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Design of Automated Warehousing System for Increased S/R Machine Utilization+

H.Hwang*
C.S.Ko**

Abstract

The objective of this study is mainly related to design aspects of Multi-aisle S/R machine system (MASS) which can substantially reduce high initial investment cost of Automated Storage/Retrieval System. Firstly, the average travel time of the S/R machine is determined under single and dual commands, from which the average performance of S/R machine is evaluated. Secondly, a design model is developed and the system parameters, such as length and height of the system, and the number of S/R machines, traversers and aisles are determined which provide minimum initial investment and operating costs. Also, through experiments, sensitivity analysis is made for the throughput and storage volume.

1. Introduction

The automated storage and retrieval systems (AS/RS) are revolutionizing the design and operation of conventional warehousing facilities. These systems consist of storage racks, storage/retrieval (S/R) machines, and input/output (I/O) stations. There are many benefits to these systems:labor cost saving, increased space utilization, improved material flow and inventory control, and a lower incidence of misplacement or theft.

However, only a limited number of manufacturing firms are enjoying these benefits mainly due to high initial investment cost, for instance, a S/R machine alone costs approximately $70,000. A measure to reduce the initial cost is utilization of multi-aisle S/R machine system(MASS). In typical AS/RS, a S/R machine operates in a single aisle and services storage racks on both sides of the aisle. In MASS, a S/R machine serves storage racks in more than one aisle through a transfer device called traverser. The S/R machine is placed on

* Department of Industrial Engineering. KAIST.
** Department of Industrial Engineering, Kyungsung University.
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the traverser and can be transferred to adjacent aisles without interrupting its ascending or descending function as illustrated in Fegure 1. The cost of a traverser is estimated approximately to be a half of that of a S/R machine.

Many questions regarding the operation and design aspects of MASS naturally arise such as 1) average travel time of the S/R machine from which the performance of MASS can be evaluated and 2) optimal design for MASS with minimum cost. This paper presents mathematical models to answer the aforementioned questions.

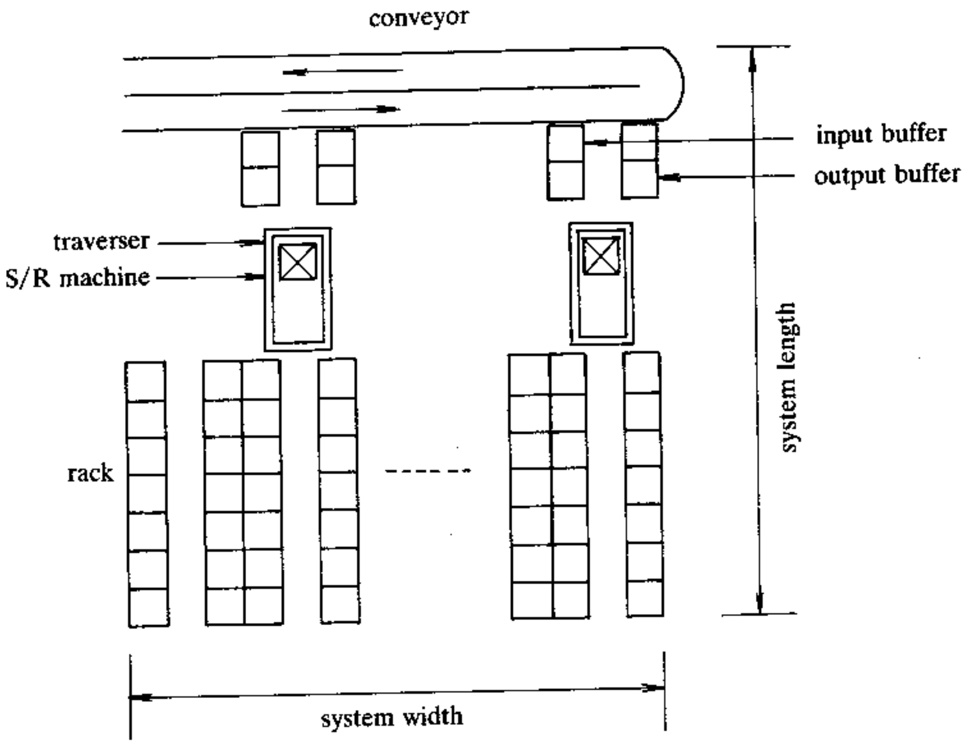

Figure 1. MASS structure.

2. Statistical analysis for travel time

A study for travel time model in AS/RS was firstly made by Hausman et al.(1976), Graves et al.(1977) and Schwarz et al.(1978) for randomized, turnover-based and class-based storage assignment rules, assuming that the rack is square in time. Later, Bozer and White(1984) presented the travel time expressions relaxing the restriction of Graves, Hausman and Schwarz (GHS). In this section, we derive expected travel times of the S/R machines in MASS under single and dual commands, with randomized storage assignment rule.

Under a single command the S/R machine is only capable of visiting a single storage location between successive returns to the I/O point. On the other hand, dual command system makes the S/R machine visit up to two storage locations between successive returns to the I/O point. After completing a given storage location for the next retrieval without returning to the I/O point.

In the randomized storage assignment rule, any pallet is equally likely to be stored in any of the rack storage locations.

To analyze the expected travel times in MASS, the following assumptions are introduced:

1. Each pallet can hold only one item.
2. All rack openings are of the same size, as are the pallets themselves. Therefore all storage locations are candidates for storing a pallet load.
3. The I/O point is located at the lower left-hand corner of the rack face in the leftmost aisle.
4. The S/R machine operates on either single or dual command.
5. The rack length and height, as well as the S/R machine speed in the horizontal and vertical directions, are known.
6. The time to transfer the S/R machine through traverser to adjacent aisles is known.
7. Pick-up and deposit times associated with load handling are constant and equal.
8. The S/R machine can travel simultaneously in the horizontal and vertical directions while being transferred to adjacent aisles.
9. A randomized storage assignment rule is used.

Also, the following notations are introduced:

M=number of aisles in which a S/R machine operates,

d=width of pallet,

X_L=length of rack,

X_H=height of rack,

$W(i)$=width from I/O point to the center of the i^{th} aisle, i.e.,$W(i)=3d(i-1)$,

V_L=velocity of S/R machine in the direction of X_L,

V_H=velocity of S/R machine in the direction of X_H,

V_W=velocity of S/R machine in the direction of $W(i)$.

Let b,c and a(i) represent the travel times required to go to the farthest point in the direction of X_H, X_L and $W(i)$, respectively. Then $b=X_H/V_H$, $c=X_L/V_L$ and $a(i)=w(i)/V_W$.

2.1 Under a single command

We first consider the average travel time under a single command. Suppose that a storage(or retrieval) command occurs in the ith aisle. Let the storage point be represented by (x,y) in time as in Figure 2 where x is the horizontal travel time, i.e.,the horizontal travel time from the I/O point to the center of the ith aisle plus the horizontal travel time to the storage location, $0 \leq a(i) \leq x \leq a(i)+c$, and y is the vertical travel time, $0 \leq y \leq b$. Travel time $t(x,y)$ from I/O point to (x,y) equals $Max(x,y)$. Now let $G(z)$ denote the probability that $t(x,y)$ is less than or equal to z. Assuming that the two coordinates are independent, $G(z)$ can be expressed as

$$G(z)=Pr(x\leqq z)Pr(y\leqq z) \quad \cdots\cdots (1)$$

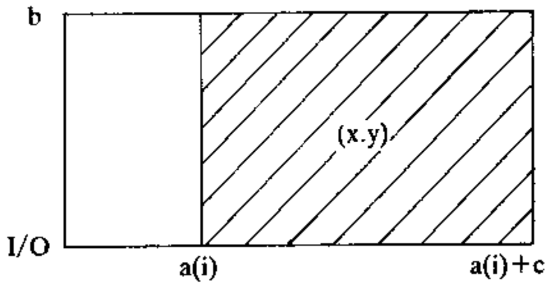

Figure 2. Stroage locations in time unit of the rack face in the i^{th} aisle.

For randomized storage assignment rule, it is assumed that the locations of x and y are uniformly distributed. Thus

$$Pr(x\leq z)=\begin{cases} |z-a(i)|/c & \text{For } a(i)\leq z<a(i)+c \\ 1 & \text{for } z\geq a(i)+c \end{cases} \quad \cdots\cdots (2)$$

and,
$$Pr(y\leq z)=\begin{cases} z/b & \text{for } 0\leq z\leq b \\ 1 & \text{or } z\geq b. \end{cases} \quad \cdots\cdots (3)$$

Since $G(z)$ depends on the relationships among b, a(i) and a(i)+c, we introduce $G_K(z)$ which denotes the distribution function of $G(z)$ under the k^{th} condition, $k=1,2,3$, as described below.

condition 1: $b\leq a(i)$.
condition 2: $a(i)<b<a(i)+c$,
condition 3: $b\geq a(i)+c$. $\cdots\cdots$ (4)

With the first condition,

$$G_1(z)=\begin{cases} |z-a(i)|/c & \text{for } a(i)\leq z<a(i)+c \\ 1 & \text{for } z\geq a(i)+c \end{cases} \quad \cdots\cdots (5)$$

The probability density function, $g_1(z)$, becomes

$$g_1(z)=\begin{cases} 1/c & \text{for } a(i)\leq z\leq a(i)+c \\ 0 & \text{elsewhere.} \end{cases} \quad \cdots\cdots (6)$$

Letting $E_K(SC)$ be the expected travel time corresponding to the condition k with the single command, we have

$$E_1(SC)=2\int_{a(i)}^{a(i)+c} z/c\, dz=2a(i)+c. \quad \cdots\cdots (7)$$

In similar ways, $E_2(SC)$ and $E_3(SC)$ can be obtained and

$$E_2(SC)=\frac{\{b-a(i)\}^3}{3bc} \quad \cdots\cdots (8)$$

and $E_3(SC)=\dfrac{3a(i)^2+3a(i)c+c^2}{3b}+b.$

Since the probability that a storage (or tetrieval) command occurs in the i^{th} aisle is 1/M, the expected travel time under the single command, E(SC), becomes,

$$E(SC)=\frac{1}{M}\sum_{i=1}^{M} E_{\delta(i)}(SC). \quad \cdots\cdots (9)$$

Where $\delta(i)=k$ if the relationship in the i^{th} aisle fits condition k.

2.2.2 Under a dual command

Each dual command involves two random points, one representing the storage point(x_1, y_1) and the other the retrieval point(x_2, y_2). Notice that the expected travel time from the I/O point to either one is one half of E(SC) in equation(9). Now let F(z) denote the probability that the time required to travel between (x_1, y_1) and (x_2, y_2) is less than or equal to z. Then we have

$$F(z)=Pr(|x_1-x_2|\le z)Pr(|y_1-y_2|\le z), \quad \cdots\cdots (10)$$

If those two points are located in the same aisle, the expected travel time between the points, $E(TB_1)$, is given by Bozer and White(1984) and

$$E(TB_1) = \frac{k_1}{3}+\frac{k_2^2}{6k_1}-\frac{k_2^3}{30k_1^2} \quad \cdots\cdots (11)$$

Where $k_1=\max(b,c)$ and $k_2=\min(b,c)$.

Thus, we are interested in the case where the aisle numbers of those two points are different each other. Suppose (x_1, y_1) is in the i^{th} aisle and (x_2, y_2) in the j^{th} aisle, $j\neq i$.
Then

$$Pr(|y_1-y_2|\le z)=\begin{cases}\dfrac{2z}{b}-\dfrac{z^2}{b^2} & \text{for } o\le z<b \\ 1 & \text{for } z\ge b.\end{cases} \quad \cdots\cdots (12)$$

Let $A(i,j) = |a(i) - a(j)|$. The probability distribution of $|x_1 - x_2|$ is equivalent to that of $x_1' + x_2' + A(i,j)$ where $x_1' = x_1 - a(i)$and $x_2' = x_2' - a(j)$. Thus

$$\Pr(|x_1 - x_2| \leq z) = \begin{cases} -\frac{A(i,j)z}{c^2} + \frac{z^2}{2c^2} & \text{for } A(i,j) \leq z < A(i,j)+c \\ (\frac{2}{c} + \frac{A(i,j)}{c^2})z - \frac{z^2}{2c^2} & \text{for } A(i,j)+c \leq z < A(i,j)+2c \\ 1 & \text{for } z \geq A(i,j)+2c \end{cases} \quad \cdots\cdots (13)$$

Here, F(z) can be specified under each of the following conditions.

condition 1 : $b \leq A(i,j)$,
condition 2 : $A(i,j) < b < A(i,j)+c$,
condition 3 : $A(i,j)+c \leq b < A(i,j)+2c$,
condition 4 : $b \geq A(i,j)+2c$. ························ (14)

Let $F_k(z)$ represent the distribution function corresponding to condition k. With the first condition,

$$F_1(z) = \begin{cases} -\frac{A(i,j)z}{c^2} + \frac{z^2}{2c^2} & \text{for } A(i,j) \leq z < A(i,j)+c \\ (\frac{2}{c} + \frac{A(i,j)}{c^2})z - \frac{z^2}{2c^2} & \text{for } A(i,j)+c \leq z < A(i,j)+2c \\ 1 & \text{for } z \geq A(i,j)+2c \end{cases} \quad \cdots\cdots (15)$$

Therefore, the probability density function, $f_1(z)$ becomes

$$f_1(z) = \begin{cases} -\frac{A(i,j)}{c^2} + \frac{z}{c^2} & \text{for } A(i,j) \leq z < A(i,j)+c \\ (\frac{2}{c} + \frac{A(i,j)}{c^2}) - \frac{z}{c^2} & \text{for } A(i,j)+c \leq z < A(i,j)+2c \\ 0 & \text{elsewhere.} \end{cases} \quad \cdots\cdots (16)$$

Letting $E_k(TB_2)$be the expected travel time corresponding to the k^{th} condition, we obtain

$$E_1(TB_2) = \int_{A(i,j)}^{A(i,j)+2C} z f_1(z)\, dz = A(i, j) + c \quad \cdots\cdots (17)$$

In similar ways, $E_2(TB_2)$, $E_3(TB_2)$ and $E_4(TB_2)$ can be found and

$$E_2(TB_2) = -\frac{7A(i,j)^5}{20b^2c^2} + \frac{7A(i,j)^4}{12bc^2} - \frac{A(i,j)^3}{6c^2} + \left(1 - \frac{b^2}{12c^2}\right)A(i,j) + c + \frac{b^3}{60c^2},$$

$$E_3(TB_2) = \frac{7A(i,j)^5}{20b^2c^2} + \left(\frac{7}{2b^2c} - \frac{7}{12bc^2}\right)A(i,j)^4 + \left(\frac{7}{b^2} - \frac{14}{3bc} + \frac{1}{6c^2}\right)A(i,j)^3 + \left(\frac{7c}{b^2} - \frac{7}{b} + \frac{1}{c}\right)A(i,j)^2 + \left(\frac{b^2}{12c^2} + \frac{7c^2}{2b^2} - \frac{14c}{3b} + 2\right)A(i,j) + \frac{7c^3}{10b^2} - \frac{7c^2}{6b} + \frac{4c}{3} + \frac{b^2}{6c} - \frac{b^3}{60c^2} \quad \cdots\cdots (18)$$

and

$$E_4(TB) = -\frac{19A(i,j)^3}{3b^2} + \left(\frac{6}{b} - \frac{17c}{b^2}\right)A(i,j)^2 + \left(\frac{10c}{b^2} - \frac{33c^2}{2b^2}\right)A(i,j) + \frac{25c^2}{6b} + \frac{b}{3}.$$

Now, the expected travel time between two randomly selected points, E(TB), is found and

$$E(TB) = \frac{1}{M^2}\left[\sum_{i=1\,(i\neq j)}^{M}\sum_{j=1}^{M} E_{\delta(i,j)}(TB_2) + ME(TB_1)\right] \cdots\cdots (19)$$

Where $\delta(i,j) = k$ if the relationship in aisles (i,j) satisfies condition k.

In conclusion, expected travel time, E(DC), in the dual command becomes

$$E(DC) = E(SC) + E(TB). \quad \cdots\cdots (20)$$

So far, we have derived the the expected travel times under single and dual commands in MASS. Now, the performance of S/R machine in MASS will be analyzed.

If the ratio, r, of the number of dual commands to that of total storage/retrieval commands can be specified, the average travel time executing either storage or retrieval task, AT_r, can be represented as

$$AT_r = \frac{r}{2}E(DC) + (1-r)E(SC). \quad \cdots\cdots (21)$$

Hence, the performance of the S/R machine, PF(M,r), in MASS whose aisle size is M, becomes

$$PF(M,r)=\frac{2*(\text{Total operating time/unit period})}{rE(DC)+2(1-r)E(SC)+2T_0} \quad (22)$$

Where T_0 is pick-up (or deposit) time of S/R machine.
In other words, PF(M,r) is the number of commands MASS can carry out per unit time.

Example 1 : Suppose that specifications for rack dimensions and S/R machine speed are as follows: $X_L=348$ ft, $X_H=88$ ft, $V_L=356$ft/min and $V_H=100$ ft/min. (the above specifications are the same as the example of [5].) In addition, pick-up(or deposit) time, T_0, pallet width, d, and S/R machine speed, V_W, associated with d, are 0.6min, 4.29 ft and 50 ft/min, respectively. Also, total operating time is 8 hours per day.

Table 1 tabulates expected travel times and PF(M,r) of example 1 for up to five aisles.

Table 1. Results of example 1.

# of aisles (M)	E(SC)	E(TB)	E(DC)	PF(M,r)		
				r=0.25	r=0.5	r=0.75
1	1.2416	0.4341	1.6757	275.8	292.7	311.9
2	1.4435	0.8549	2.2984	243.7	253.1	263.3
3	1.6849	1.0521	2.7370	217.6	225.7	234.4
4	1.9509	1.2041	3.1841	216.8	202.4	210.4
5	2.2285	1.3811	3.6096	176.3	183.4	191.2

As expected, as M increases, expected travel times are also increasing and as either r increases or M decreases, PF(M,r) increases.

3. Optimal design for MASS

Concerning the design of AS/RS, considerable reserarches have been carried out. Zollinger (1974, 1982) developed a basis for estimating AS/RS investment costs by synthesizing information for more than 60 AS/RS installations. Karasawa, Nakayama and Dohi(1980) applied a non-linear mixed-integer programming to a model of AS/RS. The resulting model was solved by using Lagrangian multipliers and then choosing the best neighborhood integer solution. Ashayeri, Geldrs and Wassenhove(1985) presented a microcomputer-based optimization model to minimize investment and operating costs. Recently, Lee and Hwang(1988) suggested an approach in the design of automated carousel storage systems of which the characteristic is similar to that of AS/RS. Other studies(Koenig 1981, Emerson et al. 1981, Ashayeri et al. 1983) utilized simulation model to develop and evaluate the automated warehousing systems. We present a mathematical model for the design of MASS in which the system parameters, such as width, length and height of the system, and the number of S/R machines, traversers and aisles are determined which provide a minimum initial investment and operating cost. Also, through experiments, sensitivity analysis is made for the throughput and storage volume and the comparison of AS/RS is made with MASS.

3.1 Development of the model

In this section, we present a design model which incorporates all the relevant cost figures and constraints for installing MASS.

The cost components consist of initial investment costs and discounted operating costs as follows:

1) S/R machine and traverser costs:The numbers of S/R machines and traversers depend on the value of M. Since randomized storage assignment rule is used throughout this paper, the total number of aisles can be divided into (N–1) M aisles and j aisles where N is the number of S/R machines and j=1, 2,…, M. Thus, the number of traversers equals $(N-1)\sigma(M)+\sigma(j)$ where $\sigma(j)$ is defined by

$$\sigma(j)=\begin{cases}0 & \text{if } j=1\\ 1 & \text{otherwise.}\end{cases}$$

Suppose an automated warehousing system with 10 aisles. If M=3, N=4 and j=1, i.e., there are three groups of aisles, each three aisles in size and being served by a S/R machine and a traverser and a single aisle in which the 4^{th} S/R machine operates. Thus, the number of traversers becomes 3. If we assume that the cost of a traverser is a half of that of a S/R machine, the cost of S/R machines and traversers can be expressed by

$$C_1[N+.5\{(N-1)\sigma(M)+\sigma(j)\}] \quad \cdots\cdots (23)$$

where C_1=cost of a S/R machine.

2) Rack structure cost: $25(a_1V+a_2VN_H+a_3VN_H^2)$ ⋯⋯ (24)

where N_H=height of rack in pallets,
V=storage volume(i.e., number of rack openings),
$a_1=0.92484+0.025v+0.000442w-w^2/82500000$,
$a_2=0.23328$,
$a_3=-0.00476$,
v=volume of a unit load,
w=weight of a unit load,

Note that this estimate is provided by Zollinger(1982).

3) Foundation and roof cost: $(C_2+C_3)\,S_WS_L$ ⋯⋯ (25)

where C_2=foundation cost per square meter,
C_3=roof cost per square meter,
S_W=system width,
S_L=system length.

4) Wall cost: $C_4S_H(S_W+2S_L)$ ⋯⋯ (26)

where C_4=wall cost per square meter.

5) Conveyor cost:$2C_5S_W$ .... (27)

where C_5=conveyor cost per meter.

6) Input/Output buffer cost:fC_6N .... (28)

Where C_6 is the cost of one buffer position and f/2 is the number of input or output positions that are provided between each S/R machine and the conveyor loop. It is assumed that f is equal to 5% of hourly throughput.

7) Land cost:$C_7S_WS_L$ .... (29)

where C_7:land cost per square meter.

8) Costs of computer and other supporting services (heating, lighting, springkler and fire detection system, ets.):C_8

9) Discounted operating costs: $\sum_{t=1}^{T}(pC_1N+S)/(1+i)^t$ .... (30)

where i is discount rate and T is the planning horizon of MASS. S is the yearly salary cost of the order pickers and pC_1N means that the total maintenance cost of the system per year is assumed to be approximately p% of the investment cost for S/R machines.

Next, the following constraints are introduced.

1) Site restrictions on the system:

$S_W=3J(d_W+d_C)\leqq l_W$, ... (31)

where d_W=width of a pallet,
d_C=clearance of a rack opening,
l_W=available site width.

$$S_L=\begin{cases}(d_L+d_C)N_L+2d_L\leqq l_L & \text{if } M=1\\ (d_L+d_c)N_L+2d_L+3d_L\leqq l_L & \text{otherwise}\end{cases} \quad \cdots\cdots (32)$$

where N_L=length of rack in pallets,
d_L=length of a pallet,
l_L=available site length.

Here, $2d_L$ and $3d_L$ are the conveyor and the traverser sites, respectively.

$S_H=(d_H+d_C)N_H\leqq l_H$ .... (33)

where d_H=height of a pallet,
l_H=legal restriction on the system height.

2) Storage volume requirement:

$$2JN_HN_L \geqq V \quad \cdots\cdots (34)$$

where J=number of aisles.

3) Throughput requirement:

$$U\{(N-1)PF(r,M)+PF(r,j)\} \geqq D. \quad \cdots\cdots (35)$$

where U=utilization factor of a S/R machine.
D=total pallet demand per unit period.

3.2 Solving the model and numerical results

The model described can be reformulated into a nonlinear integer programming problem with decision variables N_L, N_H, J, N and M. Any existing optimization technique involves very tedious and time consuming calculations to find an optimal solution. Thus, an enumeration search procedure is utilized within a reduced set of feasible solutions. An interactive computer program is developed in BASIC and implemented on an IBM PC/AT and the procedure is illustrated in Figure 3.

To demonstrate the validity and efficiency of the design model, and example problem is solved with the data given in Table 2 and the results are summarized in Table 3.

To show the use of the model further, sensitivity analysis is done on the throughput and storage volume(see Figure 4 and 5). Throughput is varied from 200 to 1400 by increments of 200. Figure 5 shows that the total cost increases in steps and approaches that of AS/RS in case of high throughput. Note that the total cost is constant in AS/RS. Thus, MASS is suitable for automated warehousing system as long as the storage/retrieval demands are relatively low. The effects of storage volume requirement is shown in Figure 5. We observe that as the volume increases, the total cost becomes larger and is always smaller than that of AS/RS.

4. Conclusion

In this study, we calculated expected travel time of the S/R machine from which the performance of MASS is evaluated and proposed a design model with the objective of minimizing initial investment cost and operating costs. Through an example, it was shown that the total cost of automated warshousing systems can be substantially reduced by applying MASS. Since this study is based on the microcomputer, cost configurations of MASS can be obtained at a very little computational burden. We believe that the approach could be a useful tool for producing a first-cut design of MASS.

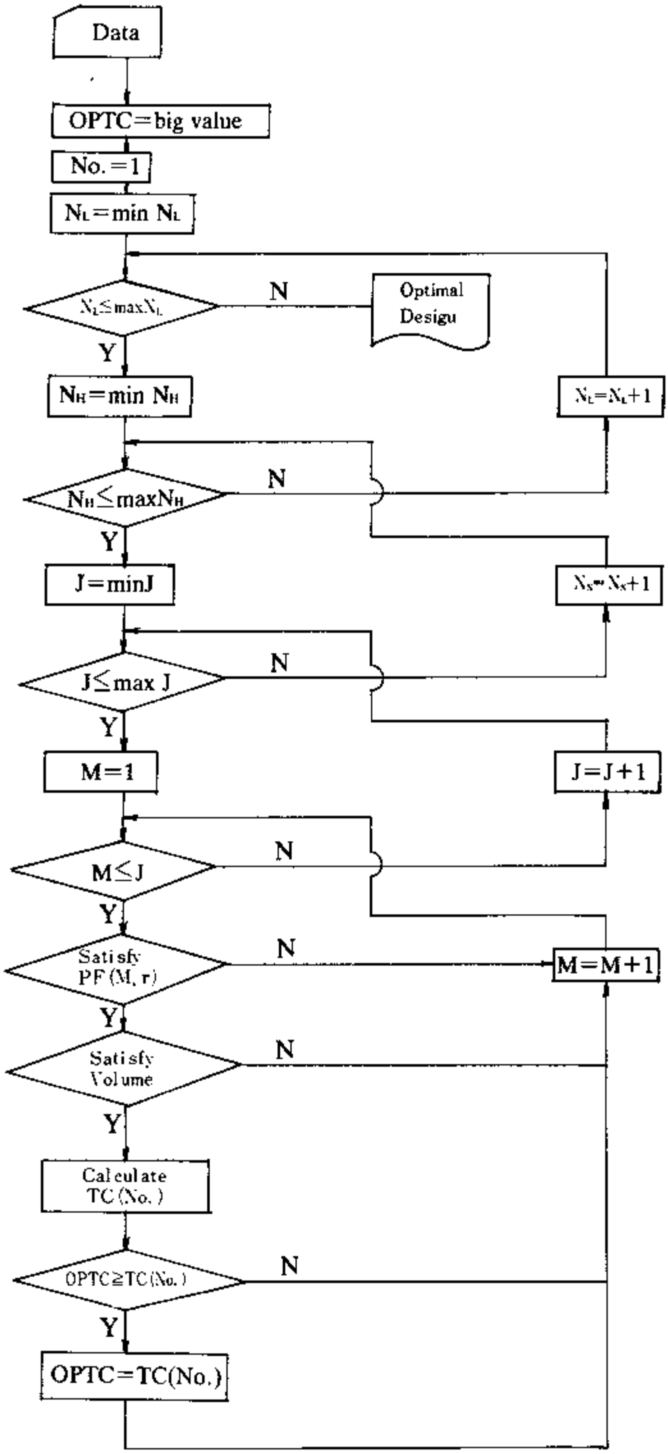

Figure 3. Porocedure for solving the model.

Note that minimum and maximum values of N_L, N_H, and J are defined as follows:

$$MaxN_L = \begin{cases} [(l_L - 3d_L)/(d_L + d_c)] & \text{if } M=1 \\ [(l_L - 5d_L)/(d_L + d_c)] & \text{otherwise,} \end{cases}$$
$$maxN_H = [l_H/(d_H + d_c)],$$
$$maxJ = [l_W/3(d_W + d_c)],$$
$$minN_L = [V/(2 \times maxN_H \times maxJ) + 1],$$
$$minN_H = [V/(2 \times maxN_L \times maxJ) + 1],$$
$$min\,J = [V/(2 \times maxN_L \times maxN_H) + 1],$$

where [x] denotes the largest integer which does not exceed x.

Table 2. Input Data.

Item	Value
Storage volume	$V=11000$
Required throughput	$D=600$pallets/day
Dimension of a pallet	$d_W=1.2$ m
	$d_H=1.2$ m
	$d_L=1.2$ m
Clearance of a rack opening	$d_c=0.15$ m
Maximum weight of a unit load	$w=1$ ton
Site restriction	$l_W=25$ m
	$l_L=120$ m
	$l_H=25$ m
Average pick-up(or deposit)time	$T_0=0.1$ min
Velocity of S/R machine	$V_W=30$ m/min
	$V_H=30$ m/min
	$V_L=150$ m/min
Utilization factor of a S/R machine	$U=0.85$
Discount rate	$i=0.2$
Planning horizon	$T=20$ years
S/R machine cost	$C_1=\$$ 50000
Foundation cost	$C_2=\$$ 110 /m^2
Roof cost	$C_3=\$$ 16 /m^2
Wall cost	$C_4=\$$ 15 /m^2
Conveyor cost	$C_5=\$$ 2500 /m^2
Buffer cost	$C_6=\$$ 5000
Land cost	$C_7=\$$ 100 /m^2
Computer and other costs	$C_8=\$$ 200000
Percentage of operating cost relative to the S/R machine	$p=0.05$
Salary cost of order pickers	$s=\$$ 2500000

Table 3. Output.

Item	Value
Total cost	$ 1801967
Initial investment cost	
S/R machine and traverser costs	$ 125000
Rack structure cost	$ 1108757
Roof and foundation costs	$ 2041
Wall cost	$ 89516
Conveyor cost	$ 81000
Buffer cost	$ 500
Land cost	$ 182979
Operating cost	$ 12174
Number of S/R machines	2
Number of traversers	2
Number of aisles	4
Height of rack in pallets	17
Length of rack in pallets	81

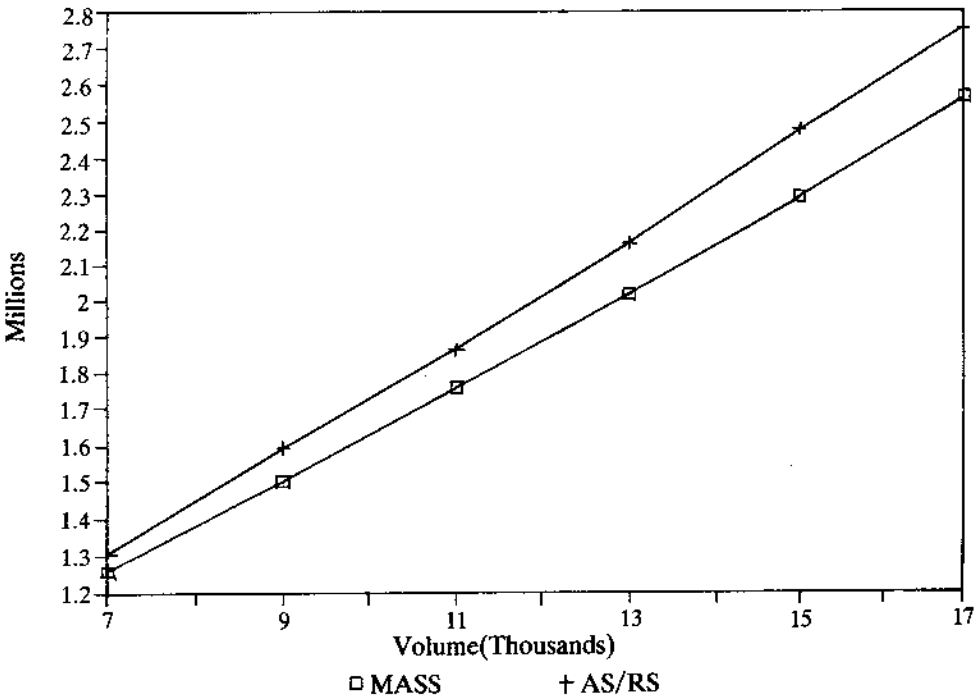

Figure 4. Total cost vs. storage volume requirement.

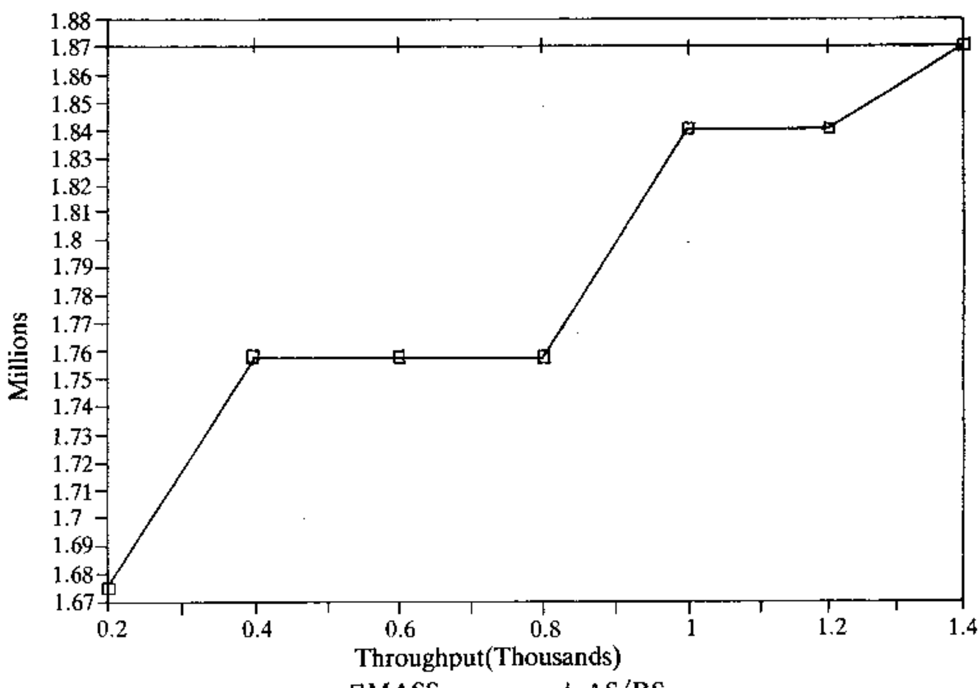

Figure 5. Total cost vs. throughput requirement.

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