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A SIMULATION MODEL FOR EVALUATING CONTROL ALGORITHMS OF AN AUTOMATED STORAGE/RETRIEVAL SYSTEM

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ABSTRACT

Automated Storage/Retrieval Systems (AS/RS's) automatically perform storage and retrieval functions in a manufacturing facility. They have assured themselves a place of value in the factory of the present, as well as in the factory of the future. This paper presents an evaluation of different control algorithms of a single-aisle single-stacker AS/RS, using computer simulation, in order to identify an optimum (or very efficient) control algorithm. Storage location assignment rules, zoning procedures, stacker movement, incoming and outgoing queue priority and sequencing rules were evaluated by grouping control variables and testing the significance of these variables on system performance. Some of the results of this simulation study confirmed some of the literature. Other results provided an interesting contrast for effects of alternate control variables on system performance. The study also provides some guidelines for designing an AS/RS control strategy.

1. INTRODUCTION

Automated Storage/Retrieval Systems (AS/RS's) automatically perform the basic storage and retrieval functions in a manufacturing system. AS/RS's have been well received for warehousing functions [2, 9, 10, 14, 15, 16], and have also been used for work-in-process storage [5, 11, 15]. It has been predicted that AS/RS's will play an important role in the automated manufacturing factory [26, 27]. Of the three basic manufacturing functions, the material handling function adds no value to the product, and can serve only to adequately move a part from one place to another. At its worst, when parts are not handled correctly, the parts can be damaged or lost. In looking for ways to increase the profitability of a system, one should always look for ways to reduce the handling time and cost. In an AS/RS, materials flow between the pick-up and delivery (P&D) station to storage locations, and/or between the storage locations. These movements take time, but handling is automatic and the inventory status is kept via a central computer.

In 1963, J. K. Heskett [6] proposed a cube-per-order index (CPO) location assignment rule for minimizing the cost of order picking in a warehouse. In 1976, Killina [8] showed the CPO rule was in fact an optimal solution. This rule, however, has never been implemented. P. R. Witt [19], in 1974, reported on the control algorithm implemented for the AS/RS at the Material Distribution Center of IBM Endicott, New York. The system assigns the closest location to the input, or the next retrieval location, as the next storage location. The paired interleaving and prioritized queue algorithms were used for job sequencing and dispatching. Witt reported the algorithms raised the stacker capacity, increased the system response and improved system balance. Hausman, Graves and Schwarz [4], [7] developed a mathematical model and showed the 20-40% reduction in travelling time by using turn-over rate based location assignment. The reduction was even greater when the interleaving was incorporated. In 1977, Waugh and Ankener [18] developed a CASP IV simulation model of an AS/RS at Phillip Morris to test surge controlled interleaving and turnover rate based storage location assigment rules. They found substantial improvement in system efficiency and surge reduction.

The literature has shown that the turnover based zone storage location assignment and interleaving job dispataching rules appear to be effective scheduing rules for AS/RS's. However these studies have assumed constant turnover rate. In reality, the market demand for different products fluctuates, and the turnover rates vary from time to time. The storage retrieval rates for an AS/RS are different from one system to another. The current study is to evaluate different rules for storage location assignment and job dispatching under varying demand for all product types.

In a typical AS/RS operation, incoming items are first sorted according to the product type, or product number, and when routed to their specified accumulation conveyors. When a sufficient number of items are accumulated, these items will be sent either directly to palletizers, or through a turning device that will change their orientation, depending on how the pallet load is to be built. The pallet loads from the palletizers will be routed through weighing and sizing stations in order to insure the correct size and weight of each pallet load. If the load fails to pass the check, it will be routed back for re-palletization. Those passed will be transported to inbound P&D stations, and will be assigned a storage location. The stacker will pick up the palletload at the P&D station, and store it at its assigned location. The information (part name, part number, quantity, location, ...) for each load will be stored in the computer memory. When the stored items are needed in the manufacturing process or shipping area, the computer will search its memory for the storage locations, and generate retrieval requests for those items. Upon the request, the stacker will go to the location where the items is stored, retrieve the load, and bring it to the outbound P&D station. A conveyor system may transport the load directly to the area where the load is needed, or to another transportation system which will continue delivering the load to its destination.

This paper deals with the system operations in which the unit loads arriving at the inbound P&D station have been defined. Storage locations are to be assigned to the loads. The stacker then moves them to storage racks. Upon retrieval requests, the stacker goes to the specified location(s) retrieves the load(s), and brings them to the outbound stations for conveyor transport to their final destination(s).

2. CONTROL POLICIES

In this paper, three basic scheduling rules, stacker movement, job sequencing and storage location assignment will be evaluated. The stacker movement includes:

1. Single addressing, in which the stacker must be at the input station to receive the next command, and

2. Pursuit mode, in which the stacker stays at the current position, after completing a command, until the next stacker command is issued.

Four sequencing rules are also studied. They are:

1. First come first serve (FCFS),

2. Shortest completion time (SCT) (The request with shortest completing time gets served first.),

3. Shortest completion time with output priority (SCTop) (The retrieval requests have the first priority, because the retrievals would clear the storage locations, and increase the storage capacity.), and

4. Shortest completion time with controlled output priority (SCTcop) (The algorithm is similiar to the SCTop, except that the priority will be shifted temporarily to input, when the input queue becomes too long, to help in balancing the queues.).

Four storage location assignment algorithms are included.

1. Random Storage Assignment (RNDM) - A location is randomly picked, and is assigned to the pallet to be stored if it is empty. Otherwise, another location is to be picked.

2. Pattern Search, Lowest Tier First (LTF) - The storage location is selected by searching for the closest empty slot in the lowest tier, if no empty slot is found, the next lowest tier will be searched.

3. Shortest Processing Time, independent of product type (SPT) - The empty location which has the minimum travelling time is selected.

4. Turnover-based Zone Assignment (ZONE) - The storage racks are divided into several zones. The zone which is closest to the output station is assigned for storing pallet type with highest turnover rate.

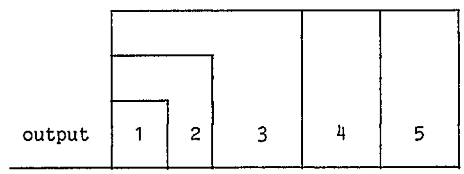
In the turnover based zone assignment algorithm, different procedures may be used to determine the zone sizes and product priority.

2.1 Zone dividing method

The racks are divided into zones according to

1. The physical rack location (PHYS)

   The storage rack is divided into rectangular shape zones as shown below. The location assignment inside of each zone will be the lowest-tier-first rule, and



2. The shortest travelling time to output station (TRVL) (The travelling time, to output station, of any location in the zone of higher priority must be less than any of the locations in the zones of lower priorities. The location assignment rule of shortest travelling time to output station will be used inside of each zone.).

2.2 Static and dynamic location assignment

Storage assigment within an AS/RS can be classified by the assignment specifics. They are:

1. Fixed zone sizes and locations (FSFL) (The zone sizes and product types associated with each of them are assigned once in the beginning, and never change again),

2. Fixed zone sizes but moving locations (FSML) (The zone division in the rack remains as it is first assigned, and never changes again. But, the product priority is reassigned every period of time. Whichever product type gets the highest priority will occupy the zone closest to the outbound station), and

3. Moving zone size and location (MSML) (Both zone size and product priority are to be evaluated and reassigned every period of time.).

2.3 Forecasting Method

When the zone size and/or product priority are varying, the product demand and priority are determined based on the forecast. Two forecasting methods, simple moving average (SMA) and exponential smoothing (EXP) methods, are included in this study.

2.4 Zone Sizing

The zone sizes are to be reassigned every period of time in MSML zone type. The sizes may be assigned based on different system characteristics. In this research, the sizing is based on the average number of storage locations forecast for the product types.

3. SYSTEM DESCRIPTION

The following assumptions hold throughout this research:

1. The AS/RS consists of a single aisle with storage racks on both sides. The simulated system is equipped with a single stacker even though actual system would usually consist of several aisles and stackers, each served by a common conveyance system. The conveyance system, unlike other types of material handling equipment, is usually continuous. Compared to the stacker, the conveyance system itself is seldom a system bottle neck in AS/RS operation. Hence, an M-aisle M-stacker system may be represented by a combination of M single-aisle single-stacker systems.

2. The pallet loads, or unit loads, are of uniform size, as are the storage locations. Therefore, all of the storage locations may be used for storing any pallet.

3. Each storage location can only store one pallet.

4. Each pallet load consists of items of one product number, or product type. Therefore, each pallet load is handled as a single item.

5. Each side of the storage rack contains I rows (tiers) and J columns (bays), or I by J, storage locations.

6. The travelling speed characteristics of the stacker, including the acceleration and deceleratin, are known, and remain unchanged through each experiment.

7. Component failures, or preventive maintenance, is not investigated in this research.

8. The three drives for horizontal, vertical, and shuttle movements operate independently.

9. The stored pallets are retrieved on the first in first out basis.

10. The input and output P&D stations are located at the same end of aisle, with input located at one side of aisle, and output at exacty the opposite side.

The above control algorithms of an AS/RS, were evaluated using computer simulation. The model was written in Discrete SLAM. The macro flow chart of the model is shown in Figure 1. The input to the model are the storage and retrieval request arrivals. In order to simulate the fluctuation of product

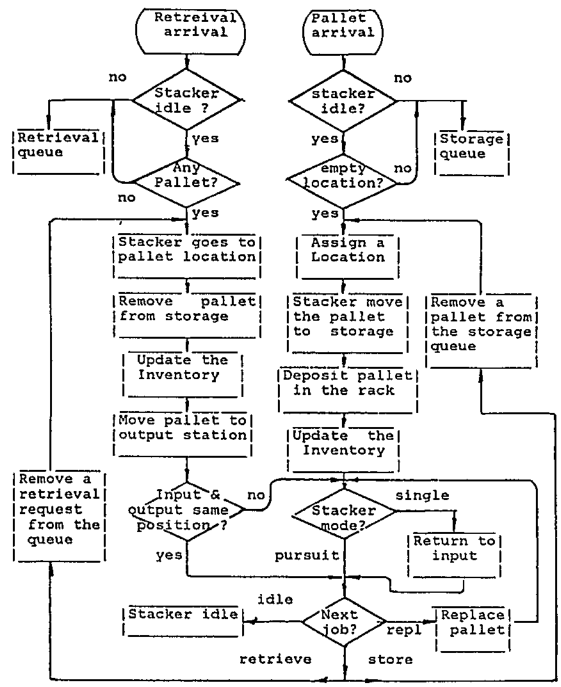


Figure 1: Macro flow chart for AS/RS simulation model.

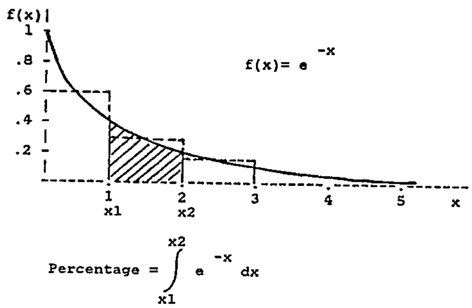
product demands, the interarrival time is assumed exponentially distributed with the mean defined by a sinusoidal intensity function:

AVG(I)=CONST(I) * (1 + .5 * SIN(6.2832wt + THETA(I)))

where AVG : Actual mean interarrival time.
CONST: Steady state (average) interarrival time
THETA: Phase shift angle
w : Reciprocal of the sine function period
t : Time
I : Product type

The steady state interarrival time CONST for a specific product type I is determined by dividing the steady state interarrival time for all product types with the fraction of product type I. Based on the Pareto's maldistribution concept [12], which is often found in a typical warehouse, the product mix, or fraction, was determined by a descretized exponential function which is shown in Figure 2, and the assigned interarrival times for each product type are given in Table 1. The phase shift angle, which is used to simulate the extreme turnover shifting among the product types, is shown in Table 2.

Input delay time, output delay time, and inventory level are selected as the performance measures for the system. A total cost of the system is generated by summing up the cost associated with each performance measure. This may be expressed by a cost function:



Where the region between x1 and x2 is assigned to product type I.

Figure 2: Convertion of exponential distribution into discrete distribution for determining the product percentage.

TABLE 1

Table of percentage and interarrival time assigned.

For 5 Product Types:

Product Type(I)	Region	Percentage (%)	Interarrival Time(CONST)
1	0< x <1	63	1.587u
2	1< x <2	23	4.347u
3	2< x <3	9	11.111u
4	3< x <4	3	33.333u
5	x >4	2	100.000u

For 10 Product Types:

Product Type(I)	Region	Percentage (%)	Interarrival Time(CONST)
1	0< x < .5	40	2.500u
2	.5< x <1.0	23	4.343u
3	1.0< x <1.5	15	6.666u
4	1.5< x <2.0	8	12.500u
5	2.0< x <2.5	6	16.666u
6	2.5< x <3.0	3	33.330u
7	3.0< x <3.5	2	50.000u
8	3.5< x <4.0	1	100.000u
9	4.0< x <4.5	1	100.000u
10	x >4.5	1	100.000u

TABLE 2

The phase shift angles and THETA values of all product types.

Product Type	Phase Shift(degree)	THETA(radians)
1	0	0
2	180	3.1416
3	0	0
4	180	3.1416
5	0	0
6	180	3.1416
7	0	0
8	180	3.1416
9	0	0
10	180	3.1416

$$TC = \sum_{i=1}^{n} PiCi \qquad \text{(EQ. 1)}$$

where TC: Total cost,
Pi: ith performance measure,
Ci: Cost coefficient associated with Pi,
n : Number of performance measures

A fictitious cost value of 1 was assumed for all performance measure cost coefficients, so that each performance measure would carry the same amount of weight in the total cost.

4. THE EXPERIMENT

The decision tree shown in Figure 3 was used to reduce the amount of time and computing expense needed to reach a local optimum. The decision tree groups the different control variables into three levels; stacker movement mode, sequencing rule, and storage location assignment rule. At the third level, the turnover based zone assignment is further extended into three levels (zone dividing method, zone types, and forecasting method). While fixing the control variables in other levels, the control variables within one decision level may be evaluated for the local optimum (the one with lowest cost). Branching from this local optimum down to next decision level, and repeating the same process, another local optimum may be obtained. When the process is replicated down to the bottom level, the one branch which has the lowest total cost is determined as the local optimal procedure, and probably the best global control procedure. The tree was simulated using a different set of stacker speeds (8 ft/min horizontal and 15 ft/min vertical, 5 and 10, and 3 and 6) to investigate the system performance under different storage/retrieval request rates, or stacker utilizations. The result of three experiments are presented in Figure 4-9.

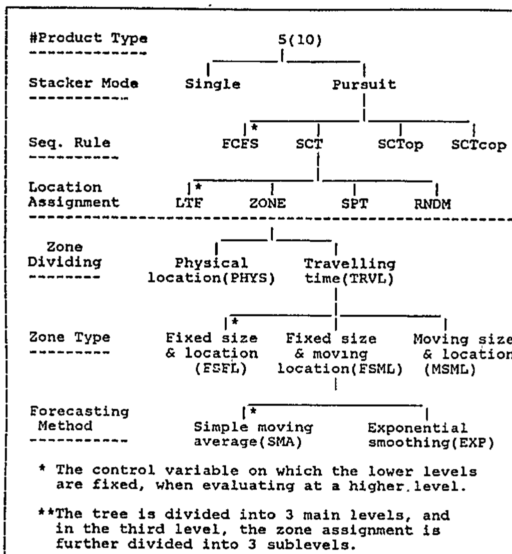


Figure 3: The decision tree with its decision levels and grouped control variables.

	PERFORMANCE MEASURE CONFIDENCE LEVEL(%)				DECISION TREE BRANCH
	INV LEVEL	IN DELAY	OUT DELAY	TOTAL** COST	
					5 TYPES
Stacker movement	50	97.5	84	93.	PURSUIT < SINGLE
Sequencing	50.	50.0	0.6	50.	SCTcop < SCTop < FCFS* < SCT
	50.	0.6	56.0	55.	SCTcop = SCTop = FCFS < SCT
	50.	84.0	44.0	45.	SCTcop = SCTop > FCFS > SCT
Storage location	50.	43.	3.	50.	RNDM < LTF* < ZONE < SPT
	45.	3.	68.	64.	RNDM < LTF = ZONE < SPT
	43.	95.	32.	35.	RNDM > LTF > ZONE = SPT
	(54)	(4)	(71)	(69)	RNDM < (SCT)
Sub-branch(ZONE) Zone dividing	50.	50.	63.	50.	PHYS < TRVL
Zone type	50.	50.	9.	50.	MSML < FSML < FSFL*
	50.	9.	63.	64.	MSML < FSML = FSFL
Forecasting	50.	43.	50.	50.	SMA < EXP*

* The control variable on which the lower levels are fixed when evaluating at a higher level.

** Total Cost = 1(Inventory level)+ 1(Input delay) + 1(Output Delay)

Figure 4: Decision tree branch of 5 product types, with speed of 8 ft/min vertical and 15 ft/min horizontal.

	PERFORMANCE MEASURE CONFIDENCE LEVEL(%)				DECISION TREE BRANCH
	INV LEVEL	IN DELAY	OUT DELAY	TOTAL** COST	
					10 TYPES
Stacker movement	50.0	99.6	74.	97.	PURSUIT < SINGLE
Sequencing	50.	0.3	50.	50.	SCTop < SCTcop < FCFS* < SCT
	50.	80.0	50.	50.	SCTop = SCTcop > FCFS > SCT
Storage location	22.	10.	44.	50.	RNDM < ZONE < LTF* < SPT
	22.	10.	44.	57.	RNDM < ZONE = LTF < SPT
	22.	10.	77.	76.	RNDM < ZONE = LTF = SPT
	(24)	(7)	(82)	(77)	RNDM < (SCT)
Sub-branch(ZONE) Zone dividing	50.	50.	50.	50.	PHYS < TRVL
Zone type	50.	50.	50.	57.	MSML < FSFL* < FSML
	50.	57.	58.	62.	MSML < FSFL = FSML
Forecasting	50.	50.	50.	50.	EXP < SMA*

* The control variable on which the lower levels are fixed when evaluating at a higher level.

** Total Cost = 1(Inventory level)+ 1(Input delay) + 1(Output Delay)

Figure 5: Decision tree branch of 10 product types, with speed of 8 ft/min vertical and 15 ft/min horizontal.

	PERFORMANCE MEASURE CONFIDENCE LEVEL(%)				DECISION TREE BRANCH
	INV LEVEL	IN DELAY	OUT DELAY	TOTA** COST	
					10 TYPES
					PURSUIT
Sequencing	41.	57.	61.	75.	SCT < SCTop < SCTcop < FCFS*
	41.	70.	61.	80.	SCT < SCTop < SCTcop = FCFS
	31.	97.	61.	93.	SCT < SCTop = SCTcop = FCFS
Storage location	50.	.05	57.	56.	LTF* < ZONE < SPT < RNDM
	50.	.05	57.	61.	LTF < ZONE < SPT = RNDM
	50.	.05	69.	65.	LTF < ZONE = SPT = RNDM
	79.	91.	72.	82.	LTF < RNDM
Sub-branch(ZONE) Zone dividing	50.	59.	53.	54.	PHYS > TRVL
Zone type	50.	15.	50.	50.	MSML < FSFL* < FSML
	50.	15.	57.	57.	MSML < FSFL = FSML
Forecasting	50.	58.	50.	50.	SMA* < EXP

* The control variable on which the lower levels are fixed when evaluating at a higher level.

** Total Cost = 1(Inventory level)+ 1(Input delay) + 1(Output Delay)

Figure 6: Decision tree branch of 10 product types, with speed of 5 ft/min vertical and 10 ft/min horizontal.

	PERFORMANCE MEASURE CONFIDENCE LEVEL(%)				DECISION TREE BRANCH
	INV LEVEL	IN DELAY	OUT DELAY	TOTAL** COST	
					5 TYPES
Stacker movement					PURSUIT
Sequencing	64.	56.	76.0	81.	SCTop < SCT
Storage location	35.	80.	45.	50.	ZONE < SPT < LTF* < RNDM
	40.	84.	57.	85.	ZONE = SPT = LTF < RNDM
	(50)	(89)	(62)	(84)	ZONE < (SCT)
Sub-branch(ZONE) Zone dividing	50.	41.	50.	50.	PHYS < TRVL
Zone type					FSFL
Forecasting					SMA

* The control variable on which the lower levels are fixed when evaluating at a higher level.

** Total Cost = 1(Inventory level)+ 1(Input delay) + 1(Output Delay)

Figure 7: Decision tree branch of 5 product types, with speed of 5 ft/min vertical and 10 ft/min horizontal.

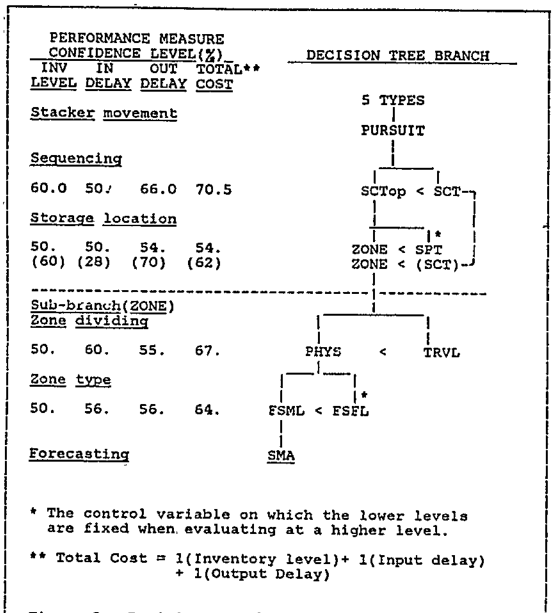


Figure 8: Decision tree branch of 5 product types, with speed of 3 ft/min vertical and 6 ft/min horizontal.

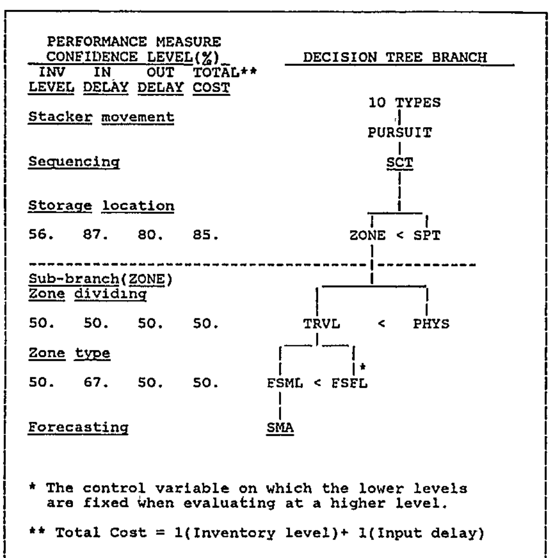


Figure 9: Decision tree branch of 10 product types, with speed of 3 ft/min vertical and 6 ft/min horizontal.

In the first experiment, the tree of five product types shows that the total cost of pursuit mode is less than the single addressing mode (93% confidence). The decision tree was continued from the pursuit mode branch down to next decision level (sequencing rules). The significance at this level is only marginal when SCTcop (the best strategy) was compared to the SCT (55% confidence). It may be concluded that little cost difference exists among the four sequencing rules. No significant difference among the different zone based location assignment rules was identified, therefore, the one with lowest cost estimate (PHYS dividing method, MSML type, and SMA forecasting) was selected for the evaluation at the storage location assignment level.

In the location assignment level, the random (RNDM) assignment is slightly better (64% confidence) than the other three assigment rules (lowest tier first (LTF), zone based (ZONE), and shortest processing time (SPT)). In order to see the cumulative effect of both storage location and sequencing rules, the best control strategy (SCTcop and RNDM) at the location assignment level was compared with the SCT rule at the sequencing rule level. The RNDM location assignment is slightly beter than SCT sequencing (69% confidence).

Overall, the only system performance improvement occurs at the first decision level (stacker movement mode, 93% confidence). Further branching (sequencing rules and location assignment) does not show significance. The same observation has been made in the ten product type tree branch. The pursuit mode is better than single addressing mode (97% confidence); Sequencing rules produces little improvement in the system performance; and the random location assignment is better than the others (76% confidence).

The second experiment was conducted with higher stacker utilization (utilization being the ratio of arrival rate and service rate). In the first level of ten product type tree, the shortest completion time (SCT) discipline is better than the others (93% confidence). The zone based location assignment (ZONE) was branched down to forecasting level. No significant difference exists among them, and the stacker utilization was down to 50% range. The zone based location assignment with travelling time dividing method (TRVL), moving size and location (MSML), and simple moving average (SMA) forecasting was selected from the ZONE sub-branch for the evaluation at the storage location assignment level. In the location assignment,the lowest tier first (LTF) proved better than random assignment (RNDM) (82% confidence); however, the LTF is no better than zone assignment.

The five product type tree shows that the shortest completion time with an output priority (SCTop) sequencing rule is better than SCT discipline (81% confidence). The first-come-first-serve (FCFS) and shortest completion time with controlled output priority (SCTcop) could not process the necessary stores and retrieves, and were eliminated from the list. The zone assignment was pursued down to the zone dividing level, and no cost difference exists between PHYS and TRVL method. The zone assignment with physical location division (PHYS), fixed zone size and location (FSFL) was selected for comparison with other location assignment rules. At the location assignment level, the LTF proved better than random (85% confidence). Tests did not show statistical difference among the ZONE, SPT, and LTF location assignments.

The second experiment shows the SCT sequencing rule was better for ten product type case, but, the SCTop discipline is better for five product type case. Random location assignment is worst among the four location assignment algorithms. However, it is difficult to tell if any difference exists among the LTF, SPT, and ZONE assigments.

In the third experiment, the five product type tree shows the SCTop performed better than SCT (70.5% confidence). The zone assignment branch indicates that the physical location dividing method was slightly better than travelling time dividing method (67%); the zone type of fixed-size-moving-location is better than fixed-size-fixed-location (64% confidence). The moving-size-moving-location was eliminated from the list because of the long queues and extended simulation time. The SPT and ZONE location assignment were equally good.

In the ten product type tree, the zone assignment branch shows no difference among the zone dividing and zone type levels. The moving-size-moving-location was also eliminated from the list because of long queue and extended simulation time. The ZONE location assignment is better than SPT location assigment (85% confidence).

The experiments showed no difference among the turnover based zone assignment rules. Supposedly, in the case of variable demands, the moving zone assignment should be superior to the fixed zone. However, the experimental results did not prove this point. The zone size and product priority assigned at each review period, in the case of five product types with moving zone size and location in the third experiment, were output from the model for investigation purposes. The zone size and priority assignment are shown in Table 3. For the five product types, shown in Table 2, the type 1 and type 2 pallets were supposed to constitute the majority of the incoming pallets (60% of the total for type 1, and 23% for type 2). The priority assignment shown in Table 3 indicates that the priority shift between the two types occurred only for a month period during the one year run length. The theoritical average interarrival time of each product type, which is shown in Figure 10, shows the two product types have little crossover. Therefore, the demand for one of them is higher than the other most of the time. This explains why the priority shifts occurs only once. When the product priorities do not switch significantly, the moving zone assignment would perform just like the fixed zone. Naturally, no improvement should be expected from the moving zone algorithm. The same explanation may be applied to the ten product type case.

Another phenomenon observed is that the SPT and ZONE location assignments are equally good when the number of product types is 5, however SPT becomes significantly worse when the number goes up to 10. The shortest processing time rule assigns every pallet to be stored a storage location with shortest possible travelling time, regardless the product type. Shortest processing time has always been a good sequencing rule for reducing the queue length, or waiting time. The SPT location assignment basically assigns a shortest possible processing time for each pallet to be stored. The zone based loctaion assignment with the zones divided by travelling time method is just an extension of the SPT rule. When the zones are divided according to the travelling time to output station, and the input and output station are at same position, the zone based assignment simply groups all the available processing times (travelling time from the input to each storage locations) into groups, according to the length of each processing time, and the group of shorter processing time is assigned to the product type of higher demand. When a pallet is to be stored, a shortest possible processing time from its own group is assigned to it. This type of zone based location assignment may be viewed as an improved SPT rule.

When the number of product types is small, the SPT location assignment is desirable, especially when one or two product types constitute the majority of the incoming pallets. In a system of a single product type, the zone based location

TABLE 3

Zone size and priority assigndd, in 5 product types, moving zone case.

------ REPLICATION 1 ------

PERIOD	ITEM	type1	type2	type3	type4	type5
1	size	50	50	50	50	50
	prior	1	2	3	4	5
2	size	13	141	10	43	43
	prior	1	2	3	4	5
3	size	2	155	20	71	2
	prior	1	2	3	4	5
4	size	2	219	7	20	2
	prior	1	2	3	4	5
5	size	2	242	2	2	2
	prior	1	2	3	5	4
6	size	2	242	2	2	2
	prior	1	3	2	5	4
Max. Inventory		52	76	9	20	8

------ REPLICATION 2 ------

PERIOD	ITEM	type1	type2	type3	type4	type5
1	size	50	50	50	50	50
	prior	1	2	3	4	5
2	size	14	2	2	20	212
	prior	1	2	3	4	5
3	size	2	2	2	242	2
	prior	2	1	3	4	5
4	size	2	2	2	242	2
	prior	1	2	3	4	5
5	size	2	2	50	17	179
	prior	1	2	3	5	4
6	size	2	242	2	2	2
	prior	1	3	2	5	4
Max. Inventory		44	24	11	20	22

------ REPLICATION 3 ------

PERIOD	ITEM	type1	type2	type3	type4	type5
1	size	50	50	50	50	50
	prior	1	2	3	4	5
2	size	185	2	2	29	2
	prior	2	1	4	3	5
3	size	150	2	2	94	2
	prior	1	2	3	4	5
4	size	126	2	2	78	42
	prior	1	3	2	5	4
5	size	140	16	2	8	42
	prior	1	3	2	5	4
6	size	169	28	2	33	18
	prior	1	2	3	5	4
Max. Inventory		212	123	10	51	35

assignment would behave just like the SPT rule, because there is no priority difference. However a system with multiple product types would perform better with zone assignment because the product with frequent turnover has shorter processing time. In the five product types case, 60% of the pallets are type 1, and 23% are type 2. Type 1 has approximately three times the demand of type 2. In the ten product types case, 40% of the pallets are type 1, 20% are type 2, 15% are type 3 and 8% are type 4. It is obvious that the five product type system behaves more like a single product type system, and the ten product type system is more like a multiple type product warehouse.

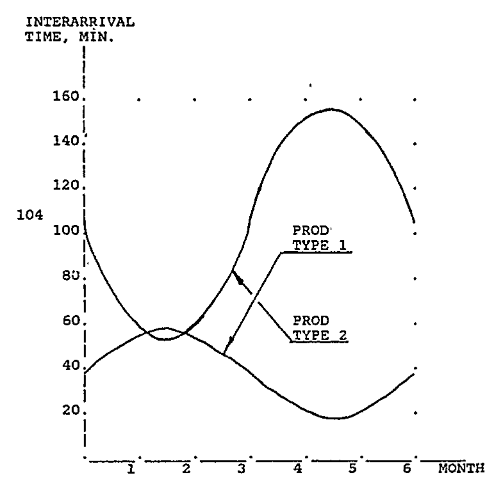


Figure 10: Average interarrival time, of product type 1 and 2 as a function of time, for the five product types system.

5. CONCLUSIONS

The following were concluded from this research:

1. The pursuit mode, in which the stacker remains at its current position after completing a command until the next command is issued, appears to be superior to the single addressing mode, and should always be used, instead of single addressing mode, for the control strategy of an AS/RS.

2. Good AS/RS control algorithm depends on storage/retrieval request rate, or stacker utilization. When the stacker in an AS/RS is poorly utilized (below a critical value), the control algorithms do not affect the system performance. The preliminary critical value found in this research is 50%. When the stacker utilization increases beyond a critical value, job sequencing rules begin affecting the system performance. As the utilization increases further, the storage location assignment rules begin affecting system performance.

3. The storage location assignment rules affect the system performance in the following manners:

   When the system is poorly utilized, the random location assignment is better; as the utilization increases, the pattern search (lowest tier first) location assignment becomes better, if the utilization increases further, the shortest processing time and zone based location assignments will be the better rules.

   This confirms Waugh and Ankener's paper that zone based assigment is a better assignment rule. Little difference can be detected among the different zoning procedures. Further research is needed for determining the demand distribution in which the zoning procedures affect the system performance.

4. The shortest completion time sequencing rule and zone based location assignment rule are better for ten product types. The sequencing rule of shortest completion time with output priority is better for five product types, but shortest processing time and zone based location assignments are identical for five product types. Further research is needed to determine the affect of the number of product types on the system control strategy. For example, the shifting point(s) at which the control strategy shifts from one to another when the product mix increases.

5. When designing the control strategy for an AS/RS of multiple product mix, the Pareto theory of vital few and trivial many should be applied. For example, if the top 20% of product mix constitute the 80% of demands volume, one should design the control strategy for the top 20% of the product mix, instead of designing for all product types (group the others as misc.).

6. Among input delay time, output delay time, and inventory level, the first two performarnce measures influence the total cost variation the most. The inventory level produces little affect on the unitized cost.

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