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—Research Paper—

# Design of Automated Warehouse Systems

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**ABSTRACT**

The warehousing of inventories is an enormous expense to industries worldwide, and yet there are few tools available that can be used to design rack storage systems while considering overall system costs. The primary objective of this paper is the development of an overall warehouse storage system costs model to aid a warehouse planner in the design of automated warehouse systems. A simulation model and statistical estimation procedures are used to determine the maximum inventory levels accumulated in the receiving, storage, and shipping areas. The overall cost model is developed to determine the required total land, the initial investment fund, the number of pieces of handling equipment, and the storage rack configuration for the main storage area. A numerical example is then presented to demonstrate the application of the overall system cost model developed in this paper.

## INTRODUCTION

Automated warehousing systems are rapidly replacing conventional warehouses for the storage and movement of high-volume goods due to such benefits as lower land costs, labor savings, and an improved throughput level. In designing automatic warehouse systems, vital warehouse building, storage rack facility, and handling equipment selection vary with the physical characteristics of the storage system. Once constructed, it is extremely difficult to meet new conditions by modifying the system(i. e., changing the number of storage aisles, increasing height or length, or changing the type of handling equipment). However, there are yet few tools available that can be used to design the automated warehouse systems. This paper presents a mathematical overall system cost model over the lifetime of a warehouse. Using this research, the designer can decide upon the warehouse storage system carefully, depending on the company's primary objective based on the following possible criteria : minimum overall system costs(land, building, handling equipment, storage rack facility, and operating and maintenance), minimum intial investment, minimum overall landrequirements, minimum travel time of the handling equipment.

The literature on automater warehouse systems contains few articles on design optimization.

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Most references (see, for example, Hausman, Schwarz and Graves (1977 and 1978), and Bozer and White (1984)) determine the layout of a warehouse by minimizing travel time of handling equipment. Robert and Reed(1972), and Bassan, Roll, and Resenblatt(1980) found optimal layout designs of warehouses by minimizing warehouse construction and handling costs. Some articles provide mathematical overall costs models, but the approach is usually quite different from the one adopted in this paper. Karasawa, Nakayama, and Dohi (1980) developed a cost model for an Automated Storage/Retrieval System(AS/RS). Their total cost function included terms for land, building, S/R machine and storage rack facility. The resulting model was solved by using Lagrangian multipliers and then choosing the best neighborhood integer solution. A recent paper Ashayeri, Gelders, and Wassenhove (1985) presents a micro computer-based optimization model to minimize investment costs and operating costs.

This paper is organized as follows : the determination of maximum inventory levels is presented. Then the mathematical system cost model over the lifetime of the storage system is developed along with a solution procedure. A numerical example is then given and the reader is taken through the analysis steps so that the quality of the results can be obtained.

## THE DETERMINATION OF MAXIMUM INVENTORY LEVELS

Suppose we want to construct an automated warehouse for storing and retrieving palletized products at one of the distribution areas. Figure 1 shows a general schematic diagram for the types of automatic warehouse layouts being considered in this research. The general automated warehouse system in this paper consists of arrival and shipping inventory areas, a shipping and receiving dock area, offices including the control system area, and the storage rack facility area (conveyor in main aisle, storage/retrieval machines in storage aisle, and storage rack facility).

Products enter or leave the warehouse at a certain rate, which may be constant or variable over time in single or multiple pallet loads. The products first arrive at the arrival dock area and are temporarily stored at the arrival inventory area. The products are retrieved from there and then stored at the storage rack facility by the selected storage/retrieval (S/R) machine along the conveyor in a main aisle. Product retrieval is the reversed procedure. Thus, the arrival and shipping inventory areas are essential. The required size of the arrival and shipping areas are dependent upon the size of arrival products, the handling capacity of the handling equipment system, and the timing of arrival and demand products.

The procedure is, in general form, suitable for different sets of product flow data in manufacturing or distribution storage systems. The input data on timing and quantity of product flow data can be input or generated by random or constant values. In addition, this simulation allows the selection of unit time, invetory planning cycle pattern and inventory shipment cycle pattern, and the numbers of product types. When random timing and quantity of product flow are chosen by the designer, the method described is used to reduce a possible under or over estimation of the maximum inventory levels.

Suppose that we have constructed a confidence interval for the maximum inventory levels based on a fixed number of replications n, assuming the maximum inventory level is a normally distributed random variable. If we assume that our estimate of the population variance, that is,

$S^2(n)$, will not change (appreciably) as the number of replications increases, an approximate expression for the total number of replications, $n(k)$, required to reduce the absolute precision of the confidence interval to a desired value $k(k>0)$ is given by

$$n(k)=\text{Min}\{i>n : t_{i-1, 1-\alpha/2}\sqrt{S^2(n)/i} < k\} \qquad (1)$$

We can determine $n(k)$ by iteratively increasing i by 1 until value of i is obtained for which $t_{i-1, 1-\alpha/2}\sqrt{S^2(n)/i}<k$. Then the upper confidence intervals(i. e., Smax, Amax, and Pmax, which are the maximum inventory levels in storage rack facility, arrival and shipping inventory areas in this research) are determined by

$$Smax=\overline{Smax}+t_{n(k)-1, 1-\alpha/2}*\sqrt{S_s^2\{n(k)\}/n(k)} \qquad (2-a)$$

$$Amax=\overline{Amax}+t_{n(k)-1, 1-\alpha/2}*\sqrt{S_a^2\{n(k)\}/n(k)} \qquad (2-b)$$

$$Pmax=\overline{Pmax}+t_{n(k)-1, 1-\alpha/2}*\sqrt{S_p^2\{n(k)\}/n(k)} \qquad (2-c)$$

Where $\overline{Smax}$, $\overline{Amax}$, and $\overline{Pmax}$ are the sample means and $S_s^2\{n(k)\}$, $S_a^2\{n(k)\}$, and $S_p^2\{n(k)\}$ are the sample variances of maximum inventory levels.

## AN INVESTMENT DECISION MODEL AND SOLUTION PROCEDURE

In any business environment, there are competitive demands for the use of limited capital investment dollars. Decisions related to material handling investments are not substantially unlike those associated with other investment opportunities. Funds allocated to material handling systems must be evaluated in the same decision-making framework as those directed to new physical plants, production equipment, and the like. The problem of limited resources is common to all of the decision making aspects. The rationale for economic justification must be consistent so that decision-makers can choose between and among all the alternatives competing for limited financial resources. Therefore, economic analysis of material handling investment is the key to management acceptance of any warehouse project. The equivalence concept is used to convert a cash flow, representing the alternative into some equivalent annual cash flow in this paper. It should be emphasized that the Annual Equivalent Total Cost(AETC) approach for choosing the alternative projects is valid only under the condition that the cash flows during the successive replacements are identical in every respect to those of the initial project. The following assumptions are required for evaluating the warehouse designs and the handling system investments.

* All the costs are incurred at the end of the year.
* With company funds for initial investments, no additional external funding source is necessary.
* No construction period is considered.
* In each group, depreciation is used in the building, handling equipment (i. e., S/R machine, computer software and hardware, and conveyor system), and storage rack facility.
* Annually increasing labor, operating and maintenance costs, and land price are directly caused by the annual general inflation rate.
* The salvage values of building, equipment, and storage rack facility equal the book values for each asset at the end of the planning horizon.

We will present a mathematical model which incorporates all relevant cost figures and the appropriate operating and system constraints. This model formalizes the storage system design process and solving it will yield the most desirable design, depending upon either minimum system cost, minimum travel time for the handling equipment, minimum initial investment system, or the minimum amount of land necessary for the storage system. A detailed description of cost elements and travel time models can be found in the Appendix. The annual equivalent total cost (AETC) model can be stated as follws :

$$AETC=[CLN+CBD+CRK+CEQ+ \tag{3-a}$$

$$\sum_{n=1}^{N}\{(COP(n)+CMN(n)+CLB(n))*(1-Tx)-DP(n)*Tx-SAV(N)\}*$$

$$(\frac{1}{1+f})^{n}*(\frac{1}{1+i})^{n}]*(A/P,\ i,\ N)$$

$$,\ \text{for } DP(n)=CBD*DB(n)+CEQ*DE(n)+CRK*DR(n)$$

$$SAV(N)=CBD*\{1-\sum_{n=1}^{N}DB(n)\}+CEQ*\{1-\sum_{n=1}^{N}DE(n)\}+CRK\{1-\sum_{n=1}^{N}DR(n)\}$$

$$+CLN*(1+f)^{N}$$

subject to

$$2*NT*YT*ZT\geq Smax \tag{3-b}$$

$$1\leq NT\leq Nmax \tag{3-c}$$

$$ZLB\leq ZT\leq ZUB \tag{3-d}$$

$$\frac{Smax}{2*NT*ZUB}\leq YT\leq\frac{Smax}{2*NT*ZLB} \tag{3-e}$$

$$NSR=NT\geq NOE \tag{3-f}$$

$$CLN+CBD+CEQ+CRK\leq IVmax \tag{3-g}$$

$$LAND\leq LDmax \tag{3-h}$$

$$\text{and } NT,\ YT,\ ZT,\ NOE,=\text{positive integer values} \tag{3-i}$$

where

AETC = general annual equivalent total costs,
i = inflation free discount rate,
N = planning horizon in years,
Tx = annual tax rate,
DP(n) = yearly depreciation deductions in year n,
SAV(N) = salvage value at the end of the planning horizon,
DB(n) = depreciation percentage for building in year n,
DE(n) = depreciation percentage for equipment in year n,
DR(n) = depreciation percentage for rack facility in year n.

The following terms have descriptions of the preceding model.

*Objective function.* The first four elements (CLN+CBD+CRK+CEQ) denote the initial investment cost of the system. The second term [{COP(n)+CMN(n)+CLB(n)}*(1−Tx)] indicates the after-tax recurring costs at period n and the third term {-DP(n)*Tx-SAV(N)} denotes the depreciation credit at period n and salvage value at the end of the planning horizon year.

*Decision variables.* The decision variables are defined as variables which determine the configuration of a rack storage system as follows :

NSR : number of required pieces of S/R machines
NT : number of storage aisles
ZT : number of storage layers in a vertical direction
YT : number of storage racks in a horizontal direction
LAND : total land required
ITC : initial investment required

*Constraints.* Constraint(3−b) represents the minimum number of required of rack openings for the storage rack facility. Nmax is defined as the maximum number of storage aisles, and ZLB and ZUB are the lower and upper boundaries of the number of storage layers for the selected storage system. Then constraints (3-c, d, and e) denote the boundary of the storage rack facility. Constraint (3-f) is the restriction of the minimum amount of handling equipment required as explained in the Appendix. Constraints (3-g and 3-h) denote the restrictions of the maximum available initial investment funds (IVmax) and the maximum land (LDmax).

A solution procedure is presented which can be used with the previously developed model to design of an automated warehouse systems.

1. Input the anticipated product flow data, equipment characteristics, storage structure parameters, components costs, economic considerations, and restrictions of fund and land.
2. Determine the maximum inventory levels (Smax, Amax, and Pmax) and the throughput rate (TR) while considering the size and timing of arrival and demand products using simulation model.
3. Determine the possible range of ZT and YT for the selected NT(NT$\leq$Nmax)based on the results of simulation(Smax) and the restrictions of the storage system (ZLB and ZUB, and LDmax). This step will reduce unnecessary computations.
4. Calculate the average round-trip travel time (TT) for the selected storage structure to determine the number of required pieces of S/R machine (NOE).
   If NT$\geq$NOE, go to step 5 ; Otherwise, go to step 3, and select the next possible storage system.
5. Calculate the overall system cost (AETC) and required initial investment fund.
   IF CLN+CBD+CEQ+CRK$<$IVmax, go to step 6. Otherwise, go to step 3, and select the next feasible storage system.
6. Repeat step 3 through step 5 as an enumeration process while considering all feasible storage rack structures. Then the systems having either minimum overall system costs, minimum travel time, minimum initial investment, or the minimum amount of land are identified.

## NUMERICAL EXAMPLE

The numerical example discussed here is in the design of a warehouse for palletized products in a distribution area. A fully Automated Storage/Retrieval System is selected in this example. The warehouse is designed for a daily throughput of approximately 960 pallets (i. e., 960 pallets are stored and retrieved daily.) Assume that the safety stock is 2880 pallets(i. e., throughput of three day's pallets).

The expected time length between arrival, MA, and demand pallets, MD, is exponentially distributed (approximately) with the following mean paramenters : MA=5 and MD=8. The expected arrival quantities, LA and UA, and demand quantities, LD and UD, at one time, are uniformly distributed (approximately) with the following lower and upper bounds parameters : (LA, UA=8, 12), and (LD, UD=10, 22).

There are 300 working days per year with 8 working hours per day. The required assumptions are that all storage locations are the same size, as are the pallets. The capacity of the handling equipment is a single unit. Pallet load for any storage or retrieval operation. Randomized storage is used. That is, any point within the pick face is equally likely to be selected for storage or retrieval. The S/R machine operators either on a single or dual command basis. Then 95% upper limit confidence intervals for the maximum inventory levels are assumed in the example. The investigation of how the warehouse storage systems are designed is based on the designer's decision criteria of : minimum overall system costs, minimum travel time of handling equipment, minimum initial investment costs, and minimum amount of land requirement sotrage system. The overall annual equivalent total costs model is used in this example.

The control system costs were set at $450,000 and the cost of one S/R machine was set at $70,000. The maximum number of storage aisles was limited to 15 (Nmax), and the upper (ZUB) and lower (ZLB) boundary of the number of storage layers for the selected equipment type and storage rack facility were 15 and 9(restricted by the designer in the input data). In addition, the results of simulation and the expected storage system data are :

(a) results of simulation :
*maximum inventory level in storage area (Smax) : 3100(pallets)
*maximum inventory level in arrival area (Amax) : 86(pallets)
*maximum inventory level in shipping area (Pmax) : 99(pallets)

(b) the characteristics of the selected handling equipment considered :
*vertical travel velocity : 100(feet/minute)
*horizontal travel velocity : 330(feet/minute)
*main-aisle travel velocity : 330(feet/minute)
*pick-up or deposit time (P/D) : 0.05(minute)
*average utilization ratio(AU) : 95(%)
*dual command operation ratio(DUAL) : 50(%)

(c) the sotrage structure parameters :
*depth of the unit rack(LTH) : 4(feet)
*width of the unit rack(WTH) : 4(feet)
*unit pallet width(Pw) : 3.5(feet)
*unit pallet lenght(Pl) : 3.5(feet)
*storage aisle width(ATH) : 6(feet)
*main aisle width(MTH) : 16(feet)

*area of the shipping and receiving dock(ADOCK) : 2800($ft^2$)
*area of the offices(OFC) : 554($ft^2$)

(d) the component costs :
*unit land cost(LC) : 22($/square feet)
*unit building cost(BC) : 35($/feet by height)
*operating cost(OP) : 35($/hour per piece of equipemnt)
*annual labor cost per one operator(LAB) : 35,000($)
*annual control system maintenance cost(CM) : 20,000($)
*annual building maintenance cost(BM) : 0.3($/square feet)
*annual equipment maintenance cost(EM) : 3,000($/equipment)
*fixed initial conveyor cost($COV_f$) : 40,000($)
*unit conveyor cost(CC) : 1,000($/ft)

(e) the economic considerations :
*planning horizon years to be investigated(N) : 8(years)
*annual rate of general inflation(f) : 5(%)
*annual inflation free interest rate(i) : 10(%)
*annual tax rate(Tx) : 46(%)
*depreciation policy : Modified U. S. ACRS method
*annually increasing rate of wage, land, and operating and maintenance costs(f) : 5(%)

(f) the other restrictions :
*initial investment fund limitation(IVmax) : $2,400,000
*maximum available land(LDmax) : 17,000square feet

The summary of solutions is illustrated in Table 1. For minimum overall annual system costs, the storage system with 4 storage aisles was selected in this example. The overall required land is 13,912 square feet. The number of storage racks in a horizontal direction is 33 racks and the number of storage racks in a vertical direction is 12 layers. For a minimum round-trip travel time storage system, the storage system with 7 storage aisles was chosen. However, the minimum initial investment fund system and the minimum amount of land requirement system resulted in the storage system with 3 storage aisles. Therefore, minimizing based on travel time or land requirements differs from minimizing based on costs. The reason for the same storage system in the minimum initial investement fund and the minimum land requirement for this example is that both are concave functions. Specifically, the land requirement model is an increasing concave function, i. e., the lower number of storage aisle systems requires a smaller amount of land. Also, the initial investment fund, which consists of the land, building, storage rack facility, and equipment system, depends mostly on land and equipment costs which increase as the number of storage aisles increase. However, the minimum overall storage system differs from the minimum land requirement system, the minimum initial investment system, and the minimum travel time system in this example. The differences in the example exist because the overall system costs not only consist of the initial investment, but also of the operating and maintenance costs.

## CONCLUDING REMARKS

The modeling approach presented in this paper has attempted to provide a means by which realistic warehouse storage systems may be designed. Integrating the overall costs model and simulation with the overall size and shape of the storage areas provides one important step toward achieving this objective. The user can use the research to design and select the warehouse system based upon either minimum system costs, minimum average round-trip travel time for the handling equipment, minimum initial investment system, or the minimum amount of land necessary for the storage system. Thus, it is felt that the resultant model and simulation are more complete than any other currently available for use by a designer in this decision-making environment.

## APPENDICES :

Appendix A : Cost Models

The cost equations presented in this section are intended to illustrate a possible way to measure each component of overall storage system costs. We certainly recognize that many readers might consider other parameters to be a more realistic representation in each equation.

*Land Cost* : The total area taken up by the warehouse constitutes the area of the storage facility, offices, arrival and shipping inventory areas, and receiving and shipping dock areas. The total required land requirements(LAND) is

$$LAND=(2*LTH+ATH)*NT*WTH*YT+(2*LTH+ATH)*NT*MTH+OFC+(Amax+Pmax)*(Pw*Pl)+ADOCK \qquad (A-a)$$

and the land cost is CLN=LC*LAND (A−b)

where

LC=unit land price per square feet,
WTH=unit storage rack width in feet,
LTH=unit sotrage rack length in feet,
ATH=unit storage aisle width in feet,
ZT=number of storage layers in a vertical direction
NT=number of storage aisles,
YT=number of storage racks in a horizontal direction
MTH=main aisle width in feet,
OFC=area of the offices in square feet,
Pw=unit pallet width in feet,
Pl=unit pallet length in feet, and
ADOCK=area of the shipping and receiving dock in square feet

*Building Costs* : the building costs(CBD) are obtained using the following expression :

$$CBD=BC*(LAND-ADOCK)*\{.986508-.005349*(WTH*ZT+4)+.0002698*(WTH*ZT+4)^2\}$$

where BC denotes the unit building cost per square feet height.

*Storage Rack Costs* : There are two rack walls on both sides of an aisle. All racks are of the same size. The rack cost per opening is assumed to be a linearly increasing function of the number of openings. Therefore, the general total storage rack cost(CRK) is determined by :

$$CRK=RC*2*NT*YT*ZT \qquad (A-d)$$

where RC is the rack cost per opening.

*Handling Equipment Costs* : The total equipment cost consists of three components : S/R machines, control system, and conveyor. The minimum required amount of S/R machines (NOE) is obtained by dividing the throughput rate per hour (TR) by the number of storage/retrieval operation cycles handling equipment can perform per hour (TRs) times average utilization ratio (AU) :

$$NOE=\frac{TR}{TRs\cdot AU}, \text{ for } TRs=\frac{60(\text{minutes})}{TT(\text{minutes})} \qquad (A-e)$$

where NOE has to be rounded to the next highest integer value and TT is an average travel time (see Appendix B). Since this storage/retrieval system needs one S/R machine per aisle, the required number of S/R machines (NSR) is

$$NSR=NT\geq NOE \qquad (A-f)$$

The conveyor cost(COV) can be obtained as the fixed initial cost ($COV_f$) plus the variable conveyor cost($COV_v$) depending on the storage structure as :

$$\begin{aligned} COV &= COV_f+COV_v \\ &= COV_f+CC*2*NT(2LTH+ATH) \qquad (A-g) \end{aligned}$$

where CC is the unit conveyor cost per foot. If the one unit cost of S/R machine is EC and the control system cost including computer softwares and hardwares is CSC, then the total equipment costs (CEQ) may be developed by

$$CEQ=EC*NSR+CSC+COV \qquad (A-h)$$

*Labor Costs* : When the control logic is off of the S/R machine or a central console is used to control all storage machines, then annual labors costs will be

$$CLB(n)=LAB*(1+f)^{n-1}*OPR \qquad (A-i)$$

where LAB denotes the annual labor cost per operator at the starting year, f is the general annual inflation rate, and OPR is the number of operators.

*Maintenance Costs* : The annual maintenance costs are composed of the maintenance costs on the building, handling equipment, and control system. If the annual building maintenance cost per square foot at the starting year is BM, and the annual equipment maintenance cost per piece of equipment at the starting year is CM, then the annual maintenance cost for the nth year {(CMN(n)} is calculated as :

$$CMN(n)=[BM*\{.986508\text{-}.005349*(WTH*ZT+4)+.0002698*(WTH*ZT+4)^2\}+EM*NSR+CM]*(1+f)^{n-1} \qquad (A-j)$$

*Operating Costs* : The operating costs consist of batteries and recharging or fuel costs in the model. OP is defined as the operating costs per hour at the starting year, and THD is the total average operating hours of handling equipment per year. Then the total operating costs for the nth year {COP(n)} are determined by

$$COP(n) = OP*(1+f)^{n-1}*THD \qquad (A-k)$$

Appendix B : Travel Time Models

We deal with an automated warehouse with aisles between which there is a S/R machine running through both vertically and horizontally at one command. We assume that each pallet is stored randomly and retrieved under an equal probability. The travel time for one storage and retrieval operation under the random storage rule can be found by complete enumeration.

The single command travel time, TTs, will be

$$TTs = \frac{4}{TO}\sum_{j=1}^{TO} t_{oj} + 4P/D \qquad (B-a)$$

and the dual command travel time, TTd, can be found from

$$TTd = \frac{2}{TO(TO-1)}\sum_{j=1}^{TO}\sum_{k=j+1}^{TO}(t_{oj}+t_{jk}+t_{ko}) + 4P/D \qquad (B-b)$$

where,

TO = total number of rack opening, (=2*ZT*YT*NT),

$t_{oj}$ = travel time from the input/output(I/O) point at the front of the inventory area to the $j^{th}$ rack,

$t_{jk}$ = travel time from the $j^{th}$ rack to the $k^{th}$ rack, called interleaving time,

$t_{ko}$ = travel time from the $k^{th}$ rack to the I/O point,

and P/D = unit pickup or deposit time.

Obviously, from a standpoint of increased throughput, it is always better to operate on a dual command ; but since it requires both a storage and retrieval order simultaneously, this may not always be possible. Therefore, the system is assumed to operate on the dual command basis by a pre-determined percent of total operation numbers provided by the user. hence, the travel time, TT, will be :

$$TT = (DUAL*TTd) + (1-DUAL)*TTs(\text{in minutes}) \qquad (B-c)$$

Where DUAL is the ratio of dual command operation.

## REFERENCES


1. Ashayer, J., Gelders, L., and Wassenhove, L., 1985. "A Microcomputer-based Optimization Model for the Design of Automated Warehouses", *International Journal of Production Research*, 23 : pp. 825-839.
2. Bassan, Y., Roll., and Rosenblatt, M.J., 1980. "Internal Layout Design of a Warehouse", *AIIE Transactions*, 12 : pp. 317-322.
3. Bozer, Y. A., and White, J.A., 1984. "Travel Time Models for Automated Storage/Retrieval Systems", *AIIE Transactions*, 16 : pp. 329-338.
4. Graves, S.C., Hausman, W.H., and Schwarz, L.B., 1977. "Storage/Retrieval Interleaving in Automatic Warehouse systems", *Managements Sceience*, 23 : pp. 935-945.
5. Hausman, W.H., Schwarz, L.B., and Graves, S.C., 1976. "Optimal Storage Assignment in Automatic Warehousing Systems", *Management Science*, 22 : pp. 629-638.
6. Karasawa, Y., Nakayama, H., and Dohi, S., 1980. "Trade-Off Analysis for Optimal Design of Automated Warehouses", *International Journal of Systems Science, 11 : pp. 567-576.*
7. Park, *Y.H., 1986.* "Modeling of Three Dimensional Warehouse Systems", *Doctoral Dissertation, Auburn University.*
8. Roberts, S.D., "Optimal Warehouse Bay Configulations", *AIEE Transactions*, 4 : pp. 178-185.
9. Roll, Y., and Rosenblatt, M.J., 1983. "Random Versus Grouped Storage Policies and Their Effect on Warehouse Capacity", *Material Flow*, 1 : pp. 199-205.
10. Schwarz, L.B., Graves, S.C., and Hausman, W.H., 1978, "Scheduling Policies for Automatic Warehouse Systems : Simulation Results", *AIIE Transactions*, 10 : pp. 260-270.
11. Tompkins, J.A., and White, J.A., 1984. *Facility Planning*, (John Wiley & Sons, Inc.).
12. Zollinger, H.A., 1982. "Planning, Evaluating, and Estimating Storage Systems", Presented at Institute of Material Management Education First Annual Winter Seminar Series, Orlando, Florida.

TABLE 1. Summary For the Example

| | Minimum AETC System | Minimum Initial Investment System | Minimum Amount of Land System | Minimum Travel Time System |
|---|---|---|---|---|
| Sotrage Structure | | | | |
| NT | 4 | 3 | 3 | 7 |
| ZT | 12 | 14 | 14 | 9 |
| YT | 33 | 37 | 37 | 25 |
| Number of S/R Machines(NSR) | 4 | 3 | 3 | 7 |
| Annual Equivalent Total Cost After Tax(AETC) | 495K | 509K | 509K | 529K |
| Travel time(TT) (minutes) | 1.31 | 1.37 | 1.37 | 1.20 |
| Initial Investment(ITC) | 2,021K | 1,940K | 1,940K | 2,318K |
| Land($ft^2$) | 13,912 | 12,512 | 12,512 | 16,992 |

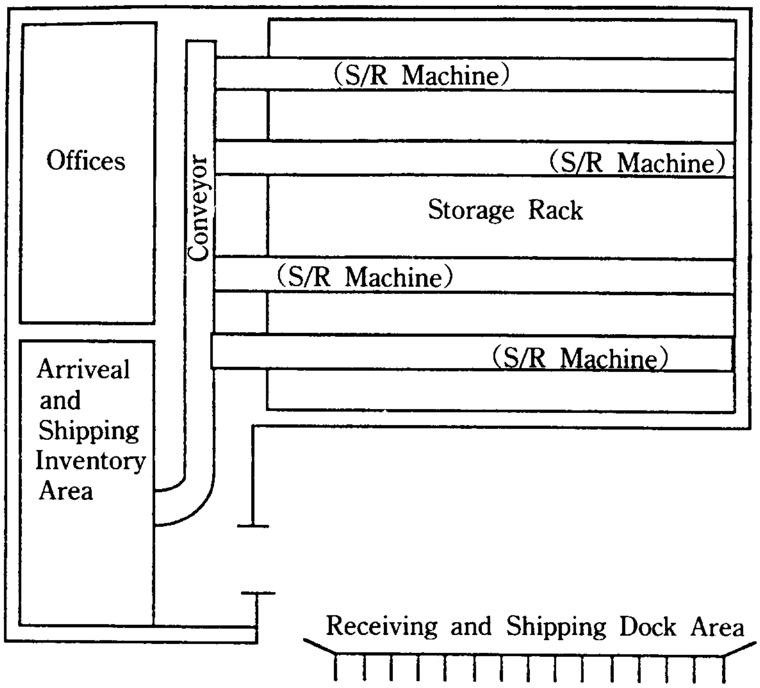


FIGURE 1. General Schematic Layout of Automated Warehouse Systems