as an installation where all the functions and activities are performed by self-regulating mechanisms and controls in such a way that very little human intervention is necessary. This study concerns itself with the pigeon-hole type warehouse, where unmixed unit loads are stacked in a static framework of racks separated by aisles. Operating in the aisles is an automatic self-contained storage machine that deposits and retrieves unit loads. If the storage machine services more than one aisle, it is transported from one aisle to another by a transfer car which serves as the pickup and deposit station. Flow to and from the storage system is accomplished by automatically regulated powered conveyors. This type of a warehouse is shown in Figure 1. There are many possible designs within this category of the pigeon-hole type warehouse. The design used in this study was chosen because it represents a typical near future warehouse for a large system.

Operation

The storage machines as used in this study are capable of performing only four distinct tasks. They are:

1. Carry a unit load from the pick-up station to a specific slot, deposit in in that slot, and return empty (single command).



Legend: SM = Storage Machine, TC = Transfer Car,
A = Aisle, C = Conveyor, R = Rack

Figure 1. Automated Warehouse.

2. Travel empty to a specific slot, retrieve a unit load and return to the deposit station (single command).
3. Carry a unit load from the pick-up station to a specific slot, deposit it in that slot, travel empty to another slot, retrieve a unit load and return to the deposit station (dual command).
4. Travel empty to a specific slot, retrieve a unit load, move to another slot, deposit it there and return empty (dual command).

Another task called transfer-in-storage is possible. This one is not considered because of its rare occurrence in actual practice.

Control

Control of the storage machine can be divided into two parts: programming and addressing. Programming refers to the method by which commands are transmitted to the storage machine. This is done remotely by a sattelite or a supervisory computer. The on-line system is under direct computer command. The computer generates the programming inputs and receives verification, directly. Continuous (real-time) communication is maintained between the computer and the storage machine. The computer runs the system by remembering scheduled parts requirements, selecting stock and stock locations, up-dating inventory records, reporting on inventory, issuing reorder commands, and performing system diagnosis on a continuous basis. It also simulates the best picking cycle, prints out each day's activity, and determines the optimum mix of single and dual commands.

Addressing refers to the method by which storage machines find their destinations. Two approaches are available: counting and matching. Counting systems operate by tripping a series of mechanical or proximity switches to determine the position of the storage machine. Matching systems use photoelectric or magnetic switches to locate the address of a slot. Either approach is acceptable in this study.

The remote on-line computer system has been used in this study since it is just beginning to realize its potential in automated warehousing. There are only about six computer controlled systems in this country today (28). However, this has an increasing trend with larger systems and more sophisticated controls. Therefore, it is believed that the on-line system represents a typical installation of the near future. The computer is housed in an atmosphere controlled room separate from the warehouse. A computer operator monitors the system and inputs product information into the system.

Handling Equipment

The storage machine used in this study looks much like a stacker crane but it moves on wheels like a fork truck. It is locked into one aisle until transported to another aisle by a transfer car. The storage machine is not a slave to just one aisle. It allows 100 per cent selectivity of any unit load stored on either side of the aisle. It is assumed to be a fully automatic slave of the remote on-line computer system.

The type of storage machine described was chosen for this study because it is programmable and more stable. Unlike many bridge-type stacker cranes, the storage machine is locked within the aisle and is guided at both the top and bottom. This prevents the "pendulum" effect or the tendency for the free end of the mast to sway. Any such movement makes automatic positioning difficult.

Aisle-to-aisle transfer of the storage machine is accomplished by means of a floor-mounted transfer car that runs perpendicular to the racks. It contains sections of conveyor and serves as a pickup and deposit station. It is assumed to be fully automatic and is controlled by the computer. There are two basic types of aisle transfer cars available: dedicated and non-dedicated. Dedicated means that each transfer car is pre-assigned to a storage machine. In the non-dedicated type, one or more transfer cars may service several storage machines. Since the dedicated aisle transfer car is available anytime for transfer, it was chosen for this study. In this type there is no delay in moving the storage machine from one aisle to another due to the unavailability of a transfer car.

Racks

Two types of rack designs are available for the automated warehouse. They are the drive-in and beam-type racks. In drive-in racks, loads are supported by means of a pair of brackets on the inner side of each pair of uprights. This style of racks is used with captive pallets (typically plywood sheets). The beam-type racks are typified by conventional wooden or metal pallets resting on shelves spanning each pair of uprights. Each rank design has definite advantages and either is acceptable in the study.

Racks may be constructed as free-standing or load-supporting. Free-standing racks are not connected to the roof of the building and are usually independent of one another. With load-supporting racks, the roof is supported by the rack structure. The study accommodates either type of rack construction.

Conveyors

The storage machines are fed by two networks of conveyors, one for incoming loads and one for outgoing loads. Each network of powered conveyors is equipped with diverting mechanisms and automatic controls to direct each unit load to the proper destination. The description of unit loads entering the warehouse is fed into the central on-line computer system. The computer system then regulates the conveyor controls and diverting mechanisms to deliver each load to a particular aisle in the rack system. The sophisticated input/output system used in this study was chosen primarily because of its compatibility with the on-line computer system. Also, the conveyor networks reduce labor and eliminate the need for batch-delivery devices.

Building

The building which houses the storage machine can be divided into three parts: foundation, roof, and walls. The floor is made of reinforced concrete. A sturdy foundation is important in automated warehousing due to the need for maintaining precision in rack alignment. The storage machine works with rack clearances of only $\pm$ 1/2 inch (29). As stated earlier, the roof may or may not be supported by the racks. This will affect the type of roof chosen by the designer. The choice of walls also depends on the mode of support. In rack-supported buildings, non-load bearing curtain walls made of reinforced concrete or steel may be used.

A very important factor in the building construction is that of fire protection. Protection is best accomplished by a system of automatic sprinklers or a combination of sprinklers and high expansion foam (30). Either type may be considered in the study.

Conventional Warehouse

Conventional warehousing may be thought of as accomplishing all of the warehouse operations (identification, dispatching, storing, recalling, or delivery) without the aid of automation, or at least a minimum of automation. Warehouse operations are performed by manual or mechanized handling methods.

In the conventional warehouse being used in this study as a basis for comparison, unmixed unit loads are stacked on pallets in a framework of racks separated by aisles. Operating in the warehouse area are one or more standard fork lift trucks with operators. The trucks move in the aisles, storing and retrieving unit loads. This type of warehouse is shown in Figure 2. The design used in this study was chosen because it represents a typical industrial warehouse.

Storage Equipment

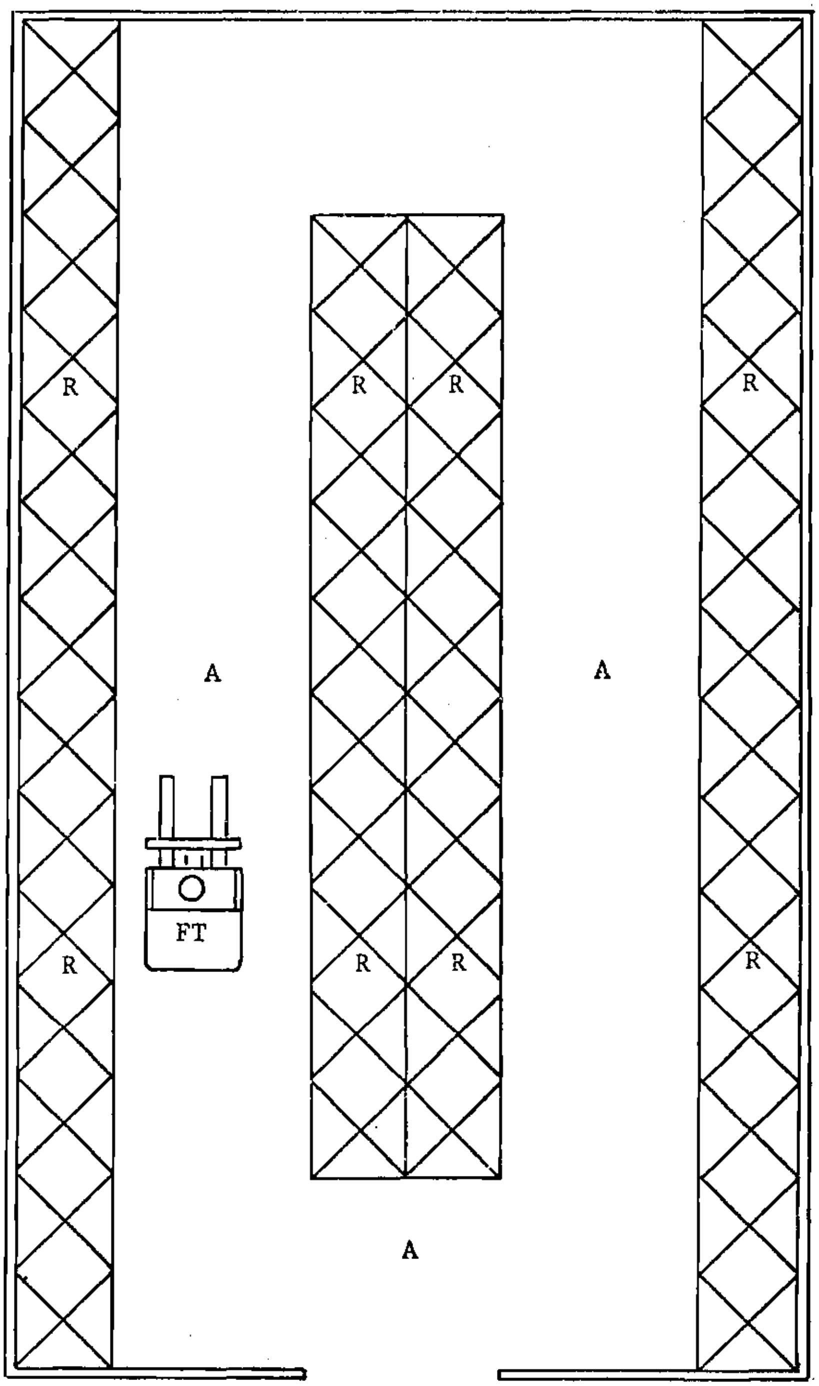
There are two basic types of lift trucks used in conventional warehousing -- the rider and the walkie. Each of these types are to be subdivided into the categories of counterbalanced and outrigger. Any combination of these may be used in this study.

Racks

Since the fork lift truck is usually limited to conventional-type wooden or metal pallets, beam-type racks are used. This type consists of shelves spanning each pair of uprights on which the pallets rest. The racks may be free-standing or load-supporting.

Dispatching

The process of selecting stock and stock locations, up-dating inventory records, reporting on inventory, and issuing reorder commands is



Legend: FT = Fork Lift Truck, R = Rack, A = Aisle

Figure 2. Conventional Warehouse.

handled by the scheduler. He is located in an office in or near the building, close to the pickup and deposit station.

Building

The type of warehouse building depends on whether the racks are free-standing or load-supporting. If free-standing, the building will contain the necessary trusses and columns to support the roof. If load-supporting racks are used, columns are not necessary. In either case, the walls may or may not be load bearing. The floor is constructed of reinforced concrete with a good running surface. The pickup and deposit station is located in or near the warehouse building. It may be a loading dock, a railroad car, a truck trailer, or an order accumulation area. Construction of the building should include ample consideration for fire protection.

CHAPTER III

INVENTORY RECORDS

Any method for determining the optimum storage slot requirement for a warehouse must operate on certain essential inputs. These are common to all companies and are derived from their inventory records. The records may be in the form of receiving reports, production orders, finished stock pallet-tickets, or actual physical inventory reports. From these documents three important bits of information can be derived. These are:

1. The average stock on hand for item i in period j in unit loads ($\bar{K}_{ij}$).[1]
2. The variance of the stock on hand for item i in period j in unit loads ($S^2{}_{ij}$).
3. The turnover time for item i in periods (P_i).

The stock level of item i in period j at each observation m in unit loads is K_{ijm}. The number of inventory observations per period is N_y. Therefore, the average stock on hand ($\bar{K}_{ij}$) is

$$= \frac{\text{sum of the stock levels at each observation}}{\text{number of observations per time period}}$$

$$= \frac{\sum_m K_{ijm}}{N_y} \text{ unit loads.}$$

---

1 The number of unit loads should not be founded off and should be kept as an exact decimal.

The variance of the stock on hand (S^2_{ij}) is a common measure of the deviation of the stock level from the average stock on hand. After finding the average stock on hand, each observation is subtracted from it and the differences are squared and summed. This sum is divided by the number of observations per time period minus one. Another commonly used measure of dispersion is the standard deviation (S_{ij}), which is the square root of the variance.

The turnover time for item i (P_i) refers to the average length of time an item i is on the shelf. It may be a matter of company policy or product shelf life.

The average stock on hand ($\bar{K}_{ij}$) and the standard deviation (S_{ij}) can be used to estimate the number of storage slots necessary for a given item so as to accommodate the items in their entirety at least a given percentage of times. Assuming that the quantity in stock for any item can be approximated by a normal distribution, the maximum number of storage slots required for item i in period j (assuming one unit load per slot) is given by

$$K_{ij} = \bar{K}_{ij} + kS_{ij}$$

where k is a percentage point of the standard normal distribution. The value of k depends on the risk of being unable to find room for incoming goods. For example, if k is 3.00, the probability of being overloaded is 0.13 per cent.

Items must be assigned a whole number of storage slots. Fractional parts of storage slots do not exist. Therefore, if the maximum required number of storage slots (K_{ij}) contains a fractional part, it must be rounded off to the next whole number.

There are essentially two methods of assigning items to storage slots. In the first, items are assigned to fixed locations in the warehouse keeping the fast moving items nearest the door. The total required slots in all locations in period j under Method 1 can be written as

$$K_j = \sum_i \bar{K}_{ij} + k\sum_i S_{ij}$$

assuming one unit load per slot. This approach assures that the risk of overloading each fixed location is no more than that depending on the value of k.

The second method consists of storing all items together in a random manner. If the stock distributions for all items are symmetrical, the distribution of two or more items taken together will approach the normal distribution. The average stock level will equal the sum of the averages and the variance will equal the sum of the variances. Therefore, the required number of slots for period j under Method 2 is given by

$$K_j = \sum_i \bar{K}_{ij} + k \sqrt{(\sum_i S^2{}_{ij})}$$

assuming one unit load per slot. This approach assures that the risk of overloading the entire warehouse is no more than that depending on the value of k.

In most cases, automated warehouses operate under Method 2, while conventional warehouses operate under Method 1. However, using Method 2 in the study would require additional processing time on the computer due to the increased number of computations and amount of core in the memory. Therefore, Method 1 will be used in the study for both automated and conventional storage.

Another important factor is the item throughput. This refers to the activity or movement of an item. Throughput (M_{ij}) is defined as the number of unit loads incoming and outgoing for item i in period j. For one item, let the throughput

$$= \frac{\text{2 x maximum required number of storage slots for item i}}{\text{turnover time}}$$

$$= \frac{2K_{ij}}{P_i} \text{ unit loads/period.}$$

For two or more items taken together, total throughput is simply the sum of the throughputs for these items, or

$$M_j = \sum_i M_{ij}$$

A proposed warehouse should not be designed according to present requirements if it is to meet the needs of the future. Past and present inventory information must be gathered and then adjusted to reflect the future needs. This is done by fitting a curve to a set of data points and then extrapolating future points using the trends of the past as predictors of the future. The curves most often used are the polynomial function, the straight line, the exponential curve, and the power function. Probably the easiest to understand and use is the straight line. Assuming that a straight line is used, the equation is given by

$$y = b_o + b_1 x$$

where b_o is the y-intercept and b_1 is the slope. For a straight line, fitted by the method of least squares, the values of b_o and b_1 can be obtained by solving the following equations:

$$b_1 = \frac{n\sum_i x_i y_i - (\sum_i x_i)(\sum_i y_i)}{n\sum_i x_i^2 - (\sum_i x_i)^2}$$

$$b_o = \frac{\sum_i y_i}{n} - b_1 \frac{\sum_i x_i}{n}$$

where (x_i, y_i) are the coordinates of each point and n is the number of points (31).

The factor that must be predicted is the maximum number of storage slots for item i in future period j. Let this be K^*_{ij}. A method of predicting K^*_{ij} using the straight line is given by the following steps:

1. Fit a straight line to the average stock on hand $(\bar{K}_{ij})$ for each period of past data using the method of least squares.
2. Find the predicted average stock on hand for item i in future period j using the straight line from step 1. Let this be given by $\bar{K}^*_{ij} = b_o + b_1 Y^*_j$ where Y^*_j is the future period j.
3. Return to the individual observations (K_{ijm}) and fit a straight line to all the stock levels for item i using the method of least squares.

4. Find the predicted stock level for item i in period j at observation m using the straight line found in step 3. Let this be K^*_{ijm}.

5. Estimate the mean square error

$$MS_e = \frac{\sum_j \sum_m (K_{ijm} - K^*_{ijm})^2}{N_t - 2}$$

6. Use $\sqrt{MS_e}$ as the predicted standard deviation of the observed stock levels. Let the predicted standard deviation of stock on hand for item i in future period j be S^*_{ij}.

7. The predicted maximum number of storage slots for item i in future period j is given by $K^*_{ij} = \bar{K}^*_{ij} + k'S^*_{ij}$ where the predicted stock on hand ($\bar{K}^*_{ij}$) comes from step 2, the predicted standard deviation (S^*_{ij}) comes from step 6, and k' will depend on the risk of overloading the warehouse.

8. If the predicted maximum number of storage slots (K^*_{ij}) contains a fractional part, round it off to the next whole number.

CHAPTER IV

MODEL DEVELOPMENT

Introduction

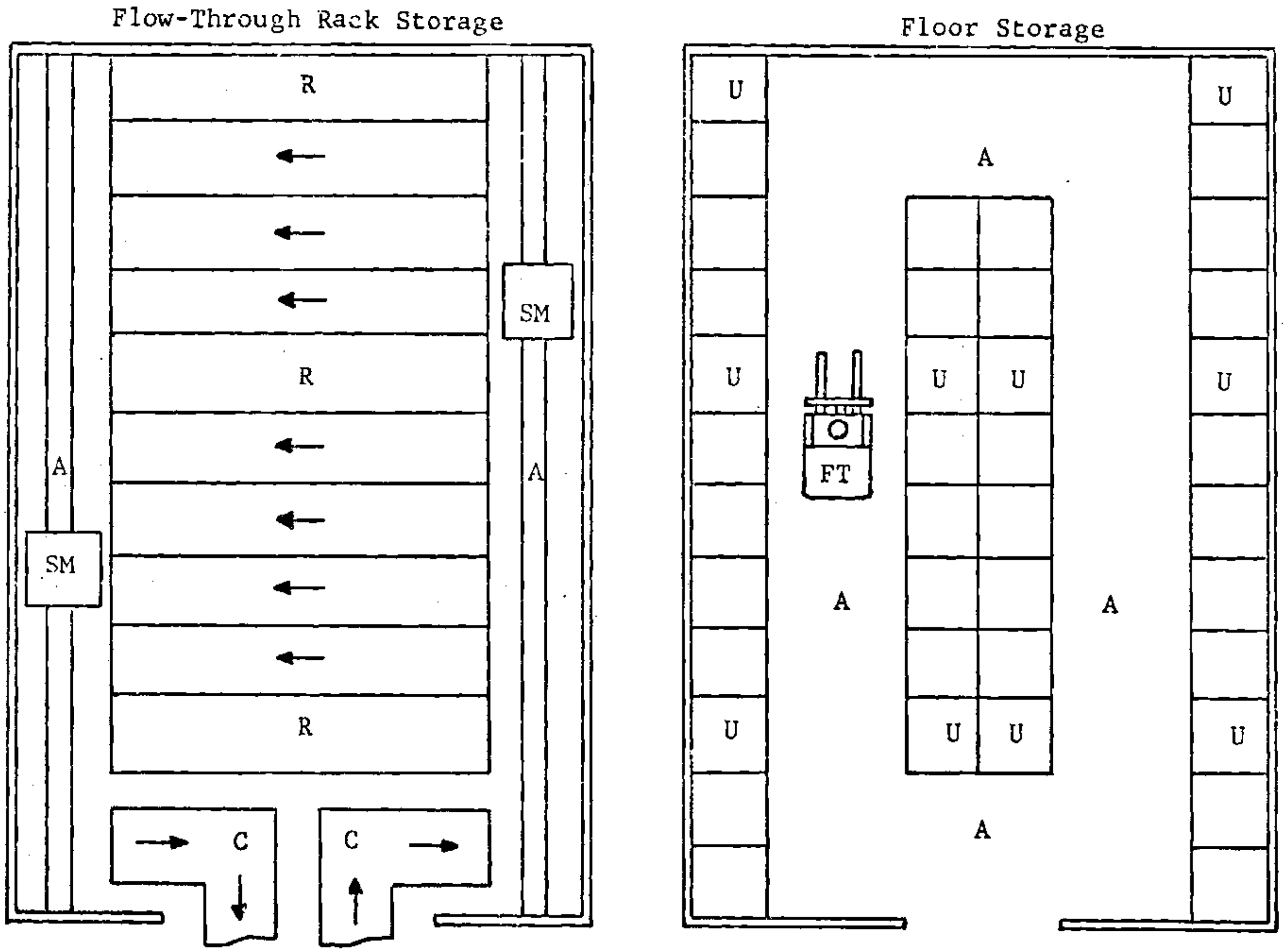
The levels of handling in a warehouse can be grouped into three distinct classifications: manual, mechanized, and automated. Each classification can then be subdivided into two categories of stored items: ready (order selection) and reserve (backup). This study will concern itself with mechanized and automated ready storage as shown in Figure 3.

There are three basic modes of storage: bulk, automated, and conventional. Automated and conventional storage were described in Chapter II. Bulk storage refers to a situation where many pallets of one item are stored together. Many designs of a bulk storage system are possible with various levels of sophistication. One possible design is the flow-through rack warehouse where pallets of a given item are stored on roller conveyor lanes on a first-in, first-out basis. This particular design is easily automated where high-rise multi-lane racks are serviced on either end by storage machines. Another possible design is the floor storage where unit loads are stacked on the floor. Floor stacks occupy a minimum of space and are usually serviced by a fork lift truck. Typical designs of bulk storage systems are shown in Figure 4.

There are some thirteen item characteristics that should be considered before choosing the appropriate mode of storage for an item (32). They are:

Storage / Handling	Ready	Reserve
Manual		
Mechanized	✓	
Automated	✓	

Figure 3. Level of Handling vs. Type of Storage.



Legend: SM = Storage Machine, FT = Fork Lift Truck, C = Conveyor, R = Racks, A = Aisles, U = Unit Loads in Floor Stacks

Figure 4. Bulk Storage

1. Dimensions
2. Shape
3. Weight
4. Package characteristics
5. Machine handleability
6. Palletizeability
7. Resistance to damage
8. Special handling requirements
9. Turnover
10. Handling characteristics
11. Volume per item
12. Ease of item delivery from factory to warehouse
13. Trends

From a study of the literature, item turnover and volume per item stand out as very important characteristics to consider in selecting the appropriate storage mode. Since both are equally important, either one may be used as the criterion for storage mode selection in this study.

Due to its ability to accommodate high storage density and small variety, bulk storage is assumed to be best suited for a few very high or very low throughput items of high volume per item. Since automated storage allows fairly high storage density and large variety, it is assumed to be best suited for a large variety of high throughput items with low volume per item. Conventional storage allows relatively low storage density and fairly large variety; therefore, it is assumed to be best suited for low throughput items with medium and low volume per item.

Determining the dividing lines between the three modes according to throughput or volume per item is no simple matter. A relationship often found in actual warehouse practice is a stock profile where 20% of the items account for 75% of the throughput. This could be represented as shown in Figure 5 along with the dividing lines in their approximate locations. Another relationship often found in actual warehouse practice is a stock profile where 20% of the items account for 60% of the volume (33). This could be represented as shown in Figure 6 along with the dividing lines in their approximate locations. This study assumes that those items best suited to bulk storage under either criterion have been chosen by management prior to the use of the proposed method. The problem then becomes one of locating only the cut off point (shown as CP) between automated and conventional storage. The accurate placement of this point is very important because it determines the appropriate items in automated storage which in turn give the required number of storage slots.

The primary goal underlying the immediate objective of determining the optimum number of storage slots in a high-rise automated warehouse is to reduce the total storage cost (TSCL). The total storage cost for an automated and a conventional warehouse refers to the sum of the total annual costs (TSC) over the lives of the warehouses. The total annual cost can be written as follows:

$$TSC = \sum_{a=1}^{9} VC(a) + \sum_{c=1}^{7} VC(c)$$

where VC(a) and VC(c) are the elemental costs listed in Appendix D of automated and conventional storage, respectively. The goal is to choose

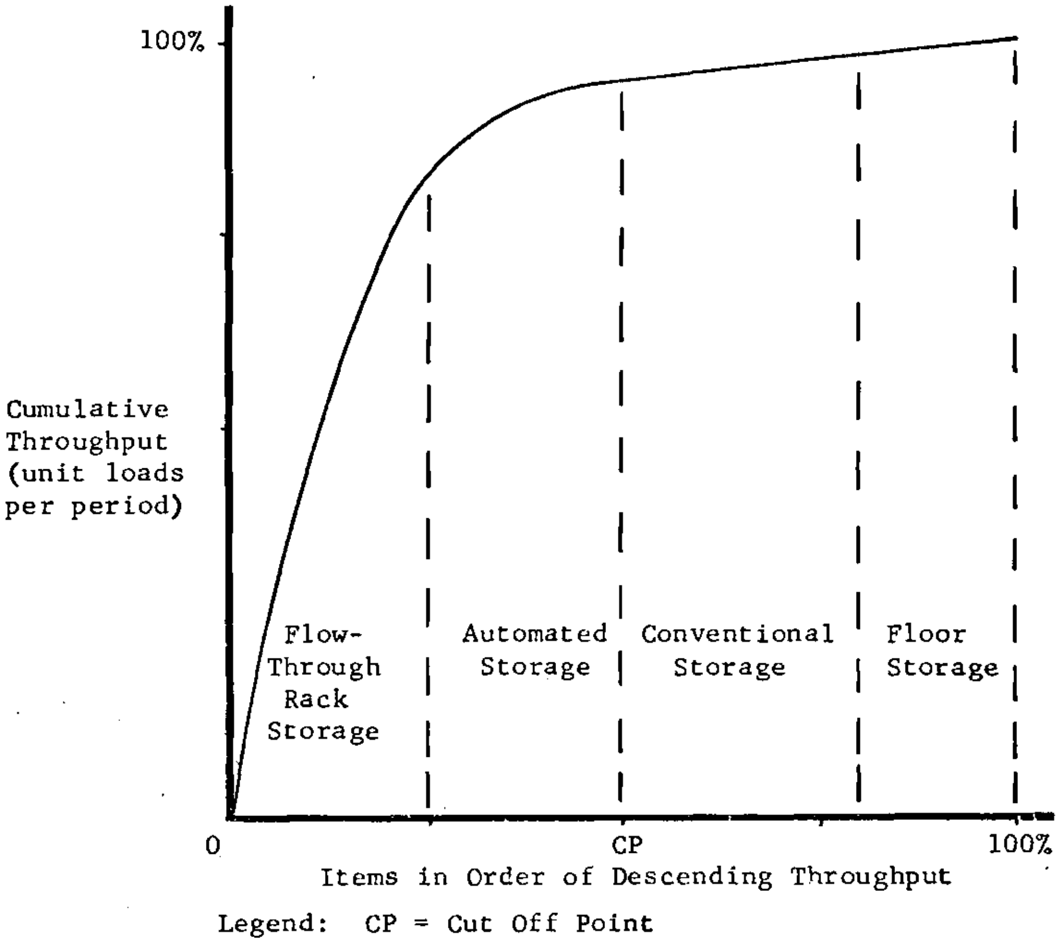


Figure 5. Stock Profile - Items vs. Throughput.

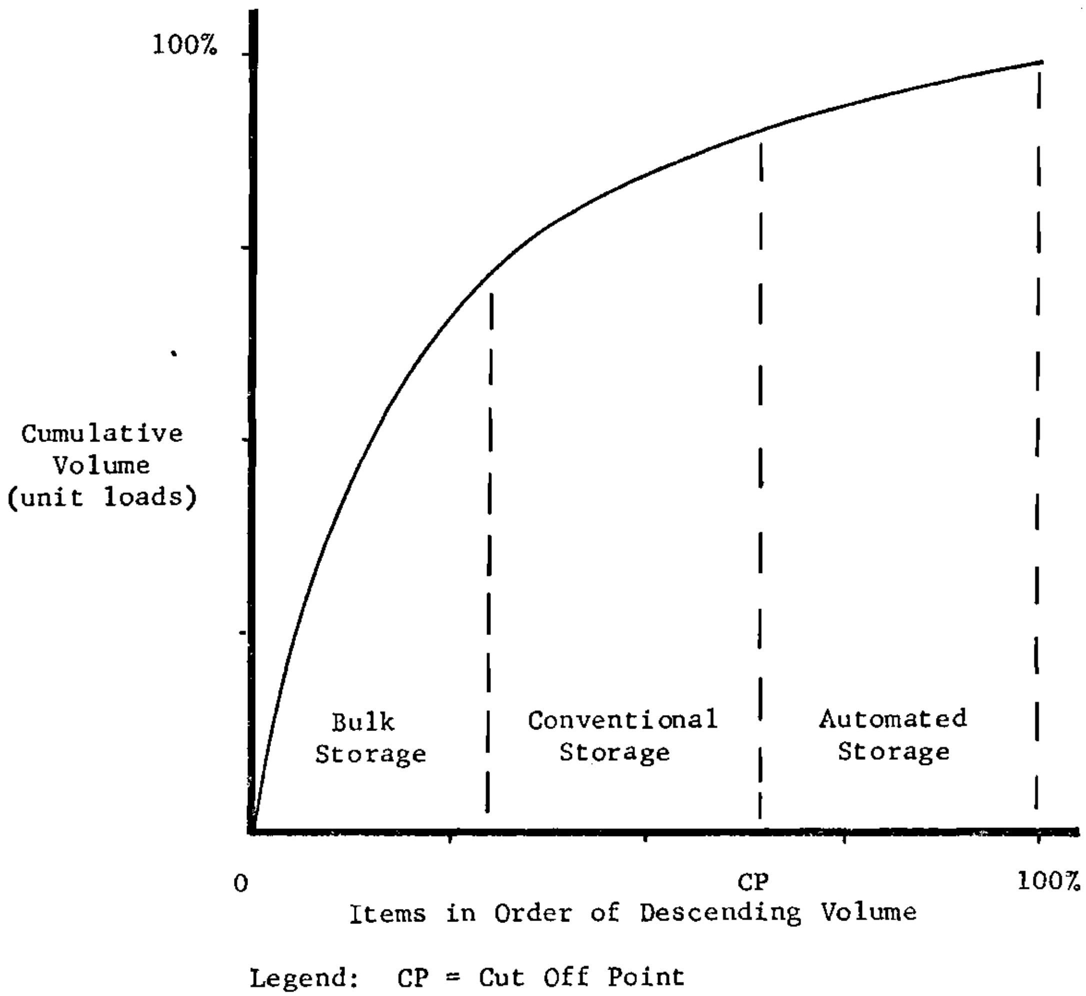


Figure 6. Stock Profile - Items vs. Volume.

the item mix under either criterion that minimizes the total storage cost (TSCL). This item mix is created by the cut off point shown in Figure 7.

Cost Formulae

In Appendix D, a detailed breakdown of elemental costs is given for the two types of warehouses. Since the study is concerned with developing an analytical technique, these costs must be expressed in terms of mathematical cost formulae.

Automated Warehouse Cost Formulae

Let

K_a = storage slot requirement for the automated warehouse (unit loads),

n = number of aisles required,

n' = number of storage machines required,

Y_a = the length of the racks (feet),

Y_{maxa} = maximum allowed rack length (feet),

Z_a = the height of the racks (feet),

xa = load spacing-size plus clearance-depth (inches),

ya = load spacing-size plus clearance-width (inches),

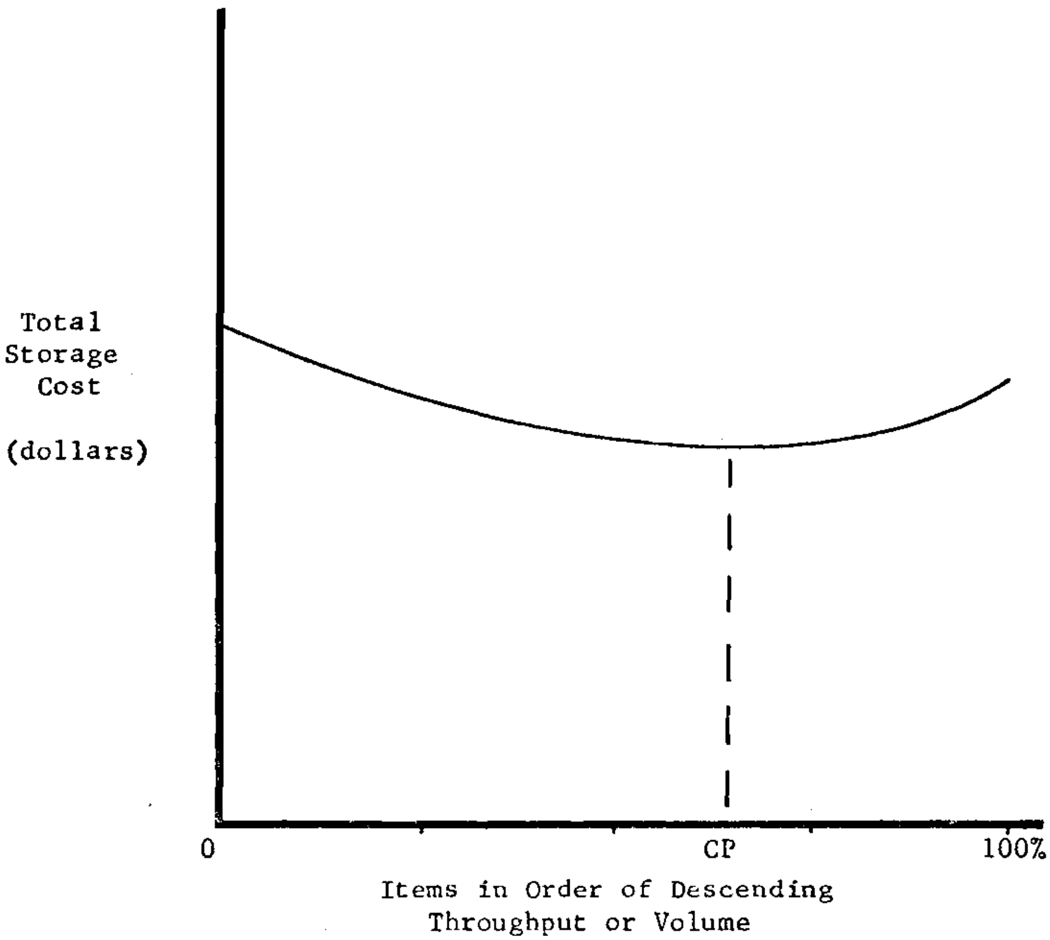
za = load spacing-size plus clearance-height (inches),

R_{xa} = aisle width (inches),

M_a = throughput for the automated warehouse (unit loads/period),

N_{ra} = number of pairs of frames required,

R_{ya} = length of the staging area from the racks to the front of



Legend: CP = Cut Off Point

Figure 7. Total Storage Cost Curve.

the warehouse building (feet),

M_{maxa} = maximum throughput capacity of one storage machine (unit loads/period).

A frame consists of the slots contained between a pair of columns in a rack row. The number of slots in a pair of frames on either side of an aisle is

$$= \frac{2 \text{ x height of the racks}}{\text{height of one slot}}$$

$$= \frac{2Z_a}{za/12} \text{ slots.}$$

The number of pairs of frames required (N_{ra}) is

$$= \frac{\text{total storage slot requirement in automated warehouse}}{\text{number of slots in one pair of frames}}$$

$$= \frac{K_a}{2Z_a/(za/12)} \quad .$$

The total length of aisle required to accommodate the number of pairs of frames required is

= the number of pairs of frames required x the width of one slot

$$= (N_{ra})(ya/12) \text{ feet.}$$

The number of aisles required is

= n, when the total length of aisle required to accommodate the number of pairs of frames required is less than or equal to n x maximum allowed rack length and greater than (n-1) x maximum allowed rack length

= n, when $(n-1)Y_{maxa} < (N_{ra})(ya/12) \leq nY_{maxa}$.

The length of the racks (Y_a) is

$$= (\frac{N_{ra}}{n})(ya/12) \text{ where } (n-1)Y_{maxa} < (N_{ra})(ya/12) \leq nY_{maxa} .$$

Note: If the quantity $(\frac{N_{ra}}{n})$ contains a fractional part, it must be rounded off to the next higher whole number.

The number of storage slots in one aisle

$$= \frac{\text{area of two racks facing aisle}}{\text{area of one slot facing aisle}}$$

$$\doteq \frac{2\ Y_a Z_a}{(ya)(za)/144} \text{ slots.}$$

The floor area occupied by one aisle, two rows of racks, and one section of staging area

= width of one aisle and two racks x length of the racks and staging area

$$= \left(\frac{R_{xa} + 2xa}{12}\right)(Y_a + R_{ya}) \text{ square feet.}$$

Number of aisles required to accommodate the storage slot requirement

= n, when the storage slot requirement is less than or equal to the number of storage slots in n aisles and greater than the number of storage slots in n-1 aisles

$$= n, \text{ when } \frac{2(n-1)\ Y_a Z_a}{(ya)(za)/144} < K_a \leq \frac{2n\ Y_a Z_a}{(ya)(za)/144} .$$

Note: the number of storage slots available is given in increments of the number of slots in one aisle.

Number of storage machines required to accommodate the throughput requirement

= n', when the throughput requirement is less than or equal to the throughput capacity of n' machines and greater than the throughput capacity of n'-1 machines

$$= n', \text{ when } (n'-1)\ M_{maxa} < M_a \leq n' M_{maxa}.$$

Each cost formula represents a linear relationship between the required number of pieces of equipment and operators and their respective costs. This relationship is not exactly correct due to quantity discounts, etc. However, it is a necessary assumption for the sake of simplicity.

1. Cost of the computer

$= 0$, when $K_a = 0$

$= VC1$, when $K_a > 0$

when VC1 is the equivalent uniform annual cost (EUA) of one computer and peripheral equipment.

Note: For the sake of clarity, one period is taken as one year.

2. Cost of the computer operators

$= 0$, when $K_a = 0$

$= VC2$, when $K_a > 0$

where VC2 is the EUA cost of one or more operators.

3. Cost of the warehouse building

$= 0$, when $K_a = 0$

$$= n\left(\frac{R_{xa} + 2xa}{12}\right)(Y_a + R_{ya})(VC3),$$

$$\text{when } \frac{2(n-1)Y_a Z_a}{(ya)(za)/144} < K_a \leq \frac{2nY_a Z_a}{(ya)(za)/144}$$

where VC3 is the EUA cost of one square foot of floor area.

4. Cost of the computer room

$$= 0, \text{ when } K_a = 0$$

$$= VC4, \text{ when } K_a > 0$$

where VC4 is the EUA cost of one computer room.

5. Cost of the racks

$$= 0, \text{ when } K_a = 0$$

$$= n\left\{\frac{2Y_aZ_a}{(ya)(za)/144}\right\} (VC5), \text{ when } \frac{2(n-1)Y_aZ_a}{(ya)(za)/144} < K_a \leq \frac{2nY_aZ_a}{(ya)(za)/144}$$

where VC5 is the EUA cost of one slot.

6. Cost of the pallets

$$= K_a(VC6), \text{ when } K_a > 0$$

where VC6 is the EUA cost of one pallet.

7. Cost of the storage machines

$$= 0, \text{ when } M_a = 0$$

$$= n'(VC7), \text{ when } (n'-1)M_{maxa} < M_a \leq n'M_{maxa}$$

where VC7 is the EUA cost of one storage machine.

8. Cost of the transfer cars

$$= 0, \text{ when } M_a = 0$$

$$= n'(VC8), \text{ when } (n'-1)M_{maxa} < M_a \leq n'M_{maxa}$$

where VC8 is the EUA cost of one transfer car.

9. Cost of the conveyor networks

$$= 0, \text{ when } K_a = 0$$

$$= n(VC9), \text{ when } \frac{2(n-1)Y_a Z_a}{(ya)(za)/144} < K_a \leq \frac{2nY_a Z_a}{(ya)(za)/144}$$

where VC9 is the EUA cost of conveyor to service one aisle.

Conventional Warehouse Cost Formulae

Let

K_c = storage slot requirement for the conventional warehouse (unit loads),

p = number of aisles required,

p' = number of fork lift trucks required,

Y_c = the length of the racks (feet),

Y_{maxc} = maximum allowed rack length (feet),

Z_c = the height of the racks (feet),

xc = load spacing-size plus clearance-depth (inches),

yc = load spacing-size plus clearance-width (inches),

zc = load spacing-size plus clearance-height (inches),[1]

R_{xc} = aisle width (inches),

R_{yc} = lateral aisle width (feet),

M_c = throughput for the conventional warehouse (unit loads/ period),

N_{rc} = number of pairs of frames required,

M_{maxc} = maximum throughput capacity of one fork lift truck (unit loads/period).

A frame consists of the slots contained between a pair of columns in a rack row. The number of slots in a pair of frames on either side of an aisle is

$$= \frac{2 \text{ x height of the racks}}{\text{height of one slot}}$$

$$= \frac{2Z_c}{zc/12} \text{ slots.}$$

The number of pairs of frames required (N_{rc}) is

$$= \frac{\text{total storage slot requirement in conventional warehouse}}{\text{number of slots in one pair of frames}}$$

$$= \frac{K_c}{2Z_c/(zc/12)} \text{ slots.}$$

The total length of aisle required to accommodate the number of pairs of

---

[1] The values of xc, yc, and zc are usually the same as the values of xa, ya, and za, respectively.

frames required is

$$= \text{the number of pairs of frames required x the width of one slot}$$

$$= (N_{rc})(yc/12) \text{ feet.}$$

The number of aisles required is

= p, when the total length of aisle required to accommodate the number of pairs of frames required is less than or equal to p x maximum allowed rack length and greater than (p-1) x maximum allowed rack length

$$= p, \text{ when } (p-1)Y_{maxc} < (N_{rc})(yc/12) \leq pY_{maxc} .$$

The length of the racks (Y_c) is

$$= \left(\frac{N_{rc}}{p}\right)(yc/12) \text{ where } (p-1)Y_{maxc} < (N_{rc})(yc/12) \leq pY_{maxc} .$$

Note: If the quantity $\left(\frac{N_{rc}}{p}\right)$ contains a fractional part, it must be rounded off to the next higher whole number.

The number of storage slots in one aisle

$$= \frac{\text{area of two racks facing aisle}}{\text{area of one slot facing aisle}}$$

$$= \frac{2Y_c Z_c}{(yc)(zc)/144} .$$

The floor area occupied by one aisle, two rows of racks, and one section of lateral aisle

= width of one aisle and two racks x length of the racks and width of the lateral aisle

$$= (\frac{R_{xc} + 2xc}{12})(Y_c + R_{yc}) \text{ square feet.}$$

Number of aisles required to accommodate the storage slot requirement

= p, when the storage slot requirement is less than or equal to the number of storage slots in p aisles and greater than the number of storage slots in p-1 aisles

$$= p, \text{ when } \frac{2(p-1)Y_c Z_c}{(yc)(zc)/144} < K_c \leq \frac{2p\ Y_c Z_c}{(yc)(zc)/144} .$$

Number of fork lift trucks required to accommodate the throughput requirement

= p', when the throughput requirement is less than or equal to the throughput capacity of p' trucks and greater than the throughput capacity of p'-1 trucks

$= p'$, when $('-1)M_{maxc} < M_c \leq p'M_{maxc}$.

1. Cost of the warehouse building

$$= 0, \text{ when } K_c = 0$$

$$= p(\frac{R_{xc} + 2xc}{12})(Y_c + R_c)(VC1),$$

$$\text{when } \frac{2(p-1)Y_c Z_c}{(yc)(zc)/144} < K_c \leq \frac{2p\ Y_c Z_c}{(yc)(zc)/144}$$

where CV1 is the equivalent uniform annual (EUA) cost of one square foot of floor area.

2. Cost of the racks

$$= 0, \text{ when } K_c = 0$$

$$= p\ \{\frac{2Y_c Z_c}{(yc)(zc)/144}\}\ (VC2),$$

$$\text{when } \frac{2(p-1)Y_c Z_c}{(yc)(zc)/144} < K_c \leq \frac{2pY_c Z_c}{(yc)(zc)/144}$$

where VC2 is the EUA cost of one slot

3. Cost of the pallets

$$= K_c(VC3), \text{ when } K_c > 0$$

where VC3 is the EUA cost of one pallet.

4. Cost of the fork lift trucks

$= 0$, when $M_c = 0$

$= p'(VC4)$, when $(p'-1)M_{maxc} < M_c \leq p'M_{maxc}$

where VC4 is the EUA cost of one fork lift truck.

5. Cost of the fork lift truck operators

$= 0$, when $M_c = 0$

$= p'(VC5)$, when $(p'-1)M_{maxc} < M_c \leq p'M_{maxc}$

where VC5 is the EUA cost of one fork lift truck operator.

6. Cost of the job scheduler

$= 0$, when $K_c = 0$

$= VC6$, when $K_c > 0$

where VC6 is the EUA cost of one job scheduler.

7. Cost of the job scheduling office and equipment

$= 0$, when $K_c = 0$

$= VC7$, when $K_c > 0$

where VC7 is the EUA cost of one job scheduling office and equipment.

Throughput Capacity

Automated Warehouse

In the automated warehouse, the required number of storage machines depends on the maximum throughput capacity of one storage machine (M_{maxa}). The number of transfer cars will depend on the number of storage machines. To determine the maximum throughput capacity of a storage machine, a measure of the average cycle time is necessary. Cycle time (CT_a) is the time for the storage machine to make one complete storage/retrieval cycle plus a delay time for aisle transfer.

Delay time for aisle transfer is made up of two parts: transfer time (TCT_t) and positioning time (TCP_t). It is assumed for this study that the storage machine makes more than one cycle in each aisle before being transferred to another aisle. It is also assumed that only transfers to adjacent aisles are permitted. Since the storage machine makes several cycles in each aisle, the delay time must be spread out over these cycles. Therefore, transfer time (TCT_t) is equal to the time to transfer from one aisle to the adjacent aisle divided by the average number of cycles in each aisle. Positioning time (TCP_t) is equal to the time to precisely position the transfer car at an aisle divided by the average number of cycles in each aisle. The delay for aisle transfer is

= 0, when the storage slot requirement is less than or equal to the number of slots in one aisle or $K_a \leq \frac{2Y_a Z_a}{(ya)(za)/144}$

= $TCT_t + TCP_t$ minutes, when the storage slot requirement is greater than the number of slots in one aisle or

$$K_a > \frac{2Y_aZ_a}{(ya)(za)/144} .$$

Cycle time depends on the type of cycle used by the storage machine. The two types, single and dual address, were described in Chapter II along with their variations. The process charts in Figure 8 describe the variations of the single address cycle. The dual address cycle's variations are shown on the process charts in Figure 9.

There are generally two methods which are used for determining the cycle time (CT_a) for the system. These are the "rule-of-thumb" method and the computer simulation method. The "rule-of-thumb" method involves determining the time required to travel to and return from the average slot of the system. For a single address cycle, the average slot is assumed to be located half-way along the length of the aisle and half-way up the height of the racks. For a dual address cycle, there is some confusion as to the location of the average slot. Some authorities accept two-thirds of the distance along the aisles and up the racks, while others accept three-quarters of the distance (34). In either case, the cycle time is taken as the time to travel to and return from the average slot of the system.

The computer simulation method for finding cycle time involves simulating the actual movement of the storage machine in the system for a certain length of time and calculating the average cycle time for a large number of cycles. Although the simulation method is more accurate, it is also more complicated and time consuming to use in a computer program. Since the results affect only two elements of the total storage cost for

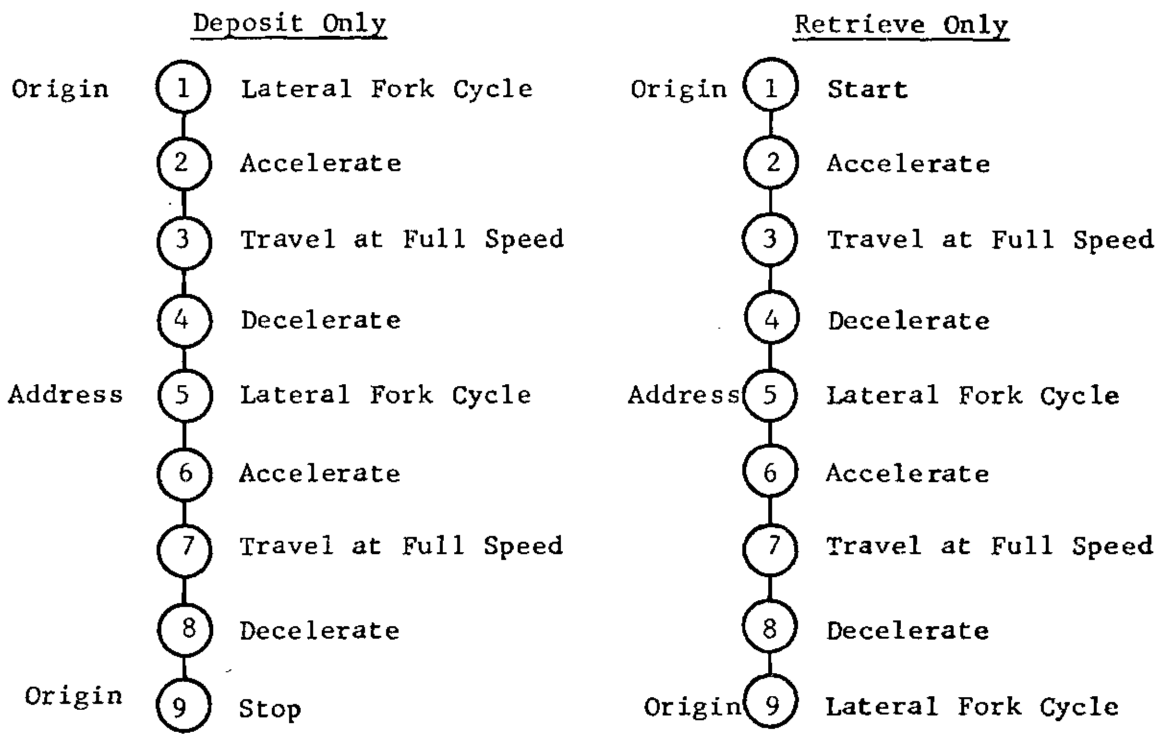


Figure 8. Storage Machine Process Charts for Single Address Cycles.

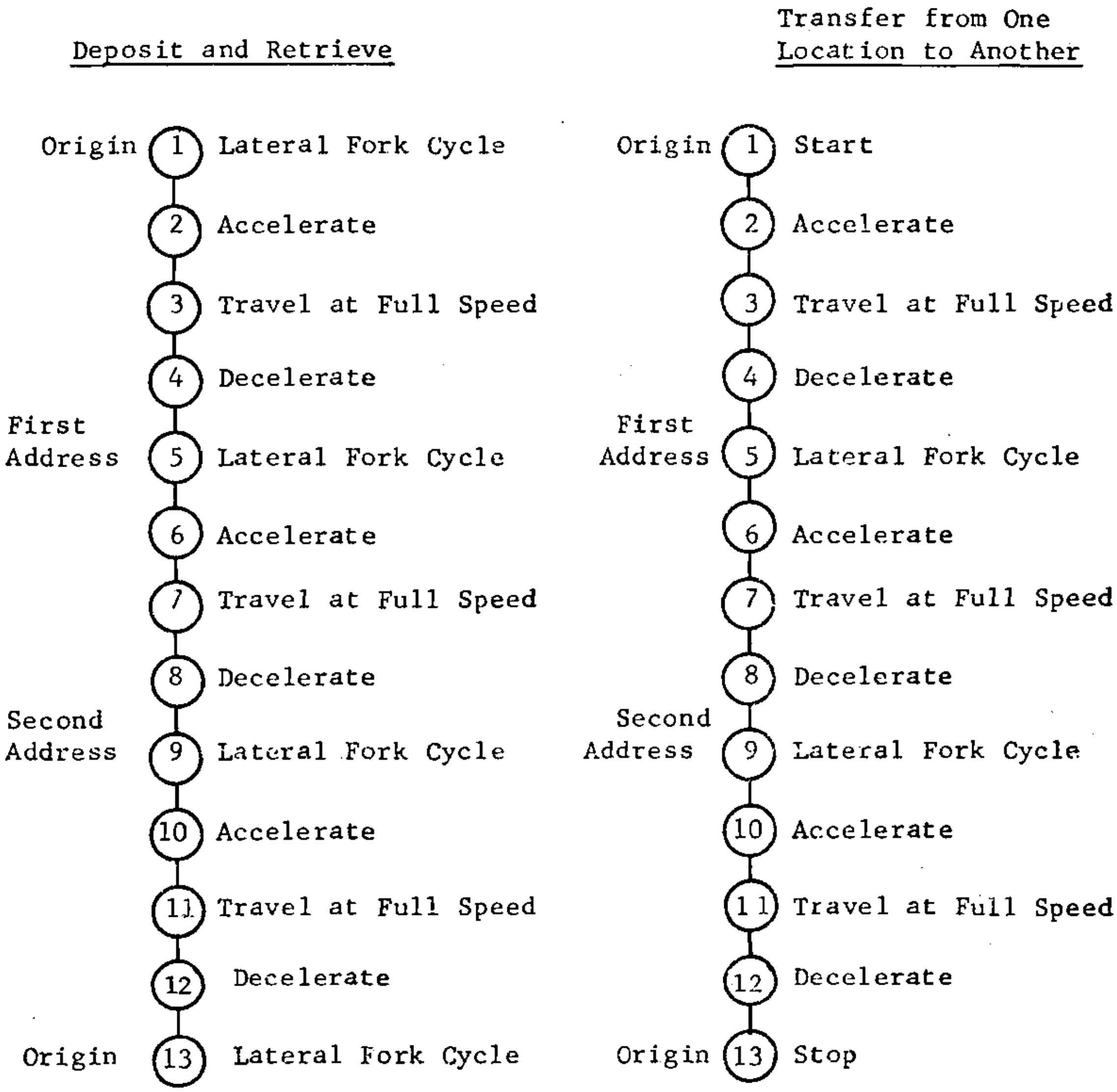


Figure 9. Storage Machine Process Charts for Dual Address Cycles.

the automated warehouse (VC8 and VC9), the slightly less accurate "rule-of-thumb" method will be used in this study.

Since the storage machine can move in the horizontal and vertical directions simultaneously, the horizontal distance to the average slot may be reached before the vertical distance or vice versa. Therefore, the cycle time will be governed by the time to cover the horizontal distance or the time to cover the vertical distance, whichever is greater.

Let

F_{ta} = lateral fork cycle time to extend forks, lift or lower the the load, and retract forks (minutes),

A_{yt} = time to accelerate from zero to full travel speed or decelerate from full travel speed to zero (minutes),

R_a = an indicator representing the relative distance of the average slot (value depends on rule-of-thumb and type of cycle),

A_{yd} = distance to accelerate from zero to full travel speed or decelerate from full travel speed to zero (feet),

V_y = storage machine travel speed (feet/minute),

D_{zt} = time to accelerate from zero to full hoist speed or decelerate from full hoist speed to zero (minutes),

D_{zd} = distance to accelerate from zero to full hoist speed or decelerate from full hoist speed to zero (feet),

V_z = storage machine hoist speed (feet/minute),

T = total available time units per period (minutes).

The time to travel the horizontal distance to the average slot for a single address cycle (35) is

= 2 x fork cycle time + 2 x acceleration time + 2 x deceleration time + 2 x travel time at full speed + delay time for aisle transfer

$$= 2F_{ta} + 4A_{yt} + 2\left(\frac{R_a Y_a - 2A_{yd}}{V_y}\right) + TCT_t + TCP_t \text{ minutes.}$$

The time to travel the vertical distance to the average slot for a single address cycle is

= 2 x fork cycle time + 2 x acceleration time + 2 x deceleration time + 2 x hoist time at full speed + delay time for aisle transfer

$$= 2F_{ta} + 4D_{zt} + 2\left(\frac{R_a Z_a - 2D_{zd}}{V_z}\right) + TCT_t + TCP_t \text{ minutes.}$$

The cycle time (CT_a) for a single address cycle is

$$= \max.\ \{2F_{ta} + 4A_{yt} + 2\left(\frac{R_a Y_a - 2A_{yd}}{V_y}\right) + TCT_t + TCP_t,$$

$$2F_{ta} + 4D_{zt} + 2\left(\frac{R_a Z_a - 2D_{zd}}{V_z}\right) + TCT_t + TCP_t\} \text{ minutes.}$$

The time to travel the horizontal distance to the average slot for a dual address cycle (36) is

= 4 x fork cycle time + 3 x acceleration time + 3 x deceleration time + travel time at full speed + delay time for aisle transfer

$$= 4F_{ta} + 6A_{yt} + \frac{2R_aY_a - 6A_{yd}}{V_y} + TCT_t + TCP_t \text{ minutes.}$$

The time to travel the vertical distance to the average slot for a dual address cycle is

= 4 x fork cycle time + 3 x acceleration time + 3 x deceleration time + hoist time at full speed + delay time for aisle transfer

$$= 4F_{ta} + 6D_{zt} + \frac{2R_aZ_a - 6D_{zd}}{V_z} + TCT_t + TCP_t \text{ minutes.}$$

The cycle time (CT_a) for a dual address cycle is

$$= \max. \{4F_{ta} + 6A_{yt} + \frac{2R_aY_a - 6A_{yd}}{V_y} + TCT_t + TCP_t,$$

$$4F_{ta} + 6D_{zt} + \frac{2R_aZ_a - 6D_{zd}}{V_z} + TCT_t + TCP_t\} \text{ minutes.}$$

Note: The above formula is based on the Deposit and Retrieve Cycle shown in Figure 9.

The maximum throughput capacity (M_{maxa}) of one storage machine for a single address cycle in one period is

$$= \frac{\text{total available minutes per period}}{\text{cycle time}}$$

$$= \frac{T}{CT_a} \text{ unit loads/period.}$$

The maximum throughput capacity (M_{maxa}) of one storage machine for a dual address cycle in one period is

$$= \frac{2 \text{ x total available minutes per period}}{\text{cycle time}}$$

$$= \frac{2T}{CT_a} \text{ unit loads/period.}$$

Conventional Warehouse

In the conventional warehouse, the required number of fork lift trucks and operators depends on the maximum throughput capacity (M_{maxc}) of the system. Since the fork lift truck is not confined to a fixed path, new variables such as turn, reverse, and tilt carriage must be added to the cycle time formulae. Consideration must be made for non-simultaneous travel and hoist movement. Human, mechanical, and operational allowances must also be included. The process charts for single and dual address cycles are shown in Figures 10, 11, and 12. These charts assume that the fork lift truck is in motion when it enters or exits the warehouse.

Using the "rule-of-thumb" method described earlier, the cycle time (CT_c) is taken as the time to travel to and return from the average slot of the system. Let

A = sum of all applicable allowances (% ÷ 100),

F_t = time to travel one foot at full travel speed (minutes/foot),

T_t = time to change direction of the fork lift truck by 90 degrees

Deposit Only

	Step	Operation
Enter Warehouse	1	Travel Forward
	2	90° Turn, Forward
	3	Travel Forward
	4	90° Turn, Forward
	5	Travel Forward
	6	90° Turn & Stop, Forward
	7	Tilt Carriage
	8	Hoist Up
	9	Run Into Slot
Address	10	Hoist Down
	11	Run Out of Slot
	12	Hoist Down
	13	90° Turn & Stop, Reverse
	14	Accelerate
	15	Travel Forward
	16	90° Turn, Forward
	17	Travel Forward
	18	90° Turn, Forward
Leave Warehouse	19	Travel Forward

Retrieve Only

	Step	Operation
Enter Warehouse	1	Travel Forward
	2	90° Turn, Forward
	3	Travel Forward
	4	90° Turn, Forward
	5	Travel Forward
	6	90° Turn & Stop, Forward
	7	Hoist Up
	8	Run Into Slot
Address	9	Hoist Up
	10	Run Out of Slot
	11	Hoist Down
	12	Tilt Carriage
	13	90° Turn & Stop, Reverse
	14	Accelerate
	15	Travel Forward
	16	90° Turn, Forward
	17	Travel Forward
	18	90° Turn, Forward
Leave Warehouse	19	Travel Forward

Figure 10. Fork Lift Truck Process Charts for Single Address Cycles.

Deposit and Retrieve

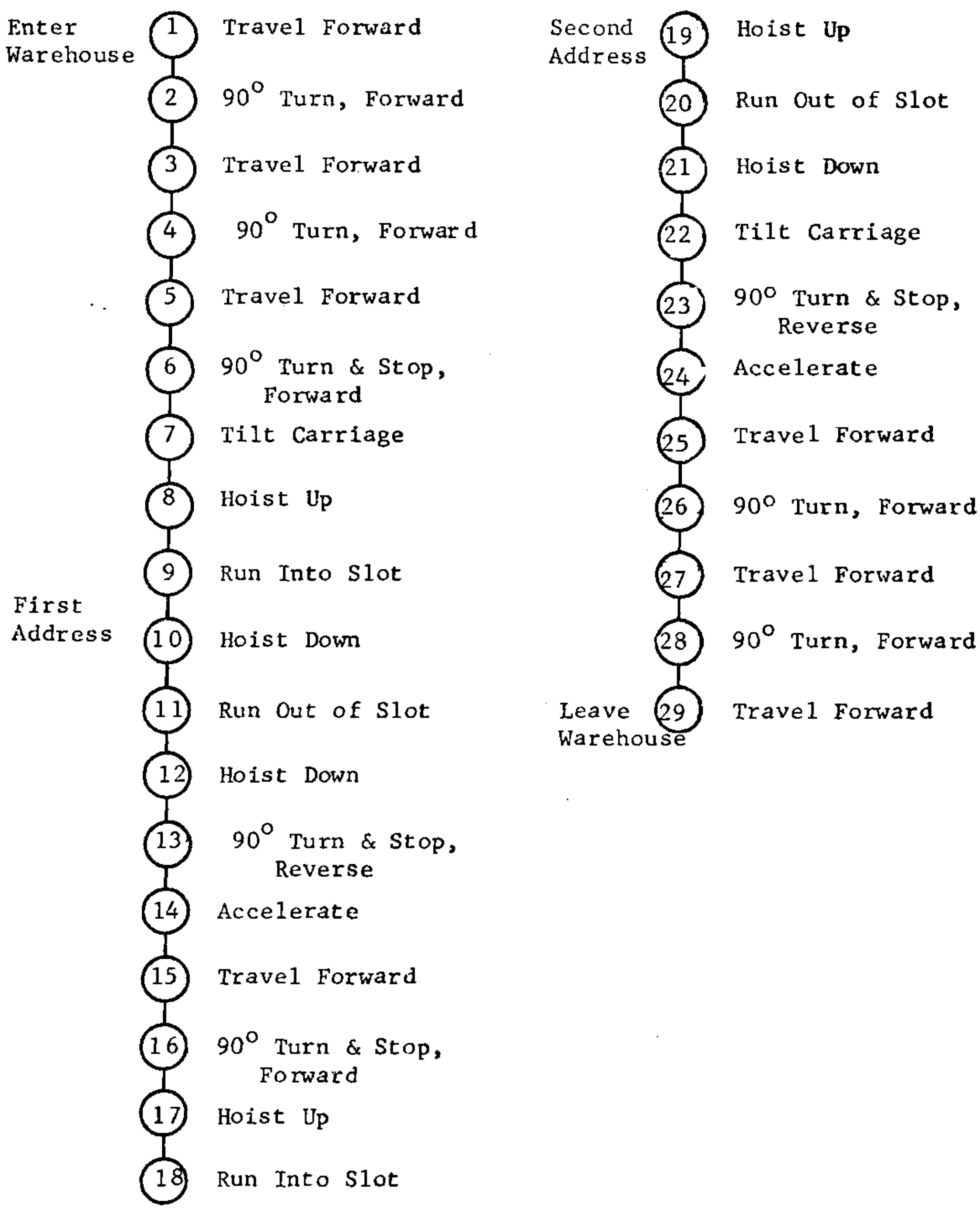


Figure 11. Fork Lift Truck Process Chart for Dual Address Cycle - Deposit and Retrieve.

Transfer from One Location to Another

Enter Warehouse
1. Travel Forward
2. 90° Turn, Forward
3. Travel Forward
4. 90° Turn, Forward
5. Travel Forward
6. 90° Turn & Stop, Forward
7. Hoist Up

First Address
8. Run Into Slot
9. Hoist Up
10. Run Out of Slot
11. Hoist Down
12. Tilt Carriage
13. 90° Turn & Stop, Reverse
14. Accelerate
15. Travel Forward
16. 90° Turn & Stop, Forward
17. Tilt Carriage
18. Hoist Up

Second Address
19. Run Into Hoist
20. Hoist Down
21. Run Out of Slot
22. Hoist Down
23. 90° Turn & Stop, Reverse
24. Accelerate
25. Travel Forward
26. 90° Turn, Forward
27. Travel Forward
28. 90° Turn, Forward

Leave Warehouse
29. Travel Forward

Figure 12. Fork Lift Truck Process Chart for Dual Address Cycle - Transfer from One Location to Another.

while in forward motion (minutes),

TS_t = time to turn the fork lift truck 90 degrees and stop (minutes),

H_t = time to raise or lower hoist per unit distance (minutes/foot),

A_t = time to accelerate to full travel speed (minutes),

RI_t = time to insert forks into a pallet or place a pallet into a slot (minutes),

RO_t = time to withdraw forks from the pallet or remove a pallet from a slot (minutes),

TL_t = time to tilt carriage (minutes),

O_t = time that the fork lift truck operates outside the warehouse building on each cycle (minutes),

X_c = total width of the warehouse building (feet),

For a single address cycle, the average aisle is assumed to be located half-way between the door and the end of the building. Within this aisle, the average slot is half-way along the length of the aisle and half-way up the height of the racks. For a dual address cycle, the average aisle is located half-way between the door and the end of the building. Within the average aisle, there is some confusion as to the location of the average slot. Assuming that the location of the average slot is the same as in the automated warehouse, some authorities accept two-thirds of the distance along the aisles and up the racks, while others accept three-quarters of the distance (37).

The cycle time of the fork lift truck depends on the location of the door. Let the entry ratio (R_e) correspond to the location of the door in relation to the width of the warehouse building (X_c). For example, if the door were located half-way between one end of the building and the other end, the entry ratio would be one-half. The door can be thought of as dividing the warehouse into two parts, each with an average slot. The distance to the aisles containing the average slots in each part are given by $\frac{R_e X_c}{2}$ and $\frac{(1 - R_e)X_c}{2}$ feet. The weighted average of these distances is the distance to the aisle containing the average slot for the whole warehouse. The weighting factors are assumed to be

$$= \frac{\text{areas of each part}}{\text{area of the warehouse}}$$

$$= \frac{R_e X_c(Y_c + R_{yc})}{X_c(Y_c + R_{yc})} \text{ and } \frac{(1 - R_e)X_c(Y_c + R_{yc})}{X_c(Y_c + R_{yc})}$$

$$= R_e \text{ and } (1 - R_e) .$$

The weighted average distance to the aisle containing the average slot is

$$= R_e \left(\frac{R_e X_c}{2}\right) + (1 - R_e)\left(\frac{(1 - R_e)X_c}{2}\right)$$

$$= \frac{R_e^2 X_c}{2} + \frac{(1 - 2R_e + R_e^2)X_c}{2}$$

$$= \frac{(1 - 2R_e + 2R_e^2)X_c}{2} \text{ feet.}$$

The width of one aisle and two rows of racks is

$$= \left(\frac{2xc + R_{xc}}{12}\right) \text{ feet.}$$

The number of storage slots available in one aisle is

$$= \frac{2Y_c Z_c}{(yc)(zc)/144} \text{ slots.}$$

The total width of the warehouse building (X_c) is

$$= 0, \text{ when } K_c = 0$$

$$= p\left(\frac{2xc + R_{xc}}{12}\right) \text{ feet, when } \frac{2(p-1)Y_c Z_c}{(yc)(zc)/144} < K_c \leq$$

$$\frac{2pY_c Z_c}{(yc)(yz)/144} .$$

The cycle time (CT_c) for a single address cycle is

= (1 + allowances) x (2 x lateral aisle width x travel time per foot + 2 x R_c x length of racks x travel time per foot + 4 x time to turn 90 degrees + 2 x time to turn 90 degrees and stop + 2 x R_c x height of racks x hoist time per foot + acceleration time + run-in forks time + run-out forks time + time to tilt carriage + outside warehouse time + travel time per foot x distance from door to aisle)

$$= (1 + A) \ \{2R_{yc}F_t + 2R_cY_cF_t + 4T_t + 2TS_t + 2R_cZ_cH_t + A_t + RI_t + RO_t + TL_t + O_t + F_t \left(\frac{(1 - 2R_e + 2R_e^2)X_c}{2}\right)\}$$

minutes.

The cycle time (CT_c) for a dual address cycle assuming both addresses are in the same aisle is

= (1 + allowances) x (2 x lateral aisle width x travel time per foot + 2 x R_c x length of racks x travel time per foot + 4 x time to turn 90 degrees + 4 x time to turn 90 degrees and stop + 2 x R_c x height of racks x hoist time per foot + 2 x acceleration time + 2 x run-in forks time + 2 x run-out forks time + 3 x time to tilt carriage + outside warehouse time + travel time per foot x distance from door to aisle)

$$= (1 + A) \ \{2R_{yc}F_t + 2R_cY_cF_t + 4T_t + 4TS_t + 2R_cZ_cR_t + 2A_t + 2RI_t + 2RO_t + 3TL_t + O_t + F_t \left(\frac{(1 - 2R_e + 2R_e^2)X_c}{2}\right)\}$$

minutes.

The maximum throughput capacity (M_{maxc}) of one fork lift truck and operator for a single address cycle is

$$= \frac{\text{total available minutes per period}}{\text{cycle time}}$$

$$= \frac{2T}{CT_c} \text{ unit loads/period.}$$

Procedural Steps

A simple enumerative technique was developed to find the storage slot requirement of an automated warehouse that minimizes the total storage cost (TSC). It is a step-by-step procedure that locates the minimum point of the total storage cost curve as shown in Figure 7.

Step One

From inventory records, determine the individual stock levels (K_{ijm}). Convert the stock levels from units to unit loads. Calculate the average stock on hand ($\bar{K}_{ij}$) for each item in each time period.

Step Two

Using the steps given in Chapter III compute the maximum required number of storage slots (K^*_{ij}) for each item in each future time period. Round off K^*_{ij} to the next whole number.

Step Three

To begin with, let all the items be in conventional storage. Using Method 1 (for fixed location storage) described in Chapter III, find the total of the predicted maximum required number of storage slots (K^*_{ij}) for every item for a given risk. Do this for each future period. These sums are the number of slots required (K^*_j) for each future period.

Step Four

Using the storage slot requirement for each future period (K^*_j) obtained in Step Three, calculate the total annual cost (TSC) for each future period. The total annual cost is the sum of all the elemental costs of Appendix D. Sum the total annual costs for all future periods to find the total storage cost for the life of the warehouse (TSCL).

Note: For the sake of comparison, the lives of the buildings and equipment are assumed to be identical for calculating the depreciation.

Step Five

Change the item mix and return to Step Three. In other words, allow the item having the highest throughput or lowest volume per item (whichever one is being used) in the conventional warehouse to be transferred to the automated warehouse.

Note: The ordering of items by throughput or volume per item is based on their predicted throughput or volume at the last future period.

Calculate the required storage slots (K^*_j) for the automated and conventional warehouses for each future period. Find the total storage cost (TSCL) for the life of the warehouses by summing the total annual cost (TSC) for each warehouse for each future period. Transfer the item having the next highest throughput or next lowest volume per item in the conventional warehouse into the automated warehouse and return to Step Three. Continue until all items are in automated storage.

Step Six

Locate the minimum total storage cost (TSCLM). Use the automated warehouse storage slot requirement (K_a) corresponding to the item mix of the minimum total storage cost as the best storage slot requirement.

These steps will provide the warehouse designer with a systematic method for determining the required number of storage slots in a high-rise automated warehouse.

CHAPTER V

MODEL TESTING

Introduction

An appropriate method of testing the model is to apply it to typical data and analyze the results. Since manually performing the procedural steps of Chapter IV would be very laborious, a computer program was developed.

The program was written in Fortran-IV and run on the Univac 1108 computer. The principal stages of the program are shown on the system flow chart in Figure 13. Fortran-IV was chosen as the programming language because relatively more programmers are familiar with it and most places have a Fortran Compiler. Also, Fortran's flexibility allows for changes and additions to the basic program without excessive reprogramming.

To test the model, design specifications typical of industry were assembled. These specifications cover three areas: item specifications, handling and storage system specifications, and inventory specifications. Items to be handled are unit loads weighing up to 2,000 pounds and stored on 48" x 48" pallets. Each unit load contains a given quantity of one item and does not exceed 48 inches in height. The handling and storage system specifications represent typical equipment available today. Inventory specifications are based on a 50 item inventory with an average volume of 4,000 unit loads. The inventory volume conforms approximately to the typical 60%-20% distribution. Inventory throughput conforms approximately to the typical 75%-20% distribution. The items are numbered 1 through 50

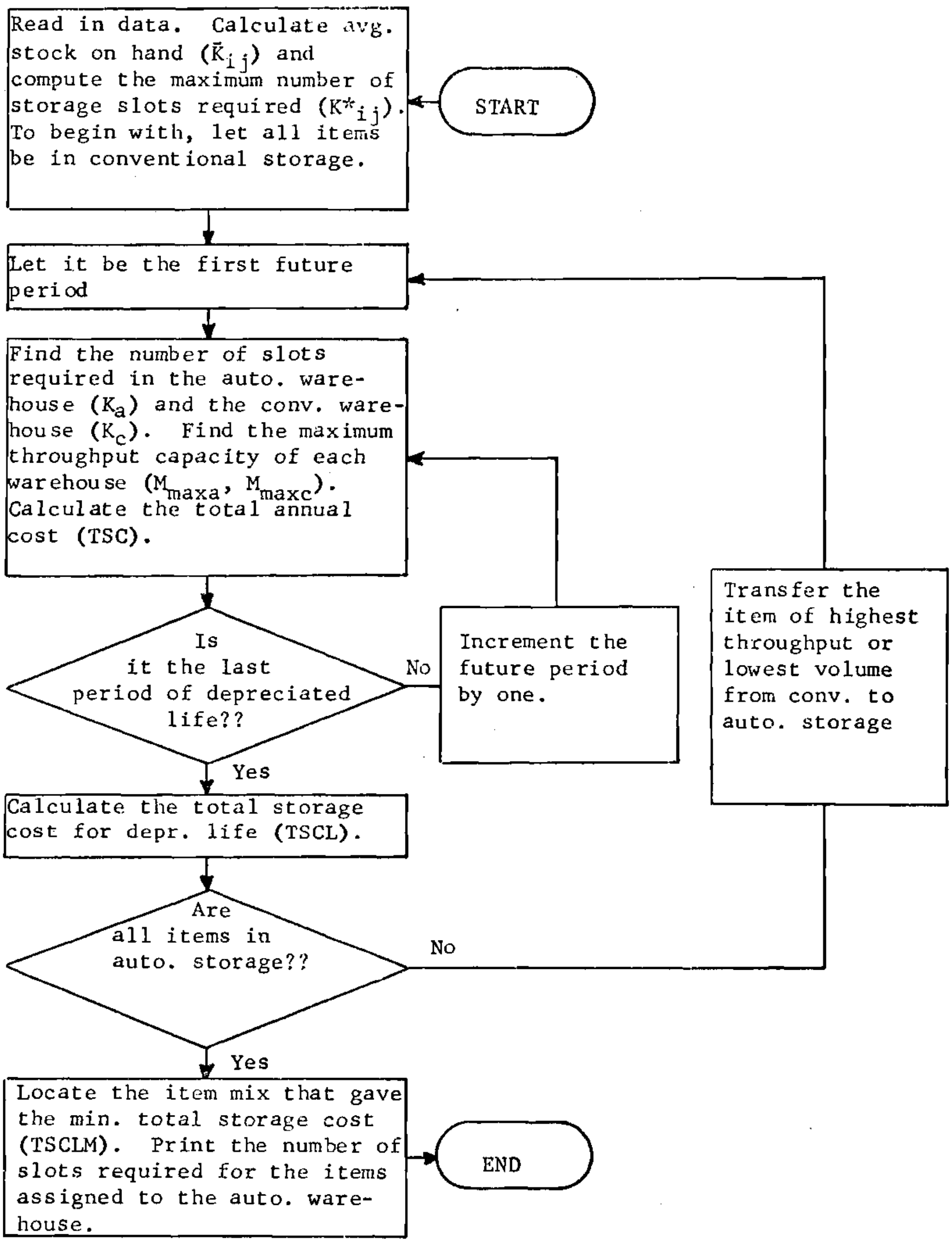


Figure 13. Principal Stages of the Program.

and the stock distributions for each item are symmetric and approximately normal. Inventory records are available on every item for the past five years with 12 observations for each year.

Preparation of Input

For input to the computer, the design specifications were divided into six sets of data cards.

Data Set No. 1

Data set no. 1 has one card containing general information applying to both warehouses. A description of the field specifications is given below.[1] The format of this card is 7F8.0.

Column	
1-8	A percentage point of the standard normal distribution representing the risk of being unable to find room for incoming goods (k').
9-16	Life of the warehouse (periods) (L).
17-24	Total number of items (N).
25-32	Number of periods of past data (N_d).
33-40	Number of inventory observations per period (N_y).
41-48	Total available time units per period (minutes) (T).
49-56	Criterion for storage mode selection -- throughput (= 1.0) or volume (= 2.0) (C).

Data Set No. 2

Data set no. 2 has two data cards with information pertaining only to the automated warehouse. The format of both cards is 12F6.0.

[1] Enter all input data as real constants.

A description of the field specifications for the first card is given below.

Column

1-6 Type of cycle (single (= 1.0) or dual (= 2.0) address) (Aadd).

7-12 Distance to accelerate from zero to full travel speed or decelerate from full travel speed to zero (feet) (A_{yd}).

13-18 Time to accelerate from zero to full travel speed or decelerate from full travel speed to zero (minutes) (A_{yt}).

19-24 Distance to accelerate from zero to full hoist speed or decelerate from full hoist speed to zero (feet) (D_{zd}).

25-30 Time to accelerate from zero to full hoist speed or decelerate from full hoist speed to zero (minutes) (D_{zt}).

31-36 Fork cycle time to extend forks, lift or lower load in slot, and retract forks (minutes) (F_{ta}).

37-42 Load spacing -- size plus clearance -- depth (inches) (xa).

43-48 Load spacing -- size plus clearance -- width (inches) (ya).

49-54 Load spacing -- size plus clearance -- height (inches) (za).

55-60 An indicator representing the relative distance of the average slot ($0 \leq R_a \leq 1$) (R_a).

61-66 Storage machine aisle width (inches) (R_{xa}).

67-72 Length of staging area from racks to front of warehouse building (feet) (R_{ya}).

The second card has the following field specifications:

Column

1-6 Transfer car positioning time (minutes/storage machine cycle) (TCP_t).

7-12 Transfer car transfer time (minutes/storage machine cycle) (TCT_t).

13-18 Storage machine travel speed (feet/minute) (V_y).

19-24 Storage machine hoist speed (feet/minute) (V_z).

25-30 Maximum allowed length of the racks (Y_{maxa}).

31-36 Total height of racks (feet) (Z_a).

Data Set No. 3

Data set no. 3 has two data cards with information pertaining only to the conventional warehouse. The format of both cards is 12F6.0. A description of the field specifications for the first card is given below.

Column

1-6 Sum of all applicable allowances; fatigue, skill, weather, etc. (% ÷ 100) (A).

7-12 Type of cycle (single (= 1.0) or dual (= 2.0) address) (Cadd).

13-18 Time to accelerate to full travel speed (minutes) (A_t).

19-24 Time to travel one foot at full travel speed (minutes/foot) (F_t).

25-30 Time to raise or lower hoist (minutes/foot) (H_t).

31-36 Load spacing -- size plus clearance -- depth (inches) (xc).

37-42 Load spacing -- size plus clearance -- width (inches) (yc).

43-48 Load spacing -- size plus clearance -- height (inches) (zc).

49-54 Time the fork lift truck operates outside the warehouse building on each cycle (minutes) (O_t).

55-60 An indicator representing the relative distance to the average slot ($0 \leq R_c \leq 1$) (R_c).

61-66 Entry ratio ($0 \leq R_e \leq 1$) (R_e).

67-72 Time to insert forks into a pallet or place a pallet in the slot (minutes) (RI_t).

The second card has the following field specifications:

Column

1-6 Time to withdraw forks or remove a pallet (minutes) (RO_t).

7-12 Aisle width -- travel (inches) (R_{xc}).

13-18 Aisle width -- lateral (feet) (R_{yc}).

19-24 Time to tilt carriage (minutes) (TL_t).

25-30 Time to turn the fork lift truck 90 degrees and stop (minutes) (TS_t).

31-36 Time to change direction of the fork lift truck by 90 degrees (minutes) (T_t).

37-42 Maximum allowed length of the racks (Y_{maxc}).

43-48 Height of the racks (feet) (Z_c).

Data Set No. 4

Data set no. 4 has two cards with information pertaining only to the automated warehouse. The format of both cards is 8F9.0. A description of the field specifications is given below.

Column

1-9 The equivalent uniform annual (EUA) cost of one computer and peripheral equipment (dollars/year) (VC1).

10-18 The EUA cost of the required number of computer operators (dollars/year) (VC2).

19-27 The EUA cost of one square foot of floor area in the warehouse (dollars/year) (VC3).

28-36 The EUA cost of one computer room (dollars/year) (VC4).

37-45 The EUA cost of one storage slot (dollars/year) (VC5).

46-54 The EUA cost of one pallet (dollars/year) (VC6).

55-63 The EUA cost of one storage machine (dollars/year) (VC7).

64-72 The EUA cost of one transfer car (dollars/year) (VC8).

The second card has the following field specifications:

Column

1-9 The EUA cost of conveyor to service one aisle (dollars/year) (VC9).

Data Set No. 5

Data set no. 5 has one data card containing information applying only to the conventional warehouse. The format of this card is 7F8.0. A description of the field specifications is given below.

Column

1-8 The equivalent uniform annual (EUA) cost of one square foot of floor area in the warehouse (dollars/year) (VC1).

9-16 The EUA cost of one storage slot (dollars/year) (VC2).

17-24 The EUA cost of one pallet (dollars/year) (VC3).

25-32 The EUA cost of one fork lift truck (dollars/year) (VC4).

33-40 The EUA cost of one fork lift truck operator (dollars/year) (VC5).

41-48 The EUA cost of one job scheduler (dollars/year) (VC6).

49-56 The EUA cost of one job scheduling office and equipment (dollars/year) (VC7).

Data Set No. 6

Data set no. 6 contains information on historical data for each item. Every item will be represented by one group of cards. A description of the field specifications (Format 12F6.0) for the first card in the groups is given below.

Column

1-6 Individual item number (N_I).

7-12 Turnover time for item i (periods) (P_i).

13-18 Quantity of item i required to form a unit load (units) (Q_i).

The remaining cards in any group contain the individual stock levels for item i in period j at observation m. Each card represents one period with m observations (eg. 12 observations in one year). If m is greater than 12, two or more cards will represent one period (be sure to adjust the format statement). The cards representing each period (year) should be placed in reverse chronological order with the latest first and the earliest last. Each card (Format 12F6.0) will have the following field specifications:

Column

1-6 Individual stock level for item i in period j at observation 1 (units).

7-12 Individual stock level for item i in period j at observation 2 (units).

.
.
.

67-72 Individual stock level for item i in period j at observation 12 (units).

Subsequent groups of cards representing each item will have the same field specifications as described above.

Results

Two runs were made using the computer program that was developed. In both of these runs, the cycle time for the storage machine was computed using dual address cycles and the cycle time of the fork lift truck was found using single address cycles. Throughput was used as the criterion for storage mode selection in both runs. Using the values for the design specifications (shown in Appendix E) in the computer program (shown in Appendix C), the following results were obtained:

Number of storage slots required in the automated warehouse = 6460.0

Number of storage slots required in the conventional warehouse = 0.0

Total storage cost = 299561.42 $/year

Number of items required in the automated warehouse = 50.0

Throughput required in the automated warehouse = 67.61 unit loads/hr.

Number of aisles required in the automated warehouse = 11.0

Number of storage machines required in the automated warehouse = 2.0

Storage machine cycle time = 2.66 minutes

Using another set of values (not shown) for the design specifications produced the following results:

Number of storage slots required in the automated warehouse = 6460.0

Number of storage slots required in the conventional warehouse = 0.0

Total storage cost = 280061.42 $/year

Number of items required in the automated warehouse = 50.0

Throughput required in the automated warehouse = 40.71 unit loads/hr.

Number of aisles required in the automated warehouse = 11.0

Number of storage machines required in the automated warehouse = 1.0

Storage machine cycle time = 2.66 minutes

Note: Since the purpose of the method is to aid in the design of an automated warehouse, assigning all items to the conventional warehouse is not considered when choosing the best cut off point.

Sample outputs showing these results are shown in Appendix C.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Warehouse designers can benefit from the use of the method proposed in this study to determine the best number of storage slots in a high-rise automated warehouse. Its use in the design phase appears to be well justified as a means of reducing the cost of a proposed warehouse. Dollar savings from the application of the method are likely to be realized from storage systems designed specifically to meet the demands of particular situations.

While conducting this study, several areas were recognized to be worthy of further study. They are as follows:

1. Determine which items are best suited to bulk storage to minimize the total storage cost.
2. Determine how many periods of past data are necessary to give accurate predictions of future stock levels.
3. Develop subroutines using the polynomial function, exponential curve, and power function to predict future stock levels.
4. Find the number of observations per period that best predicts the future inventory levels.

APPENDICES

APPENDIX A

NOMENCLATURE

General

a,b,c,d = Constants in the equation for a straight line.

C = Criterion for storage mode selection -- throughput (= 1.0) or volume (= 2.0).

CP = Cut off point

k,k' = A percentage point of the standard normal distribution representing the risk of being unable to find room for incoming goods.

K_j = Storage slot requirement for period j (unit loads).

K^*_j = Predicted storage slot requirement for future period j (unit loads).

K_{ij} = Maximum required stock on hand for item i in period j (unit loads).

$\bar{K}_{ij}$ = Average stock on hand for item i in period j (unit loads).

K^*_{ij} = Predicted maximum required stock on hand for item i in period j (unit loads).

$\bar{K}^*_{ij}$ = Predicted average stock on hand for item i in future period j (unit loads).

K_{ijm} = Individual stock level for item i in period j at observation m (unit loads).

K^*_{ijm} = Predicted stock level for item in period j at observation m (unit loads).

L = Depreciated life (periods).

L_t = Number of periods of past data (N_d) plus depreciated life (L).

M_j = Total throughput in period j (unit loads/period).

M_{ij} = Throughput of item i in period j (unit loads/period).

MS_e = Mean square error.

N = Total number of items.

N_i = Individual item number.

N_d = Number of periods of past data.

N_t = Total number of inventory observations in all past periods.

N_y = Number of inventory observations per period.

P_i = Turnover time for item i (periods).

Q_i = Quantity of item i required to form a unit load (units).

S_{ij} = Standard deviation of the stock on hand for item i in period j (unit loads).

S^2_{ij} = Variance of the stock on hand for item i in period j (unit loads).

S^*_{ij} = Predicted standard deviation of stock on hand for item i in future period j (unit loads).

T = Total available time units per period (minutes).

TSC = Total annual cost (dollars/period).

TSCL = Total storage cost over the life of the warehouse (dollars).

TSCLM = Minimum total storage cost (dollars).

Y_j = The period j.

Y^*_j = The future period j.

<u>Automated Warehouse</u>

A_{yd} = Distance to accelerate from zero to full travel speed or decelerate from full travel speed to zero (feet).

A_{yt} = Time to accelerate from zero to full travel speed to decelerate from full travel speed to zero (minutes).

Aadd = Type of cycle (single (= 1.0) or dual (= 2.0) address).

CT_a = Storage machine cycle time (minutes).

D_{zd} = Distance to accelerate from zero to full hoist speed or decelerate from full hoist speed to zero (feet).

D_{zt} = Time to accelerate from zero to full hoist speed or decelerate from full hoist speed to zero (minutes).

F_{ta} = Fork cycle time to extend forks, lift or lower the load in slot, and retract forks (minutes).

K_a = Storage slot requirement for the automated warehouse (unit loads).

K_{am} = Storage slot requirement for the automated warehouse at the minimum total storage cost (unit loads).

M_a = Throughput requirement of the automated warehouse (unit loads/period).

M_{maxa} = Maximum throughput capacity of one storage machine (unit loads/period).

n = Number of aisles required.

n' = Number of storage machines required.

N_a = Number of items in automated storage.

N_{ra} = Number of pairs of frames required.

R_a = An indicator representing the relative distance of the average slot ($0 \leq R_a \leq 1$).

R_{xa} = Storage machine aisle width (inches).

R_{ya} = Length of staging area from the racks to the front of the warehouse building (feet).

TCP_t = Transfer car positioning time (minutes/storage machine cycle).

TCT_t = Transfer car transfer time (minutes/storage machine cycle).

VC1 = The equivalent uniform annual (EUA) cost of one computer and peripheral equipment (dollars/year).

VC2 = The EUA cost of the required number of computer operators (dollars/year).

VC3 = The EUA cost of one square foot of floor area in the warehouse (dollars/year).

VC4 = The EUA cost of one computer room (dollars/year).

VC5 = The EUA cost of one storage slot (dollars/year).

VC6 = The EUA cost of one pallet (dollars/year).

VC7 = The EUA cost of one storage machine (dollars/year).

VC8 = The EUA cost of one transfer car (dollars/year).

VC9 = The EUA cost of conveyor to service one aisle (dollars/year).

V_y = Storage machine travel speed (feet/minute).

V_z = Storage machine hoist speed (feet/minute).

xa = Load spacing -- size plus clearance -- depth (inches).

ya = Load spacing -- size plus clearance -- width (inches.

Y_a = Length of the racks (feet).

Y_{maxa} = Maximum allowed length of the racks (feet).

za = Load spacing -- size plus clearance -- height (inches).

Z_a = Total height of the racks (feet).

Conventional Warehouse

A = Sum of all applicable allowances: fatigue, skill, weather, etc. (% ÷ 100).

A_t = Time to accelerate to full travel speed (minutes).

Cadd = Type of cycle (single (= 1.0) or dual (= 2.0) address).

CT_c = Fork lift truck cycle time (minutes).

F_t = Time to travel one foot at full travel speed (minutes/foot).

H_t = Time to raise or lower hoist (minutes/foot).

K_c = Storage slot requirement for the conventional warehouse (unit loads).

K_{cm} = Storage slot requirement for the conventional warehouse at the minimum total storage cost (unit loads).

M_c = Throughput requirement of the conventional warehouse (unit loads/period).

M_{maxc} = Maximum throughput capacity of one fork lift truck (unit loads/period).

p = Number of aisles required.

p' = Number of fork lift trucks required.

N_c = Number of items in the conventional warehouse.

N_{rc} = Number of pairs of frames required.

O_t = Time the fork lift truck operates outside the warehouse building on each cycle (minutes).

R_c = An indicator representing the relative distance to the average slot ($0 \leq R_c \leq 1$).

R_e = Entry ratio ($0 \leq R \leq 1$).

R_{xc} = Aisle width -- travel (inches).

R_{yc} = Aisle width -- lateral (feet).

RI_t = Time to insert forks into a pallet or place a pallet in the slot (minutes).

RO_t = Time to withdraw forks or remove a pallet (minutes).

T_t = Time to change direction of the fork lift truck by 90 degrees (minutes).

TL_t = Time to tilt carriage (minutes).

TS_t = Time to turn the fork lift truck 90 degrees and stop (minutes).

VC1 = The equivalent uniform annual (EUA) cost of one square foot of floor area in the warehouse (dollars/year).

VC2 = The EUA cost of one storage slot (dollars/year).

VC3 = The EUA cost of one pallet (dollars/year).

VC4 = The EUA cost of one fork lift truck (dollars/year).

VC5 = The EUA cost of one fork lift truck operator (dollars/year).

VC6 = The EUA cost of one job scheduler (dollars/year).

VC7 = The EUA cost of one job scheduling office and equipment (dollars/year).

xc = Load spacing -- size plus clearance -- depth (inches).

X_c = Total width of the warehouse building (feet).

yc = Load spacing -- size plus clearance -- width (inches).

Y_c = Length of the racks (feet).

Y_{maxc} = Maximum allowed length of the racks (feet).

zc = Load spacing -- size plus clearance -- height (inches).

Z_c = Height of the racks (feet).

APPENDIX B

VARIABLE NAMES USED TO REPRESENT SYMBOLIC NOTATIONS

General

a	= RA,IA
b	= RB,IB
c	= RC,IC
d	= RD,ID
C	= RCR,ICR
CP	= RCP,ICP
k,k'	= RK,IK
K_j	= RKJ,IKJ
K^*_j	= RPKJ,IPKJ
K_{ij}	= RKIJ,IKIJ
$\bar{K}_{ij}$	= RAKIJ,IAKIJ
K^*_{ij}	= RPKIJ,IPKIJ
$\bar{K}^*_{ij}$	= RPAKIJ,IPAKIJ
K_{ijm}	= RKIJM,IKIJM
L	= RL,IL
L_t	= RLT,ILT
M_j	= RMJ,IMJ
M_{ij}	= RMIJ,IMIJ
MS_e	= RMSE,IMSE
N	= RN,IN
N_i	= RNA,INA
N_d	= RND,IND
N_t	= RNT,INT
N_y	= RNY,INY
P_i	= RPI,IPI
Q_i	= RQI,IQI
S_{ij}	= RSDIJ,ISDIJ
S^2_{ij}	= RVIJ,IVIJ
S^*_{ij}	= RPSDIJ,IPSDIJ
T	= RT,IT
TSC	= RTSC,ITSC
TSCL	= RTSCL,ITSCL
TSCLM	= RTSCLM,ITSCLM
Y_j	= RYJ,IYJ
Y^*_j	= RPYJ,IPYJ

Automated Warehouse

A_{yd}	= AAYD,JAYD
A_{yt}	= AAYT,JAYT
Aadd	= AADD,JADD
CT_a	= ACT,JCT
D_{zd}	= ADZD,JDZD
D_{zt}	= ADZT,JDZT
F_{ta}	= AFT,JFT
K_a	= AKA,JKA
K_{am}	= AKAM,JKAM
M_a	= AMA,JMA
M_{maxa}	= AMMAX,JMMAX
n,n'	= AN,JN
N_a	= ANA,JNA
N_{ra}	= ANAR,JNAR
R_a	= AR,JR
R_{xa}	= ARX,JRX
R_{ya}	= ARY,JRY
TCP_t	= ATCPT,JTCPT
TCT_t	= ATCTT,JTCTT
VC1	= AVC1,JVC1
VC2	= AVC2,JVC2
VC3	= AVC3,JVC3
VC4	= AVC4,JVC4
VC5	= AVC5,JVC5
VC6	= AVC6,JVC6
VC7	= AVC7,JVC7
VC8	= AVC8,JVC8
VC9	= AVC9,JVC9
V_y	= AVY,JVY
V_z	= AVZ,JVZ
xa	= ALX,JLX
ya	= ALY,JLY
Y_a	= AY,JY
Y_{maxa}	= AYM,JYM
za	= ALZ,JLZ
Z_a	= AZ,JZ

Conventional Warehouse

A	= CA,KA
A_t	= CAT,KAT
Cadd	= CADD,KADD
CT_c	= CCT,KCT
F_t	= CFT,KFT
H_t	= CHT,KHT
K_c	= CKC,KKC
K_{cm}	= CKCM,KKCM
M_c	= CMC,KMC
M_{maxc}	= CMMAX,KMMAX
p,p'	= CN,KN
N_c	= CNC,KNC
N_{rc}	= CNCR,KNCR
O_t	= COT,KOT
R_c	= CR,KR
R_e	= CRE,KRE
R_{xc}	= CRX,KRX
R_{yc}	= CRY,KRY
RI_t	= CRIT,KRIT
RO_t	= CROT,KROT
T_t	= CTT,KTT
TL_t	= CTLT,KTLT
TS_t	= CTST,KTST
VC1	= CVC1,KVC1
VC2	= CVC2,KVC2
VC3	= VCV3,KVC3
VC4	= CVC4,KVC4
VC5	= CVC5,KVC5
VC6	= CVC6,KVC6
VC7	= CVC7,KVC7
xc	= CLX,KLX
X_c	= CX,KX
yc	= CLY,KLY
Y_c	= CY,KY
Y_{maxc}	= CYM,KYM
zc	= CLZ,KLZ
Z_c	= CZ,KZ

APPENDIX C

LISTING OF THE PROGRAM

```
      A METHOD FOR DETERMINING THE NUMBER OF STORAGE SLOTS
         REQUIRED IN A HIGH-RISE AUTOMATED WAREHOUSE.
      THE SIZE OF EACH ARRAY IS GIVEN BY THE VARIABLES
         WITHIN THE PARENTHESES FOLLOWING EACH ARRAY
         NAME--R(INY), S(INT), RPKIJ(IL,IN + 1), RPI(IN),
         RQI(IN),RMIJ(IN + 1),RNA(IN).
      DIMENSION R(12),S(60),RPKIJ(10,51),RPI(50),RQI(50),
     CRMIJ(51),RNA(50)
      READ IN THE DESIGN SPECIFICATIONS.
      READ(5,41) RK,RL,RN,RND,RNY,RT,RCR
   41 FORMAT(7F8.0)
      READ(5,43) AADD,AAYD,AAYT,ADZD,ADZT,AFT,ALX,ALY,ALZ,
     CAR,ARX,ARY,ATCPT,ATCTT,AVY,AVZ,AYM,AZ
      READ(5,43) CA,CADD,CAT,CFT,CHT,CLX,CLY,CLZ,COT,CR,CRE,
     CCRIT,CROT,CRX,CRY,CILT,CTST,CTT,CYM,CZ
   43 FORMAT(12F6.0/12F6.0)
      READ(5,44) AVC1,AVC2,AVC3,AVC4,AVC5,AVC6,AVC7,AVC8,AVC9
   44 FORMAT(8F9.0/8F9.0)
      READ(5,41) CVC1,CVC2,CVC3,CVC4,CVC5,CVC6,CVC7
      INTEGER CERTAIN SPECIFICATIONS AND COMPUTE OTHER
         VARIABLES.
      IL = RL
      IND = RND
      INY = RNY
      INT = IND * INY
      ILT = IND + IL
      IN = RN
      IND1 = IND + 1
      RNT = INT
      FIND THE PREDICTED MAX. NUMBER OF STORAGE SLOTS.
      DO 10 INA = 1,IN
      SUMYK = 0.
      SUMY = 0.
      SUMK = 0.
      SUMY2 = 0.
      N = 0
      READ(5,40)RNA(INA),RPI(INA),RQI(INA)
   40 FORMAT(12F6.0)
      DO 100 IYJ = 1,IND
      RYJ = IYJ
      READ IN THE INDIVIDUAL STOCK LEVELS.
      READ(5,22)R
```

```
   CHANGE THE FORMAT STATEMENT TO ACCOMODATE THE
      NUMBER OF OBSERVATIONS PER PERIOD.
22 FORMAT(12F6.0)
   FIND THE AVG. STOCK ON HAND (RAKIJ).
   RMEAN = 0.
   DO 180I = 1,INY
   N = N + 1
   S(N) = R(I)
180 RMEAN = RMEAN + R(I)
   RMEAN = RMEAN/RNY
   USING THE METHOD OF LEAST SQUARES, FIND THE CONSTANTS
      OF THE STRAIGHT LINE FITTED TO THE AVG. STOCK ON
      HAND.
   SUMYK = SUMYK + RYJ * RMEAN
   SUMY = SUMY + RYJ
   SUMK = SUMK + RMEAN
100 SUMY2 = SUMY2 + (RYJ)**2
   DENOM = RND * SUMY2 - (SUMY)**2
   RA = (RND * SUMYK - SUMY * SUMK)/DENOM
   RB = (SUMY2 * SUMK - SUMY * SUMYK)/DENOM
   USING THE METHOD OF LEAST SQUARES, FIND THE CONSTANTS
      OF THE STRAIGHT LINE FITTED TO ALL OBSERVATIONS.
   SUMYK = 0.
   SUMY = 0.
   SUMK = 0.
   SUMY2 = 0.
   DO 220N = 1,INT
   T = N
   SUMY2 = SUMY2 + (T)**2
   SUMY = SUMY + T
   SUMYK = SUMYK + T * S(N)
220 SUMK = SUMK + S(N)
   DENOM = RNT * SUMY2 - (SUMY)**2
   RC = (RNT * SUMYK - SUMY * SUMK)/DENOM
   RD = (SUMY2 * SUMK - SUMY * SUMYK)/DENOM
   RMSE = 0.
   FIND THE MEAN SQUARE ERROR AND THEN THE STD.
      DEVIATION.
   DO 300J = 1,INT
   U = J
300 RMSE = RMSE + (S(J) - (RC * U + RD))**2
   RMSE = RMSE/(RNT - 2.)
   RPSDIJ = SQRT(RMSE)
   SOLVE FOR THE PREDICTED MAX. NUMBER OF STORAGE SLOTS
      (RPKIJ). ROUND OFF TO THE NEXT WHOLE NUMBER.
   DO  10IPYJ = IND1,ILT
   RPYJ = IPYJ
   G = (RA*RPYJ + RB + RK*RPSD(J)/RQI(INA)
   IG = G + .999999
   RPKIJ(IPYJ,INA) = IG
10 CONTINUE
```

```
      SEQUENCE THE ITEMS BY DESCENDING THROUGHPUT OR
         VOLUME.
      IF(RCR .LT. 2.) GO TO 74
      NITEM = IN
   70 I = 0
   71 I = I + 1
      J = I + 1
      IF(J .GT. NITEM) GO TO 72
      TEMPO = RNA(I)
      RNA(I) = RNA(J)
      RNA(J) = TEMPO
      IF(RPKIJ(IPYJ,I) .LE. RPKIJ(IPYJ,J)) GO TO 71
      DO 80IPYJ = IND1,ILT
      TEMP = RPKIJ(IPYJ,I)
      RPKIJ(IPYJ,I) = RPKIJ(IPYJ,J)
      RPKIJ(IPYJ,J) = TEMP
   80 CONTINUE
      GO TO 71
   72 NITEM = NITEM - 1
      IF(NITEM .GT. 1) GO TO 70
      GO TO 79
   74 DO 75INA = 1,IN
   75 RMIJ(INA) = 2.*RPKIJ(IPYJ,INA)/RPI(INA)
      NITEM = IN
   76 I = 0
   77 I = I + 1
      J = I + 1
      IF(J .GT. NITEM) GO TO 78
      IF(RMIJ(I) .GE. RMIJ(J)) GO TO 77
      TEMPO = RNA(I)
      RNA(I) = RNA(J)
      RNA(J) = TEMPO
      TEMPT = RMIJ(I)
      RMIJ(I) = RMIJ(J)
      RMIJ(J) = TEMPT
      DO 81IPYJ = IND1,ILT
      TEMP = RPKIJ(IPYJ,I)
      RPKIJ(IPYJ,I) = RPKIJ(IPYJ,J)
      RPKIJ(IPYJ,J) = TEMP
   81 CONTINUE
      GO TO 77
   78 NITEM = NITEM - 1
      IF(NITEM .GT. 1) GO TO 76
   79 TSCLM = 0.
      TO BEGIN WITH, LET ALL ITEMS BE IN CONV. STORAGE. AT
         EACH ITERATION INCREMENT THE ITEMS IN AUTO. STORAGE
         BY ONE.
      IN1 = IN + 1
      DO 280 J = 1,IN1
      JNA = J - 1
      JNC = IN - JNA
```

```
      TSCL = 0.
      COMPUTE THE STORAGE SLOT AND THROUGHPUT REQUIREMENT FOR
         ALL ITEMS.
      DO 290IPYJ = IND1,ILT
      RMJ = 0.
      RKJ = 0.
      DO 500INA = 1,IN
      RKJ = RKJ + RPKIJ(IPYJ,INA)
  500 RMJ = RMJ + 2.*RPKIJ(IPYJ,INA)/RPI(INA)
      FIND THE STORAGE AND THROUGHPUT REQUIREMENTS FOR EACH
         WAREHOUSE.
      IF(JNA .GT. 0) GO TO 12
      AKA = 0.
      CKC = RKJ
      AMJ = 0.
      CMJ = RMJ
      GO TO 13
   12 IF(JNC .GT. 0) GO TO 9
      AKA = RKJ
      CKC = 0.
      AMJ = RMJ
      CMJ = 0.
      GO TO 11
    9 JNA1 = JNA + 1
      AKA = 0.
      CKC = 0.
      AMJ = 0.
      CMJ = 0.
      DO 320INA = 1,JNA
      AMJ = AMJ + 2.*RPKIJ(IPYJ,INA)/RPI(INA)
  320 AKA = AKA + RPKIJ(IPYJ,INA)
      DO 400INA = JNA1,IN
      CMJ = CMJ + 2.*RPKIJ(IPYJ,INA)/RPI(INA)
  400 CKC = CKC + RPKIJ(IPYJ,INA)
      FIND THE LENGTH OF THE RACKS IN AUTO. STORAGE.
   11 ANAR = AKA/(2.*AZ/(ALZ/12.))
      AN = 0.
   52 AN = AN + 1.
      IF(AYM*AN .LT. ANAR*(ALY/12.)) GO TO 52
      ANAR = ANAR/AN
      JNAR = ANAR + .999999
      ANAR = JNAR
      AY = ANAR*(ALY/12.)
      FIND THE DELAY TIME FOR AISLE TRANSFER.
      ATCCT = ATCTT + ATCPT
      IF(AKA .GT. (2.*AY*AZ)/(ALY*ALZ/144.)) GO TO 14
      ATCCT = 0.
      COMPUTE THE CYCLE TIME AND THROUGHPUT CAPACITY OF THE
         STORAGE MACHINE.
   14 IF(AADD .GT. 1.) GO TO 15
      ACT1 = 2.*AFT + 4.*AAYT + ((2.*AR*AY - 4.*AAYD)/AVY)
```

```
C+ ATCCT
   ACT2 = 2.*AFT + 4.*ADZT + ((2.*AR*AZ - 4.*ADZn)/AVZ)
C+ ATCCT
   ACT = AMAX1(ACT1,ACT2)
   AMMAX = RT/ACT
   GO TO 19
15 ACT1 = 4.*AFT + 6.*AAYT + ((2.*AR*AY - 6.*AAYn)/AVY)
C+ ATCCT
   ACT2 = 4.*AFT + 6.*ADZT + ((2.*AR*AZ - 6.*ADZn)/AVZ)
C+ ATCCT
   ACT = AMAX1(ACT1,ACT2)
   AMMAX = 2.*RT/ACT
   FIND THE NUMBER OF STORAGE MACHINES NECESSARY.
19 ANM = 0.
21 ANM = ANM + 1.
   IF(ANM*AMMAX .LT. AMJ) GO TO 21
   IF(CKC .LT. 1.) GO TO 16
   FIND THE LENGTH OF THE RACKS IN CONV. STORAGE.
13 CNCR = CKC/(2.*CZ/(CLZ/12.))
   CN = 0.
51 CN = CN + 1.
   IF(CYM*CN .LT. CNCR*(CLY/12.)) GO TO 51
   CNCR = CNCR/CN
   KNCR = CNCR + .999999
   CNCR = KNCR
   CY = CNCR*(CLY/12.)
   FIND THE WIDTH OF THE CONV. WAREHOUSE.
   CX = CN*((2.*CLX + CRX)/12.)
   IF(CADD .GT. 1.) GO TO 18
   COMPUTE THE CYCLE TIME AND THROUGHPUT CAPACITY OF THE
      FORK LIFT TRUCK.
   CCT = (1. + CA)*(2.*CRY*CFT + 2.*CR*CY*CFT + 4.*CTT
C+ 2.*CTST + 2.*CR*CZ*CHT + CAT + CRIT + CROT + CTLT
C+ COT + CFT*(CX - 2.*CX*CRE + 2.*CX*(CRE**2))/2.)
   CMMAX = RT/CCT
   GO TO 50
18 CCT = (1. + CA)*(2.*CRY*CFT + 2.*CR*CY*CFT + 4.*CTT
C+ 4.*CTST + 2.*CR*CZ*CHT + 2.*CAT + 2.*CRIT + 2.*CROT
C+ 3.*CTLT + COT + CFT*(CX - 2.*CX*CRE + 2.*CX*(CRE**2))
C/2.)
   CMMAX = 2.*RT/CCT
   FIND THE NUMBER OF FORK LIFT TRUCKS NECESSARY.
50 CNM = 0.
23 CNM = CNM + 1.
   IF(CNM*CMMAX .LT. CMJ) GO TO 23
   IF(AKA .LT. 1.) GO TO 25
   GO TO 26
   FIND THE TOTAL ANNUAL COST OF AUTO. AND CONV. STORAGE.
16 TSC = AVC1 + AVC2 + AN*((ARX + 2.*ALX)/12.)*(AY + ARY)
C*AVC3 + AVC4 + AN*((288.*AY*AZ)/(ALY*ALZ))*AVC5 + AKA*
CAVC6 + ANM*AVC7 + ANM*AVC8 + AN*AVC9
```

```
      GO TO 290
 25  TSC = CN*((CRX + 2.*CLX)/12.)*(CY + CRY) * CVC1 + CN*
    C((288.*CY*CZ)/(CLY*CLZ))*CVC2 + CKC*CVC3 + CNM*CVC4 +
    CCNM*CVC5 + CVC6 + CVC7
      GO TO 290
 26  TSC = AVC1 + AVC2 + AN*((ARX + 2.*ALX)/12.)*(AY + ARY)
    C*AVC3 + AVC4 + AN*((288.*AY*AZ)/(ALY*ALZ))*AVC5 + AKA*
    CAVC6 + ANM*AVC7 + ANM*AVC8 + AN*AVC9
    C+      CN*((CRX + 2.*CLX)/12.)*(CY + CRY) * CVC1 + CN*
    C((288.*CY*CZ)/(CLY*CLZ))*CVC2 + CKC*CVC3 + CNM*CVC4 +
    CCNM*CVC5 + CVC6 + CVC7
      FIND THE TOTAL STORAGE COST.
290  TSCL = TSCL + TSC
      CONVERT TOTAL STORAGE COST TO AN EQUIVALENT ANNUAL
         COST AND THROUGHPUT TO LOADS/HOUR.
      TSCL = TSCL/RL
      AMJ = AMJ/(RT/60.)
      FIND THE MIN. TOTAL STORAGE COST AND STORE THAT POINT.
      IF(JNA .EQ. 1) GO TO 310
      IF(TSCLM .LE. TSCL) GO TO 37
310  TSCLM = TSCL
      AKAM = AKA
      CKCM = CKC
      AMJM = AMJ
      JNAM = JNA
      ACTM = ACT
      ANNM = AN
      ANMM = ANM
      WRITE OUT THE RESULTS.
 37  IF(JNA .GT. 0) GO TO 94
      WRITE(6,90)
 90  FORMAT(1H1////54X,'** RESULTS **')
      WRITE(6,91)
 91  FORMAT(//20X,'ITEMS',19X,'NO. OF',4X,'NO. OF',6X,
    C'AUTO.',6X,'STOR.',5X,'NO. OF'/22X,'IN',18X,'SLOTS IN'
    C,2X,'SLOTS IN',6X,'STOR.',6X,'MACH.',2X,'AISLES IN',
    C4X,'NO. OF'/20X,'AUTO.',3X,'ANNUAL STOR.',5X,'AUTO.',
    C5X,'CONV.',3X,'THRUPUT-',6X,'CYCLE',6X,'AUTO.',5X,
    C'STOR.'/20X,'STOR.',3X,'COST-DOLLARS',5X,'STOR.',5X,
    C'STOR.',2X,'LOADS/HR.',2X,'TIME-MIN.',6X,'STOR.',5X,
    C'MACH.'/)
 94  WRITE(6,35)JNA,TSCL,AKA,CKC,AMJ,ACT,AN,ANM
 35  FORMAT(I25,F15.2,2F10.0,2F11.2,F11.0,F10.0)
280  CONTINUE
      WRITE(6,92)
 92  FORMAT(//33X,'** NUMBER OF SLOTS IN AUTOMATED '
    C'WAREHOUSE FOR LEAST COST **')
      WRITE(6,36)JNAM,TSCLM,AKAM,CKCM,AMJM,ACTM,ANNM,ANMM
 36  FORMAT(/42X,'**********'/I25,F15.2,2X,'*',F7.0,1X,'*',
    CF8.0,2F11.2,F11.0,F10.0/42X,'**********')
      WRITE(6,61)
```

```
61 FORMAT(/20X,'ITEM NUMBERS ASSIGNED TO AUTOMATED STOR'
  C'AGE'/)
   WRITE(6,62)(RNA(I),I = 1,JNAM)
62 FORMAT(17X,15F6.0)
   END
```

** RESULTS **

ITEMS IN AUTO. STOR.	ANNUAL STOR. COST-DOLLARS	NO. OF SLOTS IN AUTO. STOR.	NO. OF SLOTS IN CONV. STOR.	AUTO. STOR. THRUPUT- LOADS/HR.	STOR. MACH. CYCLE TIME-MIN.	NO. OF AISLES IN AUTO. STOR.	NO. OF STOR. MACH.
0	294542.77	0.	6460.	.00	.00	0.	0.
1	395919.57	365.	6095.	4.47	2.61	1.	1.
2	394666.87	730.	5730.	8.95	2.66	2.	1.
3	389294.87	1095.	5365.	13.42	2.66	2.	1.
4	374418.18	1460.	5000.	17.89	2.66	3.	1.
5	370005.92	1825.	4635.	22.37	2.66	4.	1.
6	367552.50	2190.	4270.	26.84	2.66	4.	1.
7	365845.44	2555.	3905.	31.31	2.66	5.	1.
8	346376.68	2920.	3540.	35.78	2.66	5.	1.
9	344975.15	3285.	3175.	40.26	2.66	6.	1.
10	340490.09	3650.	2810.	44.73	2.66	7.	1.
11	350973.87	3783.	2677.	46.16	2.66	7.	2.
12	359552.18	3916.	2544.	47.59	2.66	7.	2.
13	357254.67	4049.	2411.	49.02	2.66	7.	2.
14	341452.92	4182.	2278.	50.44	2.66	7.	2.
15	341196.84	4315.	2145.	51.87	2.66	8.	2.
16	341607.48	4448.	2012.	53.30	2.66	8.	2.
17	339969.82	4581.	1879.	54.73	2.66	8.	2.
18	337704.06	4714.	1746.	56.16	2.66	8.	2.
19	336221.45	4847.	1613.	57.58	2.66	9.	2.
20	336580.98	4980.	1480.	59.01	2.66	9.	2.
21	336390.42	5046.	1414.	59.48	2.66	9.	2.
22	335915.92	5112.	1348.	59.95	2.66	9.	2.
23	334915.07	5178.	1282.	60.43	2.66	9.	2.
24	334241.85	5244.	1216.	60.90	2.66	9.	2.
25	332998.14	5310.	1150.	61.37	2.66	9.	2.
26	331977.47	5376.	1084.	61.84	2.66	9.	2.
27	332066.17	5442.	1018.	62.31	2.66	10.	2.
28	332079.30	5508.	952.	62.78	2.66	10.	2.

29	331587.41	5574.	886.	63.25	2.66	10.	2.
30	331140.63	5640.	820.	63.72	2.66	10.	2.
31	331108.04	5684.	776.	63.96	2.66	10.	2.
32	330872.68	5728.	732.	64.19	2.66	10.	2.
33	330353.83	5772.	688.	64.43	2.66	10.	2.
34	329494.91	5816.	644.	64.66	2.66	10.	2.
35	328961.30	5860.	600.	64.90	2.66	10.	2.
36	327986.23	5904.	556.	65.13	2.66	10.	2.
37	327126.39	5948.	512.	65.37	2.66	10.	2.
38	326343.03	5992.	468.	65.60	2.66	10.	2.
39	326826.18	6036.	424.	65.84	2.66	11.	2.
40	326342.92	6080.	380.	66.07	2.66	11.	2.
41	326386.48	6118.	342.	66.23	2.66	11.	2.
42	326430.03	6156.	304.	66.38	2.66	11.	2.
43	326190.03	6194.	266.	66.53	2.66	11.	2.
44	325932.09	6232.	228.	66.69	2.66	11.	2.
45	326225.74	6270.	190.	66.84	2.66	11.	2.
46	325741.90	6308.	152.	67.00	2.66	11.	2.
47	325258.07	6346.	114.	67.15	2.66	11.	2.
48	324812.02	6384.	76.	67.30	2.66	11.	2.
49	324365.97	6422.	38.	67.46	2.66	11.	2.
50	299561.42	6460.	0.	67.61	2.66	11.	2.

** NUMBER OF SLOTS IN AUTOMATED WAREHOUSE FOR LEAST COST **

50	299561.42	********** * 6460. * **********	0.	67.61	2.66	11.	2.

ITEM NUMBERS ASSIGNED TO AUTOMATED STORAGE

7.	8.	9.	10.	1.	2.	3.	4.	5.	6.	15.	16.	17.	18.	19.
20.	11.	12.	13.	14.	26.	27.	28.	29.	30.	21.	22.	23.	24.	25.
37.	38.	39.	40.	31.	32.	33.	34.	35.	36.	43.	44.	45.	46.	47.
48.	49.	50.	41.	42.										

** RESULTS **

ITEMS IN AUTO. STOR.	ANNUAL STOR. COST-DOLLARS	NO. OF SLOTS IN AUTO. STOR.	NO. OF SLOTS IN CONV. STOR.	AUTO. STOR. THRUPUT-LOADS/HR.	STOR. MACH. CYCLE TIME-MIN.	NO. OF AISLES IN AUTO. STOR.	NO. OF STOR. MACH.
0	276342.77	0.	6460.	.00	.00	0.	0.
1	381919.57	365.	6095.	1.48	2.61	1.	1.
2	380656.87	730.	5730.	2.96	2.66	2.	1.
3	375294.87	1095.	5365.	4.44	2.66	2.	1.
4	374418.18	1460.	5000.	5.92	2.66	3.	1.
5	356005.92	1825.	4635.	7.40	2.66	4.	1.
6	353552.50	2190.	4270.	8.88	2.66	4.	1.
7	351845.44	2555.	3905.	10.36	2.66	5.	1.
8	346376.68	2920.	3540.	11.84	2.66	5.	1.
9	344975.15	3285.	3175.	13.31	2.66	6.	1.
10	340490.09	3650.	2810.	14.79	2.66	7.	1.
11	341223.87	3783.	2677.	16.22	2.66	7.	1.
12	340052.18	3916.	2544.	17.65	2.66	7.	1.
13	337754.67	4049.	2411.	19.08	2.66	7.	1.
14	335952.92	4182.	2278.	20.51	2.66	7.	1.
15	335696.84	4315.	2145.	21.94	2.66	8.	1.
16	323507.48	4448.	2012.	23.36	2.66	8.	1.
17	320469.82	4581.	1879.	24.79	2.66	8.	1.
18	318204.06	4714.	1746.	26.22	2.66	8.	1.
19	316721.45	4847.	1613.	27.65	2.66	9.	1.
20	317080.98	4980.	1480.	29.08	2.66	9.	1.
21	316890.42	5046.	1414.	29.43	2.66	9.	1.
22	316415.92	5112.	1348.	29.78	2.66	9.	1.
23	315415.07	5178.	1282.	30.13	2.66	9.	1.
24	314741.85	5244.	1216.	30.49	2.66	9.	1.
25	313498.14	5310.	1150.	30.84	2.66	9.	1.
26	312477.47	5376.	1084.	31.19	2.66	9.	1.
27	312566.17	5442.	1018.	31.54	2.66	10.	1.
28	312579.30	5508.	952.	31.90	2.66	10.	1.

29	312087.41	5574.	886.	32.25	2.66	10.	1.
30	311640.63	5640.	820.	32.60	2.66	10.	1.
31	311608.04	5684.	776.	33.14	2.66	10.	1.
32	311372.68	5728.	732.	33.68	2.66	10.	1.
33	310853.83	5772.	688.	34.22	2.66	10.	1.
34	309994.91	5816.	644.	34.76	2.66	10.	1.
35	309461.30	5860.	600.	35.30	2.66	10.	1.
36	308486.23	5904.	556.	35.84	2.66	10.	1.
37	307626.39	5948.	512.	36.38	2.66	10.	1.
38	306843.03	5992.	468.	36.92	2.66	10.	1.
39	307326.18	6036.	424.	37.46	2.66	11.	1.
40	306842.92	6080.	380.	37.99	2.66	11.	1.
41	306886.48	6118.	342.	38.27	2.66	11.	1.
42	306930.03	6156.	304.	38.54	2.66	11.	1.
43	306690.03	6194.	266.	38.81	2.66	11.	1.
44	306432.09	6232.	228.	39.08	2.66	11.	1.
45	306725.74	6270.	190.	39.35	2.66	11.	1.
46	306241.90	6308.	152.	39.62	2.66	11.	1.
47	305758.07	6346.	114.	39.89	2.66	11.	1.
48	305312.02	6384.	76.	40.16	2.66	11.	1.
49	304865.97	6422.	38.	40.43	2.66	11.	1.
50	280061.42	6460.	0.	40.71	2.66	11.	1.

** NUMBER OF SLOTS IN AUTOMATED WAREHOUSE FOR LEAST COST **

```
                        **********
50      280061.42     *  6460. *       0.      40.71      2.66      11.      1.
                        **********
```

ITEM NUMBERS ASSIGNED TO AUTOMATED STORAGE

1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.
16.	17.	18.	19.	20.	21.	22.	23.	24.	25.	26.	27.	28.	29.	30.
31.	32.	33.	34.	35.	36.	37.	38.	39.	40.	41.	42.	43.	44.	45.
46.	47.	48.	49.	50.										

APPENDIX D

WAREHOUSE COSTS

Automated Warehouse

A high-rise automated warehouse can be broken down into many cost elements. These costs may be grouped into the following categories:

1. Cost of the computer
2. Cost of the computer operator
3. Cost of the warehouse building
4. Cost of the computer room
5. Cost of the racks
6. Cost of the pallets
7. Cost of the storage machines
8. Cost of the transfer cars
9. Cost of the conveyor networks

In order to better understand these costs, they must be broken down further into their sub-elements.

Cost of the Computer and Peripheral Equipment

1. Rent/Depreciation expense
2. Maintenance-materials
3. Maintenance-labor
4. Operating expenses-electricity, paper, etc.
5. Taxes
6. Debt service

Cost of the Computer Operator

1. Wages
2. Social Security and pensions
3. Holiday pay
4. Merit awards
5. Payroll taxes

Cost of the Warehouse Building

1. Rent/Depreciation expense
2. Maintenance - materials
3. Maintenance - labor
4. Insurance expense
5. Lighting expense
6. Ventilation expense
7. Janitorial service
8. Fire protection and control expense
9. Telephone service
10. Taxes
11. Debt service

Cost of the Computer Room

1. Rent/Depreciation expense
2. Maintenance - materials
3. Maintenance - labor
4. Insurance expense
5. Lighting expense
6. Air conditioning expense
7. Janitorial service

8. Fire detection and control expense
9. Telephone service
10. Taxes
11. Dept service

Cost of the Racks

1. Rent/Depreciation expense
2. Maintenance - labor
3. Maintenance - materials
4. Taxes
5. Debt service

Cost of the Pallets

1. Depreciation expense
2. Taxes
3. Debt service
4. Maintenance - labor
5. Maintenance - materials

Cost of the Storage Machine

1. Depreciation expense
2. Maintenance - labor
3. Maintenance - materials
4. Operating expenses - electricity, etc.
5. Taxes
6. Debt service

Cost of the Transfer Car

1. Depreciation expense
2. Maintenance - labor

3. Maintenance - materials
4. Operating expenses - electricity, etc.
5. Taxes
6. Debt service

Cost of the Conveyor Networks

1. Depreciation expense
2. Maintenance - labor
3. Maintenance - materials
4. Operating expenses - electricity, compressed air, etc.
5. Taxes
6. Debt service

Conventional Warehouse

The cost elements of the conventional warehouse are:

1. Cost of the warehouse building
2. Cost of the racks
3. Cost of the pallets
4. Cost of the fork lift trucks
5. Cost of the fork lift truck operators
6. Cost of the job scheduler
7. Cost of the scheduling office and equipment.

These elemental costs may be subdivided as follows:

Cost of the Warehouse Building

1. Rent/Depreciation expense
2. Maintenance - materials
3. Maintenance - labor

4. Insurance expense
5. Lighting expense
6. Ventilation expense
7. Janitorial service
8. Fire detection and control expense
9. Telephone service
10. Taxes
11. Debt service

Cost of the Racks

1. Rent/Depreciation expense
2. Maintenance - labor
3. Maintenance - materials
4. Taxes
5. Debt service

Cost of the Pallets

1. Depreciation expense
2. Taxes
3. Debt service
4. Maintenance - labor
5. Maintenance - materials

Cost of the Fork Lift Truck

1. Rent/Depreciation expense
2. Maintenance - labor
3. Maintenance - materials
4. Operating expenses - oil, gas, electricity, tires, battery, etc.
5. Debt service

6. Taxes

Cost of the Fork Lift Truck Operator

1. Wages
2. Social Security and pensions
3. Holiday pay
4. Merit award
5. Payroll taxes

Cost of the Job Scheduler

1. Wages
2. Social Security and pensions
3. Holiday pay
4. Merit awards
5. Payroll taxes

Cost of the Scheduling Office and Equipment

1. Rent/Depreciation expense
2. Maintenance - labor
3. Maintenance - materials
4. Insurance expense
5. Lighting expense
6. Ventilation expense
7. Janitorial service
8. Fire detection and control expense
9. Telephone service
10. Taxes
11. Debt service

APPENDIX E

DESIGN SPECIFICATIONS

Data Set No. 1

k'	= 2.0 (represents a risk of 0.023)
L	= 10.0 years
N	= 50.0 items
N_d	= 5.0 years
N_y	= 12.0 observations
T	= 115,200.0 minutes (for one year)
C	= 1.0 (represents the criterion of throughput)

Data Set No. 2

Aadd	= 2.0 (represents dual address cycles)
A_{yd}	= 8.0 feet
A_{yt}	= 0.167 minutes
D_{zd}	= 0.6 feet
D_{zt}	= 0.046 minutes
F_{ta}	= 0.232 minutes
xa	= 54.0 inches
ya	= 54.0 inches
za	= 54.0 inches
R_a	= 0.667 (represents a rule-of-thumb of two-thirds)
R_{xa}	= 54.0 inches
R_{ya}	= 20.0 feet

TCP_t = 0.01 minutes

TCT_t = 0.04 minutes

V_y = 240.0 feet/minute

V_z = 40.0 feet/minute

Y_{maxa} = 135.0 feet

Z_a = 45.0 feet

Data Set No. 3

A = 0.31 (represents the sum of all allowances - 31%)

Cadd = 1.0 (represents single address cycles)

A_t = 0.025 minutes

F_t = 0.0024 minutes/foot

H_t = 0.028 minutes/foot

xc = 54.0 inches

yc = 54.0 inches

zc = 54.0 inches

O_t = 1.0 minute

R_c = 0.5 (represents a rule-of-thumb of one-half)

R_e = 0.5 (represents an entry ratio of one-half)

RI_t = 0.09 minutes

RO_t = 0.065 minutes

R_{xc} = 96.0 inches

R_{yc} = 10.0 feet

TL_t = 0.25 minutes

TS_t = 0.07 minutes

T_t = 0.055 minutes

Y_{maxc} = 225.0 feet

Z_c = 13.5 feet

Data Set No. 4

VC1 = 75000.0 $/year

VC2 = 12000.0 $/year

VC3 = 2.70 $/year

VC4 = 500.0 $/year

VC5 = 10.0 $/year

VC6 = 2.25 $/year

VC7 = 12000.0 $/year

VC8 = 7500.0 $/year

VC9 = 3000.0 $/year

Data Set No. 5

VC1 = 2.25 $/year

VC2 = 2.80 $/year

VC3 = 2/25 $/year

VC4 = 5000.0 $/year

VC5 = 9000.0 $/year

VC6 = 9000.0 $/year

VC7 = 9000.0 $/year

Data Set No. 6

The individual item numbers (N_i) which were used for the different items are:

item 1 1.0

item 2	2.0
.	.
.	.
.	.
item 50	50.0

The turnover times (P_i) which were used for the different items are:

items 1-10	0.085 years
items 11-20	0.097 years
items 21-30	0.148 years
items 31-40	0.195 years
items 41-50	0.257 years

The quantity of item i required to form a unit load (Q_i) which was used for each item is:

items 1-50	100.0 units

The values for the individual stock levels for each item in period j at observation m were generated from normal distributions. The means and standard deviations that were used for these distributions for the different items were:

Items	Mean	Std. Deviation
1-10	22000.0 units	5500.0 units
11-20	8000.0 units	2000.0 units
21-30	4000.0 units	1000.0 units
31-40	3200.0 units	800.0 units
41-50	2800.0 units	700.0 units

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