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SWP 23/93 EVALUATION OF AUTOMATED WAREHOUSING POLICIES: TOTAL SYSTEMS APPROACH

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Evaluation of Automated Warehousing Policies: Total Systems Approach

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ABSTRACT

Warehousing policies can be regarded as micro-level logistic decisions encompassing two basic functions of storage and handling. In automated systems, these operational policies are primarily concerned with stock allocation, storage layout and automated stacker-crane scheduling. Due to the complexity involved, decisions relating to the stacker-crane and associated storage-racks were normally studied analytically in isolation to develop efficient heuristics. In this research, relative throughput performance and interactions of stock allocation rules, storage layout policies and stacker-crane scheduling heuristics are empirically investigated as a total system. Three aspects of policies are knitted together in an integrated model and a factorial experiment has been carried out using simulation modelling. Statistical tests are used to identify those rules that perform best, both overall and in combination with other rules, on different warehouse configurations.

Subject Areas: ***Logistics/Operations Management and Simulation***

INTRODUCTION

Economic concerns and international competition are motivating companies to redesign their business processes. In logistic industries, this trend has led companies to replace their inefficient small regional warehouses by centralized automated installations for operational efficiency. Warehousing could be viewed as a logistical decision-making process at microscopic level encompassing two basic functions of storage and handling. In automated installations, these decisions are made by the management system according to the decision rules embedded in the software. Productivity mainly depends on these rules.

Various types of automated warehouses exist. However, the generic system is the pallet-in pallet-out system that handles unit loads. From a management perspective, operation of a unit load automated warehouse could be described in abstraction with

respect to operational decisions involved. When a customer order arrives, the system has to decide which stock in the warehouse should be allocated to that order. This is done according to the stock allocation rules embedded in the management system. Similarly, for inbound arrival of stock items for put-away, the system decides in which location the stock item has to be stored. Consequently, the automated stacker-cranes travel to respective storage and retrieval bay locations - directed by control rules. In unit load systems, both storage and retrieval of pallets are done within one round trip of a crane in a dual cycle. The control rules that determine which storage and retrieval locations from the queue should be combined for a crane-tour to optimize overall travelling are referred to as interleaving policies. Thus, operating policies or rules for the unit load automated warehouses are mainly involved with stacker-crane interleaving, storage layout and stock allocation. Although the three functional operations are logically interrelated, most previous research in automated warehousing has focused on just one of the above activities while using a single (arbitrary) procedure for the other. Study of a single policy in isolation would be acceptable if it did not interact with other functions, but such is apparently not the case in many real-life situations.

The objectives of this research are to investigate the interactions of stock allocation, storage layout and stacker-crane scheduling heuristics for dual command interleaving and to compare the throughput performance of various storage policies and interleaving heuristics. The next section of this paper reviews related literature and describes the simulation model. Then the paper presents several policies for investigation and compares them in a simulation experiment using statistical methods.

RELATED LITERATURE

The studies on automated warehousing can be categorised into two approaches. The first approach determines the optimal dimensions of the warehouse in order to minimize total cost, assuming a certain operating policy is in effect. Examples of this approach are found, to mention but a few, in Karasawa et al. [11], Asheyeri et al. [1] and Hwang and Ko [11]. The other approach involves introducing new operating policies that improve the performance of a system. Three bodies of literature are relevant to operating policies for unit load systems. These include: interleaving literature, storage policies literature and stock allocation literature.

Interleaving rules look ahead at a batch of retrieval requests listed in the system and sequences the list to minimize overall travelling. Interleaving policies for dual cycles are mostly studied on one particular storage layout. Schwarz et al. [15] introduced

mandatory interleaving with selection queue of K retrieval which applies only to class-based policy. They compared it with FCFS policy for randomized storage layout. Han et al. [9] addressed two sequencing rules, Nearest-Neighbour heuristics and Shortest-Leg heuristics. Both policies were addressed in randomized layout. These two policies were further analyzed by Chaime [4] and by Eynan and Rosenblatt [5]. Chaime found that blocking in Nearest-Neighbour may not be necessary in a dynamic environment and introduced a dynamic application of Nearest-Neighbour without blocking. Recently, Eynan and Rosenblatt analytically formulated expected cycle time for unit load systems operating under Nearest-Neighbour interleaving rule and turn-over based square L-Shape storage policy.

Regarding storage layout policies, Forest [6] introduced a dedicated storage method based on product popularity. Heskette [8] addressed a method which combined both turnover and size in the form of an index called "Cube-per-Order Index (COI). Malmbrog & Karishnakumar [13] proved analytically that the COI minimizes expected order picking cost in dual command mode. Randomized storage policy is favourable in warehouse space saving and dedicated policies in travel time reduction. However, most frequently cited policies were the class-based policies which took an optimal trade-off between randomized and dedicated aspects. Hausman et al. [10] addressed class-based policy to the dual command case taking turnover difference into account. However, Goetschalckx and Ratliff [7] took duration of stay instead of turnover difference for dynamic environment. Tzan [17] proposed a storage policy based on the probability of a bay location becoming a free-insertion point in multiple command order picking systems.

Regarding stock allocation rules, it was given least emphasis in the literature as FIFO policy for good stock rotation was implicitly assumed. Some neglected the issue by generating pick location randomly to study the other two policies. This is unfortunate since the generation of pick location depends a great deal on put-away rules. In this research two allocation rules have been addressed, one on strict FIFO, and another on FIFO-Band which consider a set of oldest stock items to incorporate efficient crane travel as well.

In summary, the review reveals that most of the literature took a problem solving approach to introduce new policies. It was observed that mostly, stacker-crane interleaving heuristics, storage layout policies and stock allocation rules are addressed in isolation to focus on one aspect while taking a single (arbitrary) procedure for the other. The review has failed to identify any research on interactions and relative comparison of these three basic decisions from total systems perspective.

MODEL DESCRIPTION

Operation of an automated warehouse could be viewed as an interaction of activities as illustrated in the modelling framework rather than independent decision making entities.

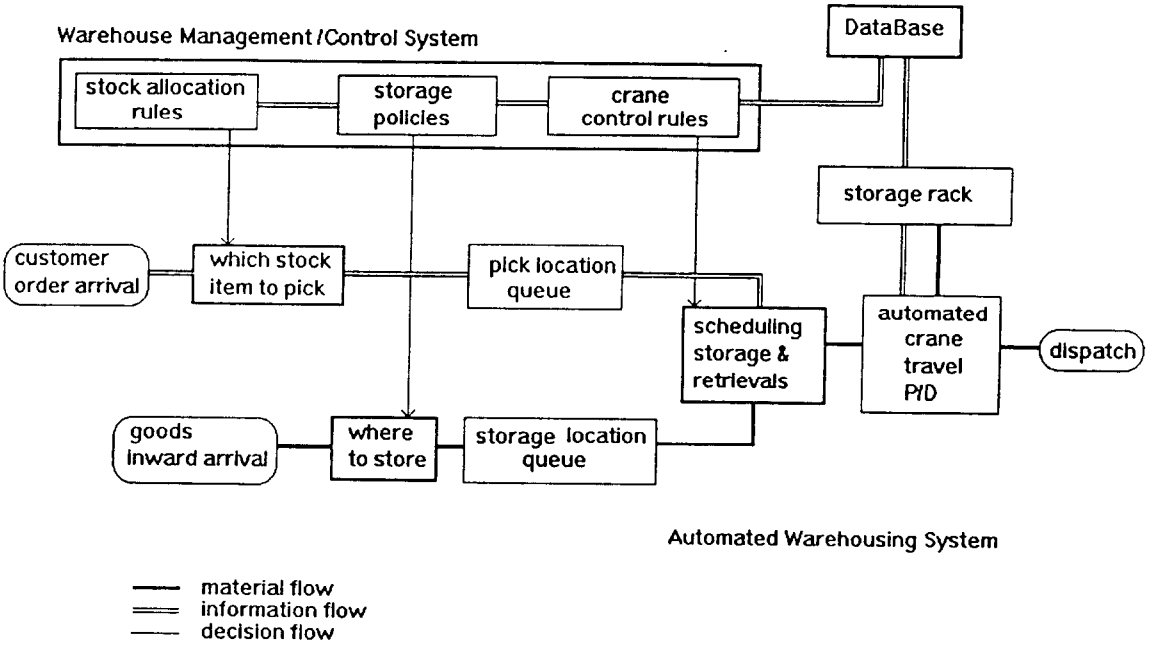

Fig 1. Modelling Framework in Total Systems Approach

The modelling framework was translated into a discrete event simulation model, AutoSim (Automated Warehouse Simulator), with which all experiments for this study were conducted. AutoSim has been developed on Visual Interactive Simulation Approach using C programming language. According to this approach, the model displays storage rack layouts with open and pick locations of different zones and animates the stacker-crane routes. It also supports both menu-driven user interrupts for validation runs and an experimental module for batch runs. Appropriate visual animation assists in gaining additional insights to explore the cause of the interactions. This facilitates interpreting the statistical results.

Like other models in the literature on which policies are based, AutoSim experiment does not necessarily represent any specific real-life system. Although it includes a number of assumptions that may not represent some special systems, the results of this study are applicable to most of the generic systems. The assumptions taken are as follows. Each pallet contains only one line of product. Retrieval requests are always for the entire contents of a pallet. All storage locations and pallet loads have identical sizes so that any pallet load may be stored in any storage location. An automated stacker crane serving racks on both sides of an aisle is considered. (As N-aisle configuration can be normally regarded as N independent single-aisle system, the results are directly applicable to the general multi-aisle systems, provided each aisle is served by one crane.) The stacker-crane travels simultaneously in both vertical and horizontal directions which is referred to as Tchebychev Norm. Acceleration and deceleration are neglected and PD time is taken as deterministic. Arriving pallets must be stored according to their order to the input station; however, retrievals need not be processed FCFS. Infinite storage and retrieval lists feed the system enforcing complete dual cycling to the cranes. Most of these modelling assumptions were similar to those taken in literature to facilitate comparisons. [1][3][4][9][17]

Regarding configuration of the system for experimentation, two different configurations with same total bay locations (1,260bays x 2racks) are considered. Based on specifications obtained from 6 stacker-crane suppliers, the horizontal and vertical speeds are taken as 150 m/min and 30 m/min respectively with 10 seconds for a PD cycle. The dimensions of each storage bay is taken as 1.33 metre in length and 1.33 metre in height. Though there could be various combinations of speed ratios and rack dimensions, Bozer and White [3] had formalized a dimensionless factor "b" ($0 \leq b \leq 1$), "the shape factor" as to normalize both speed and shape combinations. According to this approach, the two configurations taken in the experiment represent shape factors at two levels, one at the ideal case of "square-in-time" situation ($b = 1$) and the other at ($b = 0.64$).

All operational data regarding storage and retrievals were generated by random sampling from the mathematical model of Pareto Distribution (turnover distribution) by Bender [2]. Compared to usual exponential approximation which was reported to be often too steep near zero for most practical cases, Bender's model seems more appropriate for applications.

PERFORMANCE CRITERIA

In total approach, taking total cost of the system as unique performance criterion

would be most appealing. However, it was impossible to take total cost in monetary terms as the unique criterion for two reasons. Firstly, it is difficult to formulate a generalized cost function. Should total cost have been taken as the criterion, the findings would be relevant to systems that have a similar cost structure. Secondly, depending on the nature of the business, different companies have typically quite different goals. For some it is to cut cost, whereas others are more concerned with service aspects to customers and the delivery of orders in time.

To address both aspects of cost and service in the most generalized approach, throughput of the system is considered as the key performance criterion. In automated warehousing context, throughput can be defined as the total number of storage and retrieval operations the system can perform in unit time interval. Thus, throughput efficiency is fundamentally an attempt to measure the productivity of time. Improving throughput will reduce both capital and operating costs.

Other common time related performance measures in dynamic environment are time in the system of retrieval orders and the queue lengths. However, in previous studies, it was reported that storage and retrieval queue behaviours of automated warehousing systems in dynamic nature are very similar to that for simple queuing systems; that is, it is very sensitive to the utilization or traffic intensity level of the system, particularly as these levels approach one. Server's utilization or traffic intensity is the ratio of the mean service time to the mean interarrival time.[15][4] It appears that throughput and queue characteristics are obviously not contradicting criteria in automated warehousing systems, but optimizing service time will reduce traffic intensity which will significantly reduce queue lengths and waiting times.

Apart from time-based criteria, there are other measurements of productivity of physical assets through machine utilization. However, taking throughput efficiency as the key performance criteria has been emphasised recently due to the growing emphasis on so called time-based competition across supply chains in the new manufacturing era. [14] This trend of time-based competition is more obvious in a logistic environment. Compressing total cycle time across the supply-chain is vital for a competitive edge. In the light of the above, throughput has been taken as the key performance criterion for the experiment.

POLICIES TESTED

Interleaving Heuristics

Sequencing storage and retrieval requests in dual command mode for unit load systems is a difficult problem. Even with only one open location the problem is equivalent to the well known travelling salesman problem - a difficult problem. Further, it is no easier to solve with multiple open locations. [9]

Closest Open Location/ First Come First Served (COL/FCFS) A common practice, is that both storage and retrievals are processed in first-come-first-served (FCFS) manner, and that storage goes to the closest open location (COL).

Storage arrivals are normally processed in first-come-first-served policy since most automated warehouses are fed by another handling system. However, retrievals requests are no more than commands in the warehouse control system - down loaded from the order processing system periodically. It is possible to rearrange these into a favourable sequence for the crane travel.

Nearest-Neighbour Heuristics takes the nearest pair of storage and retrieval locations. Retrieval queue list consists of pick locations assigned by stock allocation module. The queue list is separated into blocks and processed in batches. Whenever a dual cycle tour has to be formed, the system checks both the first block of retrieval queue and the available open locations in the database. The nearest pair of an open location and retrieval point is selected for the tour.

Shortest-Leg Heuristics In a dual cycle, the crane always travels in the following sequence - (PD-S-R-PD), where PD is the pick-up and delivery station, S and R are the storage and retrieval bays. Shortest-Leg selects a pair of storage and retrieval locations that gives the shortest tour segment of (PD-S-R). This algorithm searches S that could be visited on the way to R with least additional travelling. As stacker-cranes travel in Tchebychev-Norm, S locations that could be visited on the way to R do not necessarily fall on the straight line, instead, all locations within an area referred to as the "free-insertion parallelogram" could be visited on the way without increasing travel time.

Both heuristics were primarily addressed by Han et al. [9] in randomized layout. To extend these heuristics to other storage policies, the algorithms were modified. Instead of searching all open locations for put-away, only those locations of the same zone to the incoming stock are searched for the storage. However, a storage and a

retrieval from different zones are allowed to interleave in a tour.

Fig (2) illustrates tour formed by Nearest-Neighbour and Shortest-Leg heuristics for the same block of storage and retrievals. For convenience, all points in the figure are connected by straight lines representing the tour routes. These straight lines do not necessarily correspond to the exact movement followed by stacker-crane simultaneous vertical and horizontal movement.

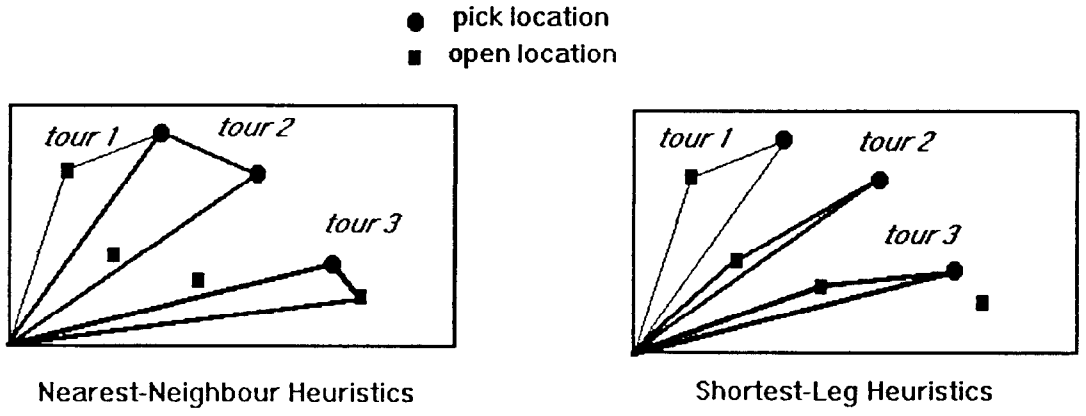

Fig (2) Tours Formed by using Interleaving Rules

Storage Layout Policies

Storage policies are sets of rules which decide where an incoming item has to be put-away.

Randomized Storage Policy with COL In pure randomized policy, an incoming item can be stored in any open location as no specific rule or zoning is imposed. The policy that has been tested is Closest Open Location (COL), the arriving stock is stored in available open location closest to the PD station. This widely applied policy is a variant of the naive randomized policy.

Square-L Shape Zone In this class-based policy, rack and pallets are partitioned into classes based on one-way travel times and turnover rates. Pallets are then assigned to their zones with respective class of turnover. High turnover rate zones are assigned closer to the input output station. Within any given zone stock items are assigned to locations randomly. Should zoning be done according to this rule, zone shapes often resulted in combination of a "Square-in-time" and "L-shape" zones. [10]

Hinterland Zone Tzan [17] proposed a new zoning policy based on the probability of a slot becoming a free-insertion point for man-aboard multiple command order picking systems. As an extension, the policy is further experimented for the dual command unit load systems. According to this class-based method, slot locations are ranked according to the free insertion index instead of one way travel time from PD station as in the Square-L Zone.

$$F_i = \sum_{j=1}^{m} \alpha_{ij} - 1$$

$$\alpha_{ij} = 1 \quad \text{if } T(0,i) + T(i,j) = T(0,j)$$
$$= 0 \quad \text{otherwise}$$

where

F_i = free insertion Index of slot i
m = number of slots in the rack
$T(0,i)$ = one-way travel time of slot i
$T(0,j)$ = one-way travel time of slot j
$T(i,j)$ = least time required to travel from slot i to slot j

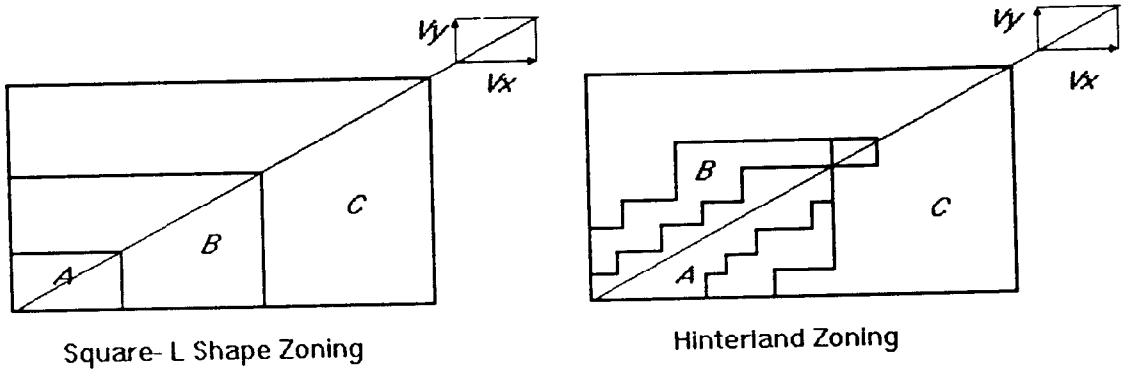

Fig (3) Zones Formed by Using Storage Policies

Stock Allocation Policies

Assigning an appropriate stock item to a customer is done according to rules based on operational requirements.

First-in-first-out (FIFO) In FIFO policy, the system searches the oldest stock item to allocate to a customer order for good stock rotation. This was often assumed implicitly in the literature.

FIFO-Band Policy It was observed that in practice, date codes are assigned to stock items and there are more than one stock item with the oldest date code. Moreover, it may not be necessary to select the oldest date code in most cases, instead all stock items within a band of date codes may be acceptable for most of the cases. Thus, additional decision is involved as to decide "the best stock" from the band. The best stock could be defined based on operational criteria of interest. In this experiment, the nearest stock item to the PD station is selected as the best stock. Intuitively, by imposing favourable crane-travel schedules even in the early stage of stock allocation, throughput could be improved while imposing rules on good stock rotation. This proposed method reflects total systems approach.

EXPERIMENTAL DESIGN

A four-factor, full factorial is used to assess the efficacy of the interleaving heuristics [three levels], storage layout policies [three levels], and stock allocation rules [two levels]. These policy combinations were further crossed completely with two different problem sets [two levels of design shapes]. Sixteen independent simulation runs are carried out for each of the 36 (3x3x2x2) treatment combinations to collect throughput performances, thus resulting in 576 independent runs. Stock items are randomly filled in initialization of the experiment so that all product lines are evenly spread across the pick face to avoid initial bias. The same starting conditions with respect to warehouse physical and operational parameters are maintained.

AutoSim simulation experiment has been subjected to usual tests for steady state performance. A series of preliminary simulation runs with different random streams were carried out to determine when approximate steady-state was achieved. Average throughput were observed to be in approximate steady-state by 259,200 simulation time units, 72 hours. Thus, at 72th hour, all statistical arrays in AutoSim were cleared and steady-state data were collected from 72th hour to 168th hour. Average throughput of each run of length 345,600 simulation time units or 96 hours, was taken

as one independent observation for further statistical analysis. This run length approximately equals 10,000 storage and retrieval operations.

Precisely, four underlying research questions are of interest in the experiment:

> Do the three basic decisions composite throughput ?
> And is there an interaction between these three ?
> Do different storage policies give different throughput performance ?
> Similarly, do interleaving heuristics differ from each other ?

Firstly, ANOVA was performed on the throughput to identify the significance of the main effects and interactions among the three decision aspects. Secondly, Duncan Multiple Range procedure set for 95 percent confidence was used to identify which interleaving heuristics significantly differs from others on the same storage policies and allocation rules. A similar procedure was used to compare storage policies on the same allocation and interleaving rules. Both of these statistical tests are based on two assumptions, normality and homogeneity of variance from independent sample. Among these the assumption of independence is generally critical [15]. Simulation outputs from a single run are often auto-correlated. Thus, instead of analysing on hourly throughput rates from a single run, the cumulative throughput of each independent run was taken as one independent observed data. All statistical tests are carried out on SPSS/Windows software.

ANALYSIS OF RESULTS

Fig (4) is a normal probability plot of observed throughput performance, where each observed value is paired with its expected value from the normal distribution - the straight line. (The expected value from the normal distribution is based on the number of cases in the sample and ranked order of the case in the sample) The points were observed to be clustered around the straight line. This provides a visual basis for checking normality. K-S Lilliefors Test was also carried out and found that the hypothesis of normality could not be rejected. The Lilliefors test, based on a modification of the Komogorov-Smirnov test was used because means and variances were estimated from the data as they are not known. No statistical test was carried out to check homogeneity of variance since the sample size of all groups are equal in the experiment. The ANOVA test was not particularly sensitive to violations of homogeneity of variance under such conditions. [15]

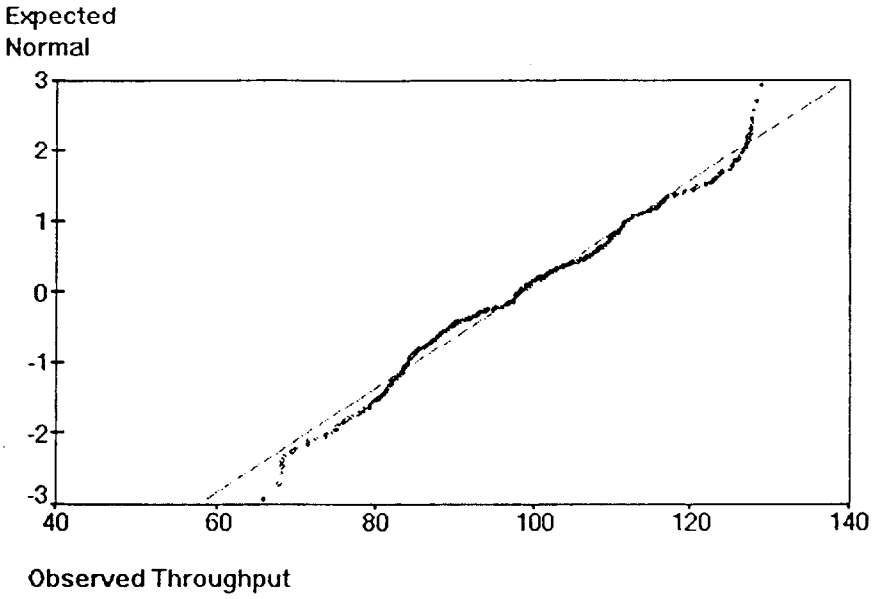

Fig (4) Normal Probability Plot of Observed Throughput

The effect of a factor is defined to be the change in response produced by a change in the level of the factor. This is frequently called the main effect. If there is a difference in response between the levels of one factor to another, it indicates that there is interaction between factors. The effects are best unscrambled via the Analysis of Variance (ANOVA) procedure where the variance is expressed in terms of sum of squared deviations from the means. The total sum of squared deviation is separated into independent components, each of which represents one of the main effects or one of the interaction effects. Table (1) is the statistical tests results on the significance of the sum of squares which represent the main effects and interactions.

Table (1) ANOVA Results on Throughput

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	95744.926	6	15957.488	3307.976	.000
STORAGE	2499.206	2	1249.603	259.042	.000
SCHEDULE	41303.800	2	20651.900	4281.125	.000
ALLOCATE	46201.711	1	46201.711	9577.583	.000
DESIGN	5740.209	1	5740.209	1189.941	.000
2-Way Interactions	8572.619	13	659.432	136.700	.000
STORAGE - SCHEDULE	805.419	4	201.355	41.741	.000
STORAGE - ALLOCATE	7249.129	2	3624.565	751.370	.000
STORAGE - DESIGN	454.927	2	227.463	47.153	.000
SCHEDULE - ALLOCATE	20.397	2	10.199	2.114	.122
SCHEDULE - DESIGN	22.333	2	11.166	2.315	.100
ALLOCATE - DESIGN	20.415	1	20.415	4.232	.040
3-Way Interactions	730.153	12	60.846	12.613	.000
STORAGE - SCHEDULE - ALLOCATE	82.344	4	20.586	4.267	.002
STORAGE - SCHEDULE - DESIGN	57.987	4	14.497	3.005	.018
STORAGE - ALLOCATE - DESIGN	552.136	2	276.068	57.229	.000
SCHEDULE - ALLOCATE - DESIGN	37.686	2	18.843	3.906	.021
4-Way Interactions	20.479	4	5.120	1.061	.375
STORAGE - SCHEDULE - ALLOCATE - DESIGN	20.479	4	5.120	1.061	.375

At overall significance of 99 percent (ie. $\alpha = .01$), the results support the notion that all experimental factors affect the throughput performance. Also, results indicated that most of the cross-effects at two-way interactions are significant except those of schedule-allocation and schedule-design. Regarding three-way interactions, both interactions of design-storage-schedule and design-schedule-allocation were not significant. The critical finding of this test was the significance of the three-way interactions of the three basic decisions: the storage policy, the crane scheduling heuristics and the stock allocation rules. Though three decision aspects are

interrelated, the four-way interactions of these decision rules to the design factor or the problem sets is insignificant.

Several explanations given in the introduction are consistent with the result of this study. The ANOVA results validate the logical link between series of decision making in warehouse operations. The lack of interactions regarding scheduling heuristics need to be emphasized as well. The quality of scheduling heuristics is observed to be robust to the shape of the warehouse as well as to the stock allocation rules. However, storage policies are highly interrelated with other decision aspects.

Intuitively, for the same number of storage bay locations and speed combinations, the "square-in-time" rack provides higher throughput. However, it is not always possible to design the ideal square-in-time rack due to economic considerations and site constraints. This is well explained in optimal design models, considering the trade-off between the throughput and the cost of the system in search of the minimum cost design [1][11][12]. Thus, changing operating policies seems a reasonable option to upgrade throughput performnce of a system.

When interactions are significant in factorial experiments, comparison between means of a factor may be obscured by the interactions. One approach to this situation is to fix other factors at a specific level and apply pair-wise comparison test procedures to test the means of a factor at that level. Performing t-test on all pairs of means seems a possible approach; however, it has considerable distortion in the "type I error" especially when there are many possible pairs [15]. Thus, Duncan Multiple Range Test Procedure which took the same assumptions as in ANOVA is taken for the study.

Table (2) Comparison of Interleaving Heuristics

DUNCAN MULTIPLE RANGE TEST — SIGNIFICANT LEVEL AT 0.05

DESIGN (Shape Factor)	ALLOCATE	STORAGE	INTERLEAVING Heuristics Performance Ranking (paired heuristics are not significantly different)		
B = 0.64	FIFO	RANDOMIZED	71.5881	FCFS/COL	
			78.3356	S-Leg	
			91.0788	N-Neighbour	
		SQUARE-L	83.3350	FCFS/COL	⌐
			83.6094	S-Leg	⌐
			101.8687	N-Neighbour	
		HINTERLAND	83.2319	FCFS/COL	⌐
			84.1669	S-Leg	⌐
			101.5975	N-Neighbour	
	FIFO-BAND	RANDOMIZED	97.6031	FCFS/COL	
			107.6006	S-Leg	
			121.7812	N-Neighbour	
		SQUARE-L	92.5544	FCFS/COL	⌐
			93.0481	S-Leg	⌐
			111.1444	N-Neighbour	
		HINTERLAND	97.9438	FCFS/COL	⌐
			99.0519	S-Leg	⌐
			115.9050	N-Neighbour	
B = 1.0	FIFO	RANDOMIZED	79.9031	FCFS/COL	
			84.3769	S-Leg	
			99.4894	N-Neighbour	
		SQUARE-L	87.6406	FCFS/COL	⌐
			88.1513	S-Leg	⌐
			106.200	N-Neighbour	
		HINTERLAND	88.4806	FCFS/COL	
			84.6000	S-Leg	
			108.4044	N-Neighbour	
	FIFO-BAND	RANDOMIZED	104.1588	FCFS/COL	
			110.2281	S-Leg	
			124.1119	N-Neighbour	
		SQUARE-L	97.1531	FCFS/COL	⌐
			97.7606	S-Leg	⌐
			115.6538	N-Neighbour	
		HINTERLAND	109.9875	FCFS/COL	
			111.1606	S-Leg	
			126.6800	N-Neighbour	

Table (3) Storage Policy Comparison

DUNCAN MULTIPLE RANGE TEST — SIGNIFICANT LEVEL AT 0.05

DESIGN (Shape Factor)	ALLOCATE	SCHEDULE	STORAGE POLICIES Performance Ranking (paired policies are not significantly different)	
B = 0.64	FIFO	FCFS/COL	71.5881	RANDOMIZED
			83.2319	HINTERLAND
			83.3350	SQUARE-L
		N-NEIGHBOUR	91.0788	RANDOMIZED
			101.5975	HINTERLAND
			101.8687	SQUARE-L
		S-LEG	78.3356	RANDOMIZED
			83.6094	SQUARE-L
			84.1669	HINTERLAND
	FIFO-BAND	FCFS/COL	92.5544	SQUARE-L
			97.6031	RANDOMIZED
			97.9438	HINTERLAND
		N-NEIGHBOUR	111.144	SQUARE-L
			115.9050	HINTERLAND
			121.7812	RANDOMIZED
		S-LEG	93.0481	SQUARE-L
			99.0519	HINTERLAND
			107.6006	RANDOMIZED
B = 1.0	FIFO	FCFS/COL	79.9031	RANDOMIZED
			87.6406	SQUARE-L
			88.4806	HINTERLAND
		N-NEIGHBOUR	99.4894	RANDOMIZED
			106.200	SQUARE-L
			108.4044	HINTERLAND
		S-LEG	84.3769	RANDOMIZED
			88.1513	SQUARE-L
			89.6000	HINTERLAND
	FIFO-BAND	FCFS/COL	97.1531	SQUARE-L
			104.1588	RANDOMIZED
			109.9875	HINTERLAND
		N-Neighbour	115.6538	SQUARE-L
			124.1119	RANDOMIZED
			126.6800	HINTERLAND
		SQUARE-L	97.7606	SQUARE-L
			110.2281	RANDOMIZED
			111.1106	HINTERLAND

Regarding interleaving rules, the paired comparison gives a consistent ranking in the following order - Nearest-Neighbour, Shortest-Leg and FCFS/COL. Though FCFS/COL was the most common policy in the real-world, the performance was disappointing in all situations. In some cases, Shortest-Leg was observed to have no significant difference from the FCFS/COL policy. The reason seems to be the distribution of open locations similar to those of COL policy. At the steady-state, open locations are available only at the far end of the rack. This reason, observed from visual animation of the model, validates previous research findings [9].

The relative comparisons of storage policies for FIFO stock allocation are consistent with most of the past research. This implies that the best is the Square-L shape zoning and the worst is the randomized. However, it is most counter intuitive that when stock allocation rules are extended to introduce FIFO-Band Policy, the relative performance of storage policies are significantly altered. These findings from Duncan's test is consistent with the above mentioned ANOVA results which indicated that storage policies are interrelated with other decision aspects.

Surprisingly, in FIFO-Band, randomized policy could perform nearly as well as most of the zoning policies in some cases. This could not be better explained than by visual animation of the model which animates the distribution of pick and open locations and the tours formed during the simulation run. In FIFO-Band policy, stock items of the same date code nearer to the PD station are first allocated. In the long run, more open locations are generated closer to the PD station. Consequently, storage and retrievals are often carried out nearer to the PD station. FIFO-Band indirectly facilitates similar benefits of turn-over based zoning.

To ensure the validity of this unique finding regarding FIFO-Band, it is necessary to check that at the steady-state condition taken, all stock items are completely in rotation. In the experiment, the FIFO-Band width was taken as two days while data are collected at the 7th day, after more than 17,500 storage and retrieval operations. To check the steady-state, the model is further executed under FIFO-Band for one additional month of simulation run. No serious change in performance was observed indicating the validity of the steady-state condition.

The performance of Square-L zoning in FIFO-Band policy was both surprising and discouraging. From visual animation of the model, it was observed that "blocking" of the retrieval list hinders the performance, especially when the list becomes nearly exhausted. In such cases, distant pairs from the fast and the slow zones may have to interleave under Square-L zoning policy. This is less affected in the Hinterland storage as all zones are available in the region near the PD station where most of the

operations took place. Randomized zoning does not impose such a constraint at all since stock items could be stored in any open location and as a result most of the operations could be done near the PD station. This seems to be one of the underlying reasons for the unexpected performance of the randomized policy in the FIFO-Band.

Combination of the Nearest-Neighbour heuristics, Hinterland storage and FIFO-Band allocation out-performs others. The most common combination of Randomized zoning with FCFS/COL interleaving and strict FIFO allocation is the poorest performer. The throughput difference between these two combinations is as large as 76.95% under the experimental conditions.

DISCUSSIONS

To provide a meaningful comparison, systems of equal work load should be compared in the experiment. The work load in a dynamic environment could be expressed as the utilization of the server, the stacker-crane. Utilization is the ratio of mean service time to inter-arrival time. Although arrival rates could be controlled, service time happens to be the response variable and it is difficult to maintain constant utilization over all runs. In the experiment, complete dual cycling is assumed imposing 100% utilization across the runs.

It was also recognized that automated warehousing systems could hardly operate in complete dual cycles in the real-world operation as single cycles have to be carried out whenever either storage or retrieval queues are empty. This is referred to as mixed mode operation. The expected cycle time of the mixed mode operation is the weighted sum of the dual and the single command cycle times, where the weight factors are the probabilities of respective single and dual command modes. [3] As the expected single command cycle time is independent of dual command interleaving rules, the average single command cycle time will remain the same over all policy combinations. Therefore, the results of this experiment on relative comparison and interactions of policies are generally applicable to the mixed mode operation as well.

"Blocking" or batching of retrieval requests causes unfavourable side effects. Based on the queuing theory, it was reported that blocking may not be necessary in Nearest-Neighbour heuristics as the queue will be exhausted from time to time with crane utilization factor less than one. None of the retrieval requests will have infinite waiting time and further throughput improvement is also possible. [4] However, most of the systems developers and operations managers pointed out in our initial interviews that should retrieval re-sequencing be applied, blocking is necessary due to operational

constraints, particularly in a logistic environment. In most of the distribution centres, retrievals have to be scheduled according to "van runs" (departure time of the trailers). Similar conditions apply to some cases where the unit load warehouse serves as the reserve storage feeding the pick line. These may imply that the maximum time in the system of a retrieval request needs to be "deterministic" within the specified time limit. It is most unlikely that this could be achieved without blocking the retrieval request queue.

From empirical findings, it seems doubtful to assume storage and retrieval locations are always randomly located within a zone. The distribution of both open and pick locations depends a great deal on the stock allocation and the put-away rules which are found to be highly interrelated. Also, this non-random distribution of locations was observed to be consistent with actual location maps produced by the warehouse management systems being studied in the real-world applications.

This paper addresses FIFO-Band stock allocation rules which facilitate not only good stock rotation but also travel time savings for throughput improvement. In this paper, "the best stock" is selected as the stock item with the same date code within the band and closest to the PD station. Should other operational requirements be necessary, the definition of the best stock may be extended. This may involve adding additional rules. For instance, if the system has to handle part-pallets as well as whole-pallets, additional rules could be imposed to search the same stock within the date codes, nearest to PD and part-pallets to part-orders, full-pallets to full-orders. FIFO-Band could be most flexible for various warehousing applications.

Regarding operational data, 20/60 turn over distribution was taken in the experiment, that is 20% of stock items constitute 60% of turnover. Rack utilization was taken as 80%. Actual percentage savings of policies depend on such warehouse parameters. The research does not focus on numerical saving percentages; instead a generalized conclusion is drawn to emphasise the need of total systems approach to warehousing.

This research does not compare computational efficiency of heuristics as most of them are known to be "polynomial-bound" - efficient algorithms requiring negligible computational time. AutoSim experiment was designed as a "fixed effect model", in which a finite set of policies was considered. Naturally, the findings could not be extended for policies not addressed in the experiment and may not necessarily be true should new policies be introduced. The performance measures were analyzed under the steady-state conditions for the long-term performance evaluation. The results do not apply if operational characteristics are permanently under change. Also, the results are relevant only if the system is throughput-bound.

CONCLUSION

The research addressed the interactions and relative performance of operating policies for unit load automated warehousing systems. Though total systems approach has been widely applied in strategic decision making, application of such an approach analytically at the operational level, particularly in warehousing, still seems a formidable task. An empirical approach has been taken in this research. The important results presented are:

Three scopes of operating policies affected throughput performance and have cross-effects as well. Interleaving rules are observed to be robust to the shape factor and stock allocation rules. Nearest-Neighbour performs best in all situations. There seems to be no unique storage policy that performs best in all situations due to its interactions.

The results of interleaving and storage policies for Strict-FIFO are consistent with earlier research findings. However, it is possible to further improve throughput by extending stock allocation rules in total approach. With this approach in FIFO-Band, the performance of storage policies become different and randomized policy performs much better than in Strict-FIFO.

Combination of the Nearest-Neighbour heuristics, Hinterland storage and FIFO-Band allocation out-performs others. The most common combination of Randomized zoning, FCFS/COL interleaving and strict FIFO allocation is the poorest performer. The throughput difference between these two combinations could be as large as 76.95% within the experimental conditions.

In conclusion, stock allocation, crane interleaving and storage policies could not be addressed in isolation in any warehouse configuration. The most favourable solutions are combinations of these rules which facilitate each other towards the "goal" - throughput efficiency.

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