AN ABSTRACT OF THE THESIS OF

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Automated storage and Retrieval (AS/R) systems have had a significant impact on storage and retrieval of finished goods, work-in-process, and raw materials and supplies. A microcomputer-based simulation model was developed to evaluate different unit load AS/R systems serving multiple input sources and output destinations. The simulation results were statistically analyzed on different performance measures including throughput, mean waiting times maximum waiting times and rejects.

The results showed that for single-dock, square-in-time layouts, the class based arrangement produced significantly higher throughput for all scheduling policies. Among the scheduling policies, the relief nearest neighbor produced consistently higher throughput. Comparing square-in-time versus non-square-in-time layouts, the square-in-time layout performance was better; the performance deteriorated as deviations from square-in-time increased. For the two dual-dock layouts, at lower arrival rates the dedicated layout produced higher throughput; there was no significant difference between the two layouts at higher arrival rates.

Simulation-Based Design Evaluation of Automated Storage/Retrieval Systems

by

Raj N. Shroff

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DEDICATION

This thesis is dedicated to

my grandfather

Late Mr. Govind L. Shroff

my parents

Dr. Nalin M. Shroff
and
Mrs. Saroj N. Shroff

and

my aunt

Mrs. Saroj J. Shah

for their perpetual support,
motivation and care during
my graduate studies here at
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Simulation-Based Design Evaluation of Automated Storage/Retrieval Systems

CHAPTER 1

INTRODUCTION

1.1 Importance of Automated Storage and Retrieval Systems

In the 1950s the rapidly expanding use of the forklift truck changed handling procedures and introduced a new technique for handling unit loads. It replaced the hand bar and largely eliminated manual loading/unloading of vehicles.

We are now experiencing another exciting advance in material handling, that of the automatic warehouse. In itself it is important as a labour saving device with a high return on investment for the right application, but more importantly it is a key factor in the success of computerized inventory control system.

Warehousing can be defined as the activity concerned with the orderly storage and release of goods or products, either within a plant or to external locations. Material handling activities that parallel the physical flow of materials include (1) receiving goods at the dock ,(2) identification and sorting ,(3) inspection (4) storage, and (5) order picking or retrieval. The ultimate objective of Automated Storage and Retrieval (AS/R) Systems in a warehouse is the efficient distribution and storage of goods and products through optimum space utilization and increased throughput rate at reduced cost.

Investment in an automated system is a decision that balances the return on investment against the risks involved. The savings from an automated warehouse system will frequently not arise from materials handling operations within the warehouse, but rather from improved control over storage and retrieval operations. This results in better ability of the system to react to increased service levels and sales. Due to significant increase in the cost of storage space and AS/RS equipment, it is important that scarce resources be optimally utilized. Proper scheduling and control of AS/R systems play an important part in achieving optimal storage space utilization and increasing demand satisfaction.

An AS/RS system is primarily a combination of equipment and controls for handling, storing and retrieving materials with precision, accuracy and speed under a defined degree of automation. Systems vary from relatively simple manually controlled order picking machines operating in small storage structures to giant, computer controlled storage and retrieval systems totally integrated into the storage and distribution process.

The configuration of AS/R systems vary considerably depending upon the particular application. A typical AS/R system consists of storage racks, automatic stacker cranes, link conveyors and input/output stations. The pallet rack is the most familier type of storage rack. It is a frame structure designed to allow individual pallet loads to be stored and retrieved. In its simplest form, a stacker crane is a device with a rigid upright mast or support suspended from a carriage, mounted on an overhead traveling crane (or equivalent) and fitted with forks or a platform to permit it to place in or retrieve items from racks on either side of the aisle. Link conveyors are fixed path handling systems that carry loads. Input/ Output (I/O) points or docks are the locations where the transfer of pallets takes place between the conveyor and AS/RS machine.

1.2 Background

Scheduling of AS/R system plays a prominant role in improving system efficiency and performance. The use of computers in scheduling have helped industries attain higher throughput and increased efficiency. These savings result from reduction in crane travel time, higher floor space utilization and improved material flow and inventory control. The published research in this area has focused on the use of mathematical techniques or computer simulation for solving specific problems related to scheduling rules and policies for automated storage and retrieval system. Some of the published papers in this area deal with the general scheduling problems relevant to the automated storage systems used in warehouseing. Others focus on optimization of system throughput by minimizing crane travel time. The research, however, initiated with a single dock system, which was later extended to a dual dock system. A brief review of the major achievements in this area follows.

Major research in the area of AS/R systems began with Hausman, Schwarz and Graves (1976) who studied computer-directed warehousing systems using stacker cranes and palletized loads for storage and retrieval. A system consisting of a single crane (single dock), serving a single two-sided aisle with single command cycle and a predetermined number of racks was analyzed. The system was referred to as "Single Address System" since the crane is capable of visiting a single rack location between successive returns to the I/O point. In this system, the item is conveyed to the I/O point with the help of a conveyor and the system is bounded at the point where the crane and I/O conveyor transfer pallets. The I/O point is located at one corner of the rack. It was assumed that the pallet holds only one part number or item type (unit load concept); all storage locations are of the same size and the crane, which is capable of moving horizontally and vertically simultaneously, takes the same time to reach the most distant row as it takes to reach the most distant column (referred to as "square in time" system). It was further assumed that the turnover frequency of each item was known and constant through time. Crane interleaving and actual time for crane to load/unload a pallet at the I/O point or at the storage location were ignored. The requests were served on a first-come-first-serve basis. Scheduling was broken down into three elements: the assignment of multiple items to the same pallet(pallet assignment), the assignment of pallet loads to storage locations (storage assignment), and rules for sequencing storage and retrieval requests (interleaving).

The paper primarily focused on storage assignment. Three storage assignment rules, random assignment, turnover-based assignment and class-based assignment, were formulated using mathematical techniques and the results were compared. In the random storage assignment rule the pallet is equally likely to be stored in any of the available locations; priority is given to the closest open location regardless of pallet turnover .This is an approximation to the "closest open location" rule often used in practice. The turnover-based assignment is applicable for assigning the highest turnover pallet randomly to the closest open location in order to minimize expected one way travel time. Using random storage assignment rule as a primary basis, an expression for the percentage reduction in expected one way travel time with turnover based assignment was developed. The distribution for pallet turnover was derived on the basis of "ABC" concept used in inventory modeling.

The class-based turnover assignment rule is slightly different from the other two rules in that the other rules assumed that the turnover of each pallet to be stored in the system was a predetermined constant, whereas the class based rule also incorporates partioning of the racks and the pallets in various classes. Pallets are assigned to a storage class according to their turnover, that is, the highest turnover class to the closest location, etc. However, assignment inside any class are made on the random basis. Systems with two class storage assignment and three class storage assignment were analyzed.

It was found that the class-based turnover assignment yielded the most desirable results. Nonetheless, by using turnover-based assignment rule a 26% to 71% reduction in crane travel time over random storage assignment could be conceived. It was revealed that over a wide range of inventory distributions, the two-class system yielded 70% improvement over the fully turnover based system, whereas the three-class system resulted in 85% potential improvement over fully turnover based rule and 44% over random storage assignment.

Graves, Hausman and Schwarz (1977) extended their work by using crane interleaving. In their previous work crane interleaving was not allowed. Therefore, the crane could handle only one activity at a time (i.e., either storage or retrieval). The crane would travel empty back to the I/O station after storage was completed ,and while performing retrieval request travel empty to the retrieval point. As a result, increased crane travel time is incurred that subsequently decreases throughput rate. With a view to eliminate this inefficiency in crane travel time and increase the throughput rate, a single dock system with interleaving was analyzed. In such a system (called the dual address system), the crane is capable of visiting up to two rack locations between successive return to I/O point by completing a given storage request snd moving directly to the rack location for the next retrieve without returning to I/O point. Under all the assumptions of their previous model several combinations of scheduling policies, including mandatory interleaving (MIL) and mandatory interleaving with a predefined retrieval queue size,K,(MIL/Q-K) were analyzed.

In the MIL system, it is assumed that the crane always interleaves. The continuos analytical model developed in 1976 was used as a basis for developing analytical expressions for the expected travel times of a crane system operating under various storage assignment/interleaving policies. Scheduling policies using random storage assignment, class-based storage assignment (two or three classes), and fully turnover based storage assignment were studied. Operating performance was measured in terms of: (1) expected one way travel time, (2) expected interleave time, and (3) expected round trip time. The results were presented in terms of the continuous model, and empirically by analyzing a discrete rack system using a computer program. For example, in a dual address system using random storage assignment, the expected round trip time with mandatory interleaving was equal to twice the expected one way interleave time. The expected interleave time was calculated as weighted sum of the crane travel times between all storage locations, weighted by the probability of corresponding interleave. A similar expression for round trip travel time was also developed for the other dual address systems. With reference to class based assignment, an analysis was carried out to determine the shape of the class boundaries. With no interleaving, class boundaries were assumed to be "SQUARE - L" shaped as it was found to be the best for the system. With interleaving, the best class boundry shape (in terms of expected round trip time) is probably not of SQUARE-L type because the travel also occurs between storage locations. As an alternative, an arrangement in which Class I based assignment was placed in the center with Class II and Class III on each of the sides was analyzed. It was found that the expected interleave time was fairly insensitive to boundary shape. Empirical results suggested that expected round trip time with "SQUARE-L" boundaries might be at the most 3% above optimal. The researchers were unable to find any configuration that could result in better performance over "L" shaped boundaries. Hence, the analysis was confined to "L" shaped boundaries only.

In class based MIL/Q-K system, after completing a store, the first K items in the retrieve queue are sequentially examined to retrieve an item of the same class. If one is found, it is retrieved; if not, then the first item in the retrieve queue is selected for retrieval. As a contrast to the previous study, this study found the fully turnover based assignment policy to be the best. The random assignment rule resulted in the worst performance. The expected round trip time in a system using MIL policy with random storage assignment could be reduced by 32%, irrespective of the turnover destribution. In addition to MIL, a class based storage assignment rule was implemented in which the average round trip time was reduced by 52.5% for Class II system and 58% for Class III system. However, class based assignment could represent only 87% to 94% of the total improvement observed through using turnover based assignment. The class based assignment system had some cost associated with it for not assigning the desired location to an item belonging to a particular class. Therefore, the number of racks for each of the class needed to be increased by 2% to 3% in order to satisfy all the storage requests. This could also reduce the throughput rate.

Schwarz, Graves and Hausman (1978) developed a simulation model to examine and extend the theoretical results developed previously. This model took into account the dynamic behavior of the system as crane and rack utilization are varied and provided more flexibility to interleaving rule. The scheduling policies were examined in a stochastic environment and the results were extended to conditions of imperfect information. The remaining assumptions of the earlier models were retained. An expression for pallet's length of stay (LOS) was derived. It was assumed that the crane would always interleave as long as both the store and retrieve queues are nonempty. Nonetheless, if one of the queues was empty, the crane would store/retrieve pallets using no interleaving (NIL) policy. The simulation results showed that the dynamic behavior of the system was very sensitive to the rack utilization (as indicated by storage/retrieve queue behavior). It was revealed that the turnover based assignment resulted in the highest increase in throughput rate and system utilization. Nevertheless, the actual improvements were slightly smaller than expected owing to the discreteness of the rack system and the inability of the system to interleave every time. The simulation results were similar to those obtained analytically.

In the studies summarized above, the AS/R system I/O point was assumed to be located at either the left or the right corner of the storage rack. Every trip started and ended at this I/O point. Bozer and White(1984) incorporated dual docks and relaxed some of the assumptions made in earlier studies. Various sizes of storage racks, I/O locations and dwell point (location of S/R machine when it becomes idle) strategies were examined for both the single and the dual address systems. Only random storage assignment rule was analyzed without imposing the requirement of racks being square in time. Three different alternative configurations for I/O locations were considered: (1) input and output points at opposite ends of the aisle (2) input and output points at different elevations but at the same end of the aisle, and (3) input and output points at the same elevations, but at the mid point in the aisle.

In the first configuration it was assumed that all the storage orders were initiated at the input station while all the retrieval orders were terminated at the output station (dual dock system). Two dwell point strategies were evaluated. In one of the dwell point strategies, the machine returned to the input station following a single command storage and remained at the output station after the completion of either a single command retrieval or a dual command cycle. The only difference in the second dwell point strategy was that the S/R machine remained at the storage location following the completion of the single command storage. On the basis of this comparison, it was found that the first strategy performed better with a 14% reduction in the expected travel time .

In the second configuration, the input station was located at the lower left hand corner of the rack while the output station was located at some predetermined time units above the input station. An expression for travel time was developed for a single command cycle by considering the rack to be two separate racks. The same dwell strategy as the previous configuration was applied for the dual command cycle. The results showed that the second configuration performed better than the first configuration due to savings in travel time in the vertical direction resulting from the elevation of the output station.

In the third configuration, the input station was assumed to be located at the center of the rack. Such a system can be conceived as the delivery and take-away conveyors running halfway into the aisle through a set of rack openings located at the midlevel on either side of the aisle. It was deduced that by implementing a system with this configuration, a 26.2% reduction in expected travel time per operation can be achieved.

Han, McGinnis, Sheih and White (1987) considered retrieval sequencing in conventional unit load automated storage and retrieval system when several requests are available and dual command cycles are performed. In the research work prior to this paper, it was assumed that storage/retrieval follows first-come-first-serve (FCFS) rule. For retrievals the FCFS seemed to be less restrictive, since retrieval requests are nothing more than computer initiated messages. Thus, the "nearest neighbour heuristic" was developed with a view to improve throughput performance resulting from the reduced amount of time spent in traveling between the storage and retrieval locations in a dual command cycle. By assuming a randomized storage policy, a block of retrievals is selected and the retrieval is sequenced in that block. When the block of retrievals has been completed, another block is selected. It was shown that the maximum throughput increase with such an arrangement is 22%. The analysis indicated that with a typical AS/RS configuration operating with 100% dual command, a 60% reduction in travel between times (time required by the AS/R machine to travel from storage location to the retrieval location) would yield a 12% increase in throughput with a block of 15 to 20 retrievals. This was applicable with one open location. As the nunmber of open locations increases , the throughput improvement increases for a dual address system. It was shown that for significant improvement in throughput (10% or more), the travel between must be reduced by over 50%, relative to FCFS retrievals. A lower bound on expected dual cycle time was determined to explore the extent of (theoretical) additional reduction in average cycle time based on different retrieval block sizes and number of open locations.

Randhawa, Wang and McDowell (1991) analyzed AS/R system with single and dual-docks. Two sources of storage pallets as well as of retrieval request were included. Three different layout configurations were analyzed. These were: one dock (layout1), two docks with "hybrid" arrangement (layout2) and two docks with "dedicated" arrangement (layout3). In the one dock system the pallets from the two storage sources and retrieval sources are assigned to the same dock placed at the left corner of storage rack. The crane operates in accordance with MIL rule as long as both the storage and retrieval requests are available. However, in case of non availability of the any of the requests, the crane works in conjuction with NIL rule.

In the dual dock system the docks are located at opposite corners of the rack and each is allowed to handle input and output transactions. In the "hybrid" arrangement, the storage pallets from any source can be retrieved by any destination, while in the "dedicated" arrangement each destination interacts with only one source. The point of origin or termination could be either the same dock or the opposite dock. Hence, the storage travel time is a function of the originating dock. Similarly the retrieval travel time is a function of the dock at which the retrieval travel is terminated.

The scheduling policies were a combination of storage and retrieval rules. For storage, FCFS rule was utilized between the external source and the docks. On arrival to the dock, the closest open location rule (COL) rule was found to be appropriate. For retrievals, the pallets are chosen randomly from the pallets currently stored in racks (i.e., each rack was assumed to have equal turnover frequency). The FCFS and Nearest Neighbour (NN) retrieval policies were used. A discrete event simulation model was developed to analyze the system. Operating performance was measured in terms of system throughput, mean waiting times, and maximum waiting times.

The results showed that with an initial rack utilization of 75%, for the scheduling policies FCFS/NN, the throughput for Layout 3 was 35% higher than the throughput for Layout 1 and 45% higher than that of Layout 2. Layout 1 yielded 7% higher throughput as compared to that of Layout 2. With a maximum retrieval waiting time of 30 minutes the NN rule did not show any significant improvement over FCFS due to the waiting time of retrieval requests being more than 30 minutes. It was found that throughput was inversely proportional to rack utilization due to increased amount of crane travel time. The mean waiting times with Layout 3 and FCFS/NN60 (maximum waiting time of 60 minutes) were also compared with the other two layouts. The former system resulted in less mean waiting time. For Layouts 1 and 2 FCFS was found to be the best policy for minimizing the mean waiting storage time and mean waiting retrieval times. When the maximum waiting time was analyzed, Layout 3 performed better because the storage rack was equally split between two docks consuming less travel time. The authors concluded that a potential improvement is possible through the involvement of two docks operating independently.

As mentioned earlier, some research work has also been carried out in the industrial sector focusing on the assembly lines using AS/RS. Chow (1986) analyzed AS/RS in the manufacturing assembly lines. An M/M/1 queuing model was used to study the system performance with first-come-first-serve dispatching rule under stochastic environment. The SR machine configurations were similar to the ones used in warehouses. In addition, the arm or the mast had a rotation capability to take care of the situation where the dispatching and receiving stations are located at different sides of the racks. The work stations were assumed to be adjacent to each other, either placed on one side of the carriage track or evenly distributed on both sides of track. Each work station had a pick and a delivery port (P/D port) serving the station as a local I/O port. In addition, there was a buffer space near the P/D port. Physically, this space can be a multilevel rack installed above or beside the P/D port. When the SR machine attempted to deliver an object and finds the port occupied, the object will be placed in buffer. With such a system, the SR machine utilization, average waiting time and average queue length were recorded. It was assumed that SR machine serves ten-12 feet wide work stations. each station was so busy that the P/D port is always occupied upon delivery (storage). Therefore, side buffers are used to send the materials first to the buffer and from there to P/D port (retrieval) in workstations. Four dispatching rules were evaluated : Nearest First (NRFS), Shortest Processing Time First (SPTF), and Maximal Number of Services (MXSV). With NRFS, the SR machine always serves the nearest work station where the service request has been generated immaterial of order of arrivals. Under SPTF, the machine serves the request that has the shortest service time. In the MXSV, the SR machine travels in a loop fashion and serves all those requests waiting to be performed in the same direction. Prime intent was to maximize the number of services in one trip. The machine, however, should be equipped with an on-board storage. On its return trip the SR machine moves objects in the the opposite direction. It was found that FCFS, NRFS and SPTF were better than MXSV and close to one another. While implementing MXSV, the queue length and waiting time were observed to be larger due to inclusion of on board storage and additional time consumed in arm rotation. As a result, the throughput declined.

1.3 Research Objective

As the previous section indicates, research in the area of AS/R systems has been limited. The objective of this research is to analyze the performance of different single-dock and dual-dock configurations under different scheduling policies. Single dock layouts analyzed in this research include: end-of-aisle dock; middle-of-aisle dock; square-in-time and non-square-in-time layouts; and class based arrangements. The dual-dock layouts considered here are the dedicated and the hybrid layouts.

The primary performance measures used to evaluate the layouts are throughput, mean storage and mean retrieval waiting times, maximum retrieval waiting times and number of storage and retrieval requests rejected (not satisfied).

System throughput is defined as the number of requests served by the AS/R machine for a certain time period under steady state conditions. Throughput is the primary performance measure. The job waiting time for the storage requests (pallets) is the amount of time a pallet spends in the conveyor queue before it is picked up by the AS/R machine for the storage. Similarly, the job waiting time for the retrieval request is defined as the amount of time it spends in the retrieval queue before it is served. The rejections occur if storage and retrieval queues have limited capacity.

Simulation modeling was used to analyze the layouts alternatives. Different simulation models are developed by interfacing SIMAN and FORTRAN. The results were analyzed graphically using STATGRAPHICS; additionally, multi factor analysis of variance technique was used to evaluate statistical significance of the results.

CHAPTER 2

PROBLEM DEFINITION

2.1. Test Hypothesis

A number of different layout alternatives are compared in this study. The independent variables are the layout configurations and scheduling policies. The dependent variables are system throughput, mean storage and retrieval waiting times, maximum retrieval waiting time and storage and retrieval rejects.

2.1.1 Single-Dock Layout Comparisons

1. End-of-Aisle versus Aisle-Mid-Point - This hypothesis tests two single dock layouts. In the end point dock layout, the dock is located at one end of the aisle. In the mid aisle dock layout, the dock is located at the middle of the aisle. Hence, the independent variables are the two single dock layouts and the scheduling policies.

2. Uniform versus Class-Based - This hypothesis evaluates the layouts with uniform and class based arrangements. In the uniform arrangement, the pallets can be stored in any location that is closest to the dock. In a class-based arrangement, the rack is divided into two classes and within each class, the pallets are stored on the basis of the closest open location rule. Hence, independent variables are the two rack arrangements and the scheduling policies.

3. Square-in-Time versus Non-square-in-time - Layouts having square-in-time dimensions and non-square-in-time dimensions are compared. In both cases the dock is located at the end of the aisle. The independent variables are rack dimensions and the schedling policies.

2.1.2 Dual Dock Layout Comparisons

1. Hybrid versus Dedicated - In a dual dock layout with the hybrid arrangement, a dual command cycle may consist of storage request from one department and the retrieval request from the same or from the other department, whereas in a dedicated arrangement the dual dock is dedicated to only one department. Therefore, the independent variables are the two dual dock arrangements and the scheduling policies.

2.2 Layout Configurations

The System primarily constitutes layouts with three distinct dock arrangements :

1. Single dock layout with the dock located at either end of the aisle, (end-of-aisle arrangement).
2. Single dock layout with the dock located at the middle of the aisle, (mid-aisle arrangement).
3. Dual dock layout with the dock located at both ends of the aisle.

Each of these layouts is briefly described below -

2.2.1. End-of-Aisle Layout

The end-of-aisle arrangement is shown in Figures 2.1 and 2.2. The location of the dock is shown at the left end of the aisle, but it may be located at the right end. The conveyor is located at the dock end. The pallets arrive to the system through this conveyor belt from two different departments S1 and S2. Similarly, there are two retrieval sources, R1 and R2. The elevation of the dock is equal to the lowest row of rack.

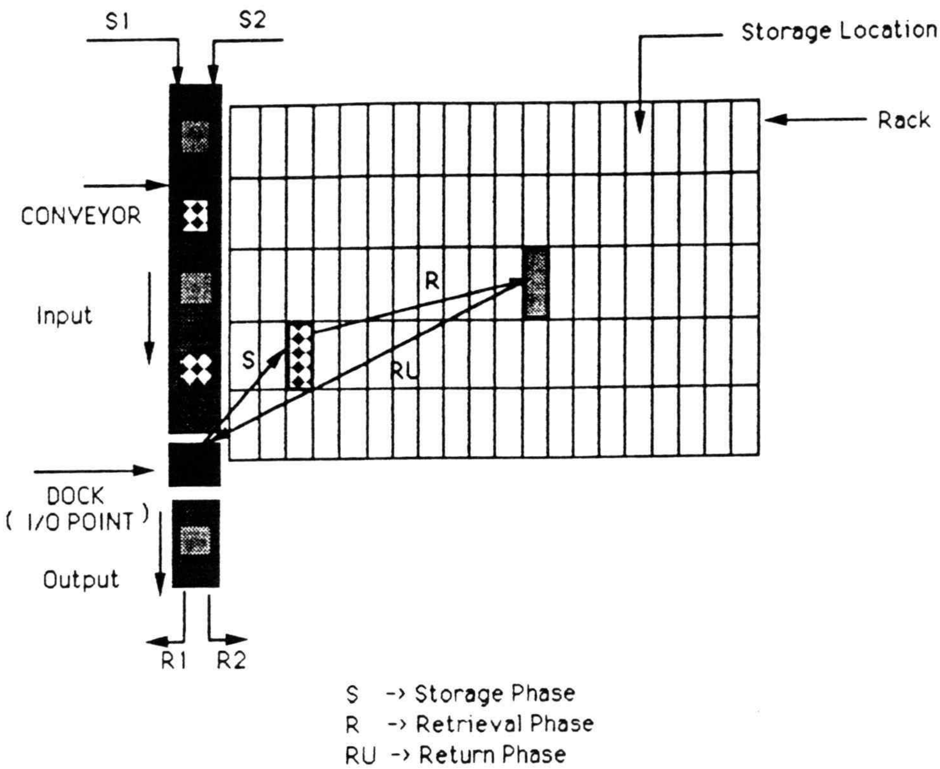


Figure 2.1. End-of-Aisle Single-Dock Layout: Closest Open Location Assignment with Uniform Turnover.

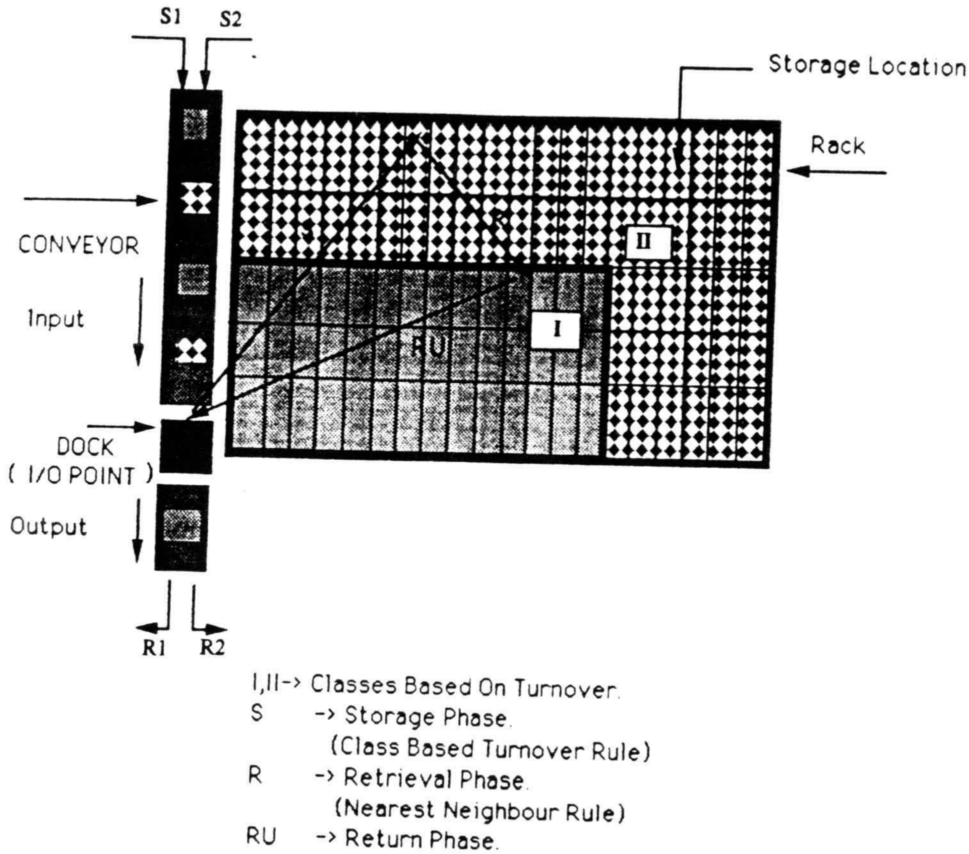


Figure 2.2. End-of-Aisle Single-Dock Layout: Class based Turnover Assignment.

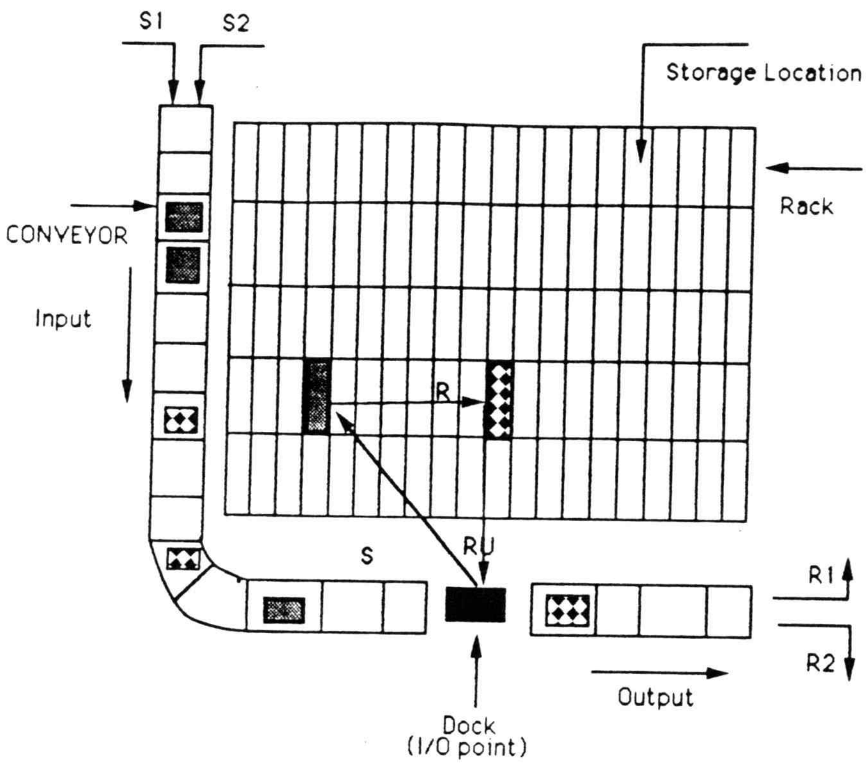
The transfer of pallets, input as well as output, occurs at the dock. Therefore, it is also referred to as Input/Output (I/O) point. In a single dock arrangement the crane is always located at the I/O point when it is idle. The crane remains idle when there are no storage and no retrieval requests. For the square-in-time-system, the crane requires the same amount of time to reach the farthest row as it does to reach the farthest column. For the layouts in Figure 2.1 and 2.2, there are 5 rows and 20 columns, which together result in 100 storage locations. The crane operation cycle may consist of the following: (1) storage and retrieval before returning to the dock, (2) storage only, or (3) retrieval only. In the first case, the crane executes a dual command cycle. For the later two cases, the crane executes single command cycles. When the crane only performs a storage request, it travels back empty to the dock. Similarly, when the crane is required to execute only the retrieval request, it traverses empty to the location from where the material has to be retrieved.

2.2.2. Mid-Aisle Layout

In a mid ailse arrangement the dock is located at the middle of the aisle at an elevation equal to the lowest row of the rack. The aisle mid-point rack arrangement is as shown in Figure 2.3. The configuration for this system can be envisioned as input and output conveyors installed halfway into the aisle. Like the previous arrangement, the transfer of incoming and outgoing pallets occurs at the dock. In this layout, the time taken by the crane to reach the row most distant from the dock is twice the time taken to reach the most distant column. The crane operations are similar to the end of aisle layout.

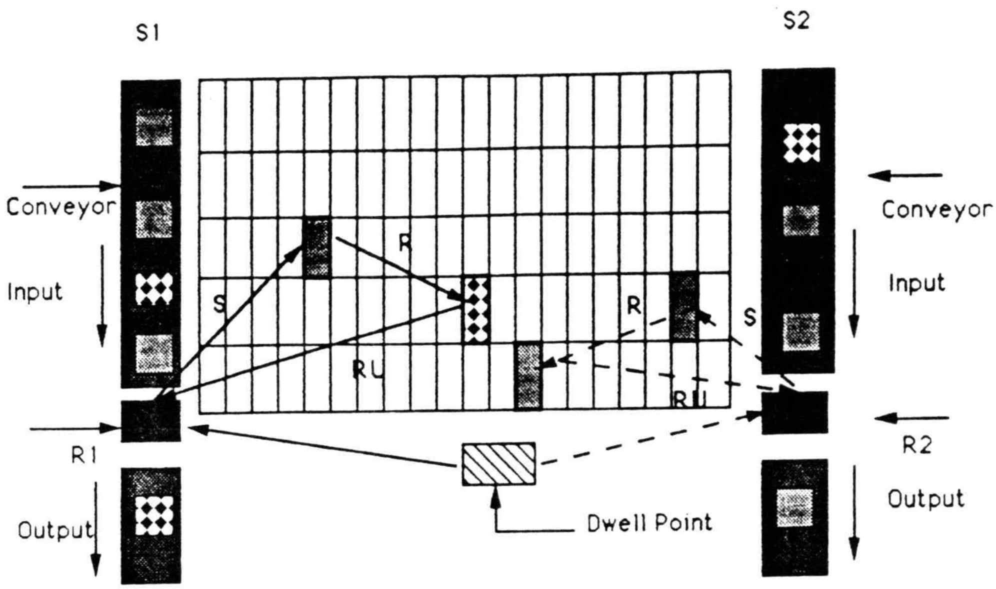
2.2.3. Dual Dock Layout

Dual dock layouts are shown in Figures 2.4 and 2.5. With such an arrangement, the system uses two docks or I/O points



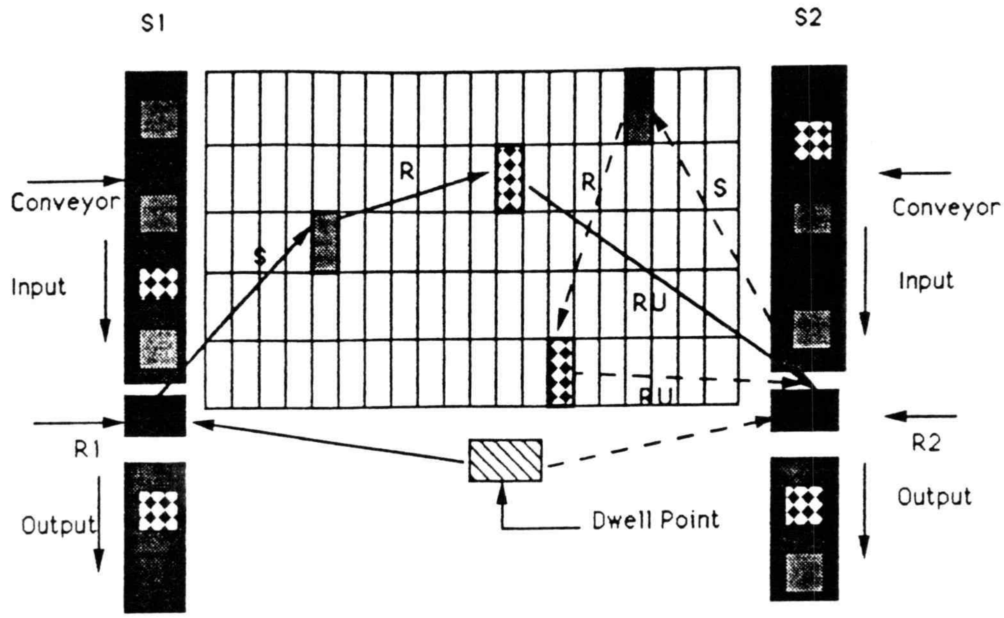
S -> Storage Phase.
(Closest Open Location
Rule)
R -> Retrieval Phase.
(Nearest Neighbour Rule)
RU -> Return Phase.

Figure 2.3. Mid-Aisle Single-Dock Layout:
Closest Open Location Assignment with Uniform Turnover.



S1,S2 -> Sources.
R1,R2 -> Destinations.
S -> Storage Phase.
(Closest Open Location Rule)
R -> Retrieval Phase.
(Nearest Neighbour Rule)
RU -> Return Phase.

Figure 2.4. Dedicated Dual-Dock Layout: Closest Open Location Assignment.



S1,S2 -> Sources.
R1,R2 -> Destinations.
I,II -> Classes,based on Turnover.
S -> Storage Phase.
(Class Based Turnover Rule)
R -> Retrieval Phase.
(Nearest Neighbour Rule)
RU -> Return Phase.

Figure 2.5. Hybrid Dual-Dock Layout: Closest Open Location Assignment.

with two different conveying systems. The storage and retrieval requests are received from two different departments S1 and S2. The pallets from source S1 arrive through the input conveyor located on the left end of the aisle. Similarly the pallets from source S2 arrive through the input conveyor located at the right end of the aisle. The retrieved pallets are sent to the departments by using the output conveyor located at the two docks. The transfer of pallet occurs at either dock. When the crane is idle(i.e. there are no storage and retrieval requests), the crane rests at the aisle mid point.

In the dual-dock layout with dedicated arrangement (Figure 2.4), each dock is dedicated to one specific department (represented by the storage source). Therefore, when the crane is at the dwell point, it can go to either dock. Nevertheless, the requests received from one particular department can be fulfilled only when the crane is at the associated dock or at a destination dedicated to handle the requests received from that department. For example, if a retrieval request is received from S1, and the crane's current position is at R2, it will not perform that request.

In the dual dock layout with the hybrid arrangement (Figure 2.5), the crane can also handle the requests received from either department, irrespective of the crane's location. In a dual dock layout with dedicated arrangement, the crane cycle would terminate at the dock from where it commenced. In a dual dock layout with hybrid arrangement, the termination point can be either dock.

2.3 Scheduling Policies

2.3.1. Storage Policies

1. <u>Single-dock layout</u>: The following scheduling rules will be used in a single dock layout for storing the pallet in the rack:

a. Closest Open Location (COL) rule - The closest open location rule is illustrated in Figures 2.1,2.2 and 2.3 for the single-dock-layout. In general, the closest open location is defined as an open location from among all available open locations which has the smallest sum of storage travel time from the dock to the open location and retrieval travel time from that open location to the dock. To execute this rule, the list of open rack locations is scanned before starting the storage phase to determine the location closest (in terms of time) to the I/O point. To do this, the sum of travel time to the storage location and the expected retrieval travel time is found for each potential location. The pallet is stored in the open location which minimizes this measure. Assuming that the rack capacity utilization (load factor) remains constant over time, the closest open location rule will store pallets in square subset of the rack location closer to the I/O point.

b. Class Based Turnover Rule - The execution of the class based turnover rule is shown in Figure 2.2. Under this rule, the racks and pallets are partitioned into K classes based on turnover frequency. Pallets are then assigned to a class of storage based on their turnover frequency. For example, with two classes, pallets with the higher turnover are assigned to class I, where as the pallets with smaller turnover are assigned to class II. Class I is located closest to the I/O point. Within each location the pallets are stored using the closest open location rule. During the execution of the storage phase, the class of the arriving pallet is determined. Then the list of open locations for that class of pallet is determined. The pallet is stored in the open location in a specific class which has the least travel time from the dock.

2. Dual - dock layout: The closest open location rule (COL) is used for scheduling storage requests in the dual dock systems.

a. Closest Open Location (COL) rule - The closest open location rule works as shown in Figures 2.4 and 2.5. When a pallet arrives at any of the docks for storage, the system scans all the possible open locations available at that point in time. Next, the travel time of the crane from that dock to all possible open locations is calculated. The pallet is stored in the location which minimizes this travel time. The Crane performs dual command cycle (mandatory interleaving) if possible, otherwise, it performs a single command (no interleaving) cycle. The single command cycle for storage comprises of crane's traversing to the storage location and returning to the dock without retrieving any pallet. In the dedicated arrangement, the crane returns to the same dock from where it initiated the storage sequence, whereas in the hybrid arrangement, the crane may return to either of the docks depending on the travel time from the storage location to the docks.

It is important to mention here that all the storage requests are served on First-Come-First-Serve (FCFS) basis independent of the type of layout or the scheduling policy.

2.3.2. Retrieval Policies

The following retrieval rule will be used in the single dock and the two dock layouts:

1. Random retrieval rule with maximum waiting time limit - When the crane initiates a retrieval cycle, a target retrieval location is selected randomly from all the retrieval requests waiting to be served. The random retrieval location is

determined from the available occupied locations through the generation of random numbers. The crane performs the dual command cycle, if possible; in absence of the storage request, it executes the single command cycle in which case it only performs the retrieval request. For the single-dock layout, the retrieved pallets for both destinations are exchanged at the same dock or I/O point. For the dual-dock layouts, the retrieval policy depends on the type of arrangement. For the dedicated layout, each storage-retrieval combination has a specific dock assigned to it, for the hybrid arrangement, a stored then can be retrieved by either dock. The maximum time limit is introduced to avoid having retrieval requests wait for a very long before being retrieved. Based on result of previous research (Randhawa, Wang and McDowell,1991), a time limit of 60 minutes was selected tobe used in conjuction with the random retrieval rule.

If a request in the retrieval queue waits for 60 minutes, priority is given to that request, independent of the traveling time. If more than one requests have been waiting for more than 60 minutes, these are served on a first-come-first-serve basis.

2. Nearest Neighborhood rule - The execution of this rule is such that it always looks for the closest occupied cell from the current crane location. In case of a dual command cycle, once the
storage location is determined, the time distance for each of the occupied cells from the previously determined storage location is calculated. The cell that results in the least crane cycle time is selected as the next retrieval location. While executing the single command retrieval cycle, the time distances for the possible retrieval locations are determined from the I/O point. The location closest to the I/O point becomes the next retrieval location. The crane performs dual command cycle if at all possible.

c. Relief Nearest Neighborhood rule - This rule is a combination of FCFS rule and the Nearest Neighborhood rule. The primary criteria for using this rules is the queue size. In this study it is assumed that the retrieval requests are served on the FCFS basis as long as the number of requests in the retrieval queue is less than ten. When this limit is exceeded, the model reverts to the Nearest Neighborhood rule.

A combination of a storage and a retrieval request is referred to as scheduling policy. The scheduling policies evaluated in this study are summarized in table 2.1.

Scheduling Policy	**Storage Rule**	**Retrieval Rule**	**Abbr.**
1	First - Come - First - Serve Closest Open Location	Random Retrieval with Maximum waiting time limit of 60 minutes.	COL/RR60
2	First-Come-First-Serve Closest Open Location	Nearest Neighbor	COL/NN
3	First-Come-First-Serve Closest Open Location	Relief Nearest Neighbor	COL/RNN
4	First-Come-First-Serve Class Based Turnover	Random Retrieval with Maximum waiting time limit of 60 minutes.	COL/RR60 (within class)
5	First-Come-First-Serve Class Based Turnover	Nearest Neighbor	COL/NN (within class)
6	First-Come-First-Serve Class Based Turnover	Relief Nearest Neighbor	COL/RNN (within class)

Table 2.1: Scheduling Policies.

2.4 Model Assumptions -

To keep the analysis with in manageable size, some assumptions were made in model formulation. These can be divided into three different categories: general assumptions, square rack assumptions, and non-square rack assumptions.

2.4.1 General Assumptions -

Gneral assuptions comprise of assumptions used in both square rack arrangements and nonsquare rack arrangements.

1. AS/R SYSTEM

The AS/R system considered in this study is a single crane serving a single aisle with storage racks placed on one side of the aisle. A conveyor provides the link between the system and the source of destination of pallets. The I/O exchange between crane and conveyor occurs at the dock (I/O point).

2. JOB DEFINITION

For storage and retrieval jobs, it is assumed that each storage or retrieval job incorporates a single pallet assignment. This assumption removes the dispatching problem related to crane capacity to be considered as an independent factor in this study.

3. PALLETS

Each pallet contains only one part number or item type and the sizes of all pallets are equal. This assumption removes pallet assignment as an independent variable in the study.

4. STORAGE SOURCES AND RETRIEVAL DESTINATIONS

There are two sources for storage pallets from two different production departments, S1 and S2, respectively. Similarly, the two sources of retrieval requests are two different production areas, R1 and R2, respectively.

5. DOCK (I/O POINT)

The system under consideration uses either a single dock layout or a dual-dock layout. In a single dock layout the dock is located either at the left corner or at the aisle-mid-point. In the two dock layout, dock 1 is located at the right corner of the rack and dock 2 is located at the left corner of the rack. The elevation of the dock is equal to the lowest row of the rack.

6. DWELL POINT

When the crane is idle, its location is referred to as the dwell point. Dwell point may affect system performance. In order to concentrate on factors chosen for evaluation in this study, the effects of dwell point variance are excluded from this study. The dwell point policy adopted for this study is as follows :

(a). In a single-dock layout, the dwell point is at the dock (i.e. either at one of the two ends of the aisle or at the aisle mid point where the dock is located).
(b). In a dual-dock layout, the dwell point is at the midpoint of the lowest row in the storage rack.

7. BASIC CRANE OPERATION

A single dock system is further classified based on the dock location: middle or end of aisle. However, crane operations pertinent is the same for both systems. These are:

(a) Store one pallet plus retrieve one pallet, if both storage and
retrieval queues are non-empty, or
(b) Store one pallet, if retrieval queue is empty, or
(c) Retrieve one pallet, if storage queue is empty.

Crane operation is subject to a dual-command rule, allowing the completion of both a storage request and a retrieval request on a single cycle from the dock. The crane operates in accordance with this rule as long as both the storage and retrieval queues are not empty. When one of the queues is empty, the crane will perform the requests from the other queue without interleaving.

In case of a dual dock system, the docks are located at opposite corners of the rack and each dock is capable of handling transactions for both input and output. Two distinct configurations that are considered in this research are hybrid and dedicated. In the "hybrid" arrangement the storage pallets from the sources S1 and S2 can be retrieved by either destination R1 or R2. In "dedicated" arrangement,the storage pallets from S1 are only handled by R1; similarly the storage pallets from S2 are only handled by R2.

In the "hybrid" arrangement, when a storage pallet arrives at dock 1, the sum of storage travel time to an open location and expected retrieval travel time to either dock1 or dock2 is determined. The crane stores the pallet to that open location which minimizes this sum. In the case of class-based assignment, first, the class of the arriving pallet is identified and then the sum of the storage travel time to an open location within the class boundary and the expected retrieval travel time to either dock 1 or dock 2 is determined. The crane stores the pallet into that location which minimizes this sum. Similar assumptions about the crane operations can be formulated for dock 2.

In the "dedicated" arrangement, for a storage pallet arriving at dock 1, the sum of travel time to an open location and expected retrieval time to dock 1 is determined. The pallet is stored in the location that minimizes this time. When the class-based storage assignment rule is used, first, the class of the arriving pallet is identified and then the sum of the storage travel time to an open location within the class boundary and the expected travel time to dock1 is determined. The crane stores the pallet into that location which minimizes this sum. Similar assumptions about the crane operations for dock 2 can be formulated.

For crane retrieval operations the nearest neighbor rule is used. When the crane initiates travel for a retrieval cycle, a target retrieval location is selected from all the retrieval request queues. The nearest neighbor retrieval location is determined when the sum of the travel time from the current crane location to the target location and from that location to the dock is the smallest of all options available from the retrieval queues.

8. <u>CRANE CAPACITY AND VELOCITY</u>

The maximum capacity of the crane is one pallet and the crane is capable of moving horizontally and vertically concurrently. In calculating the travel time, constant velocities are used for horizontal and vertical travel, and acceleration is ignored. In this study the crane horizontal velocity is 4 seconds per column and the crane vertical velocity is 20 seconds per row.

9. PICKUP AND DEPOSIT TIME

The pickup and deposit (P/D) time is generally independent of the crane travel velocity and the shape of the rack. Furthermore, given the crane load and unload characteristics, P/D time is usually deterministic. Hence, it is useful to include P/D time only after average travel time is computed. Henceforth, the P/D time may be ignored.

10. ARRIVAL RATES AND QUEUE SIZE LIMIT

In order to examine maximum throughput for different scheduling rules, it is necessary that all of crane's trips be maintained in the dual command cycle during the simulation period. Thus, an exponential distribution with a mean time of four minutes is used as the interarrival time for storage pallets from S1 or S2 and for retrieval requests from R1 or R2. The maximum queue size for storage and retrieval is restricted to 10 for random retrieval and nearest neighbor retrieval policies. For the relief nearest neighbor policy, it is not reasonable to have a finite queue The critical queue length is where the switch is made from FCFS to nearest neighbor and this is assumed to be ten.

11. INITIAL RACK UTILIZATION

Initial rack utilization is assumed to be 90%. The system with 90 percent utilization has been shown to be a nontrivial system in scheduling literature.

2.4.2 Square Rack Assumptions -

The assumptions applicable to the square rack arrangements are as follows.

1. Rack Dimensions

A storage rack of 5 rows and 20 columns (100 storage locations) is located on one side of the aisle. Given that all storage locations are identical in size, any pallet load may be stored in any storage location. This assumption removes the corresponding sizes of the pallet and storage locations as an independent variable in this study.

2. Travel Time

It is assumed that the racks are square in time. Therefore, given that the dock is located at the lower left or right corner of the rack at an elevation equal to the lowest row, the horizontal and vertical crane velocities are such that the time for the crane to travel to the farthest column equals the time for crane to travel to the farthest row. In the system with mid-aisle dock the time consumed by the crane to reach the most distant column is half the time it takes to reach the most distant row. Given the horizontal and vertical crane velocities of 4 seconds for columns and 20 seconds for row, respectively, the horizontal travel time to the column farthest from the dock is 80 seconds for the end-of-aisle arrangement and 40 seconds for the aisle-mid-point arrangement. Also the vertical travel time to the highest row, when the dock is located at an elevation equal to that of the lowest row is 80 seconds for all the arrangements.

2.4.3 Nonsquare Rack Assumptions -

In addition to the general assumptions, the following set of assumptions is also used in the non-square rack system:

1. <u>Rack dimensions</u>

Different rack dimensions were evaluated by varying the number of rows and the number of columns but holding the total number of openings constant. Table 2.2 summarizes the dimensions evaluated in this study.

2. <u>Shape Factor</u>

Shape factor (b) is defined as: (Bozer and White, 1984)

shape factor = minimum(t_h / T , t_v / T)

where,

t_h = the horizontal travel time required to go to the farthest column from the I/O station,

t_v = the vertical travel time required to go to the farthest row

from the I/O station, and

T = Denormalizing factor = maximum(t_h , t_v)

Table 2.2 shows various values for the "shape factor" to be used during simulation.

NOR	10	5	4	2
NOC	10	20	25	50
NOP	100	100	100	100
T(H)	40	80	100	200
T(V)	180	80	60	20
T(H)/T	.222	1.0	1.0	1.0
T(V)/T	1.0	1.0	0.6	.10
b	.222	1.0	0.6	.10

NOR = NO. OF ROWS
NOC = NO. OF COLUMNS
NOP = NO. OF OPENINGS

Table 2.2: Non-Square Rack Dimensions.

3. Travel Time

In the case of the nonsquare rack arrangement, the time taken by the crane to travel to the most distant row from the I/O point is not the same as the time it consumes to travel to the most distant column.

2.5 Performance Measures

The following are the performance measures which are considered to be of primary importance to the performance of AS/R system:

1. Throughput

The throughput is defined as the number of requests executed during a specified time period. Hence, throughput is also a measure of the number of cycles, either with mandatory interleaving or without interleaving, executed by the crane. The prime objective in warehousing is to maximize throughput.

2. Mean Storage and Retrieval Waiting Times

Mean waiting time is defined as the average amount of time spent by a request (either storage or retrieval) in the queue before it is executed. The objective is to minimize mean storage and retrieval waiting times.

3. Maximum Retrieval Waiting Time

The maximum retrieval waiting time is defined as the maximum value of waiting time recorded during simulation analysis. The storage arrivals are independent of the system; however processing of retrievals affect the performance of subsequent prduction layouts; hence, the emphasis on maximum retrieval times.

4. <u>Number Of Rejects</u>

This number represents requests which are not executed because of (1) the queue size constraint or the time constraints, (2) unavailability of storage location. The number of rejects is a function of interarrival rate and storage rack utilization.

CHAPTER 3

METHODOLOGY

3.1 General Discussion

Discrete event simulation is used to analyze the AS/R system. Thus, scheduling of requests(either storage or retrieval) are modeled as events at discrete points in time. The time at which an event takes place is considered to be at the completion of the crane cycle time from the previous request(s). Alternatively, the event time can be the time at which a request arrives for storage or retrieval and the crane is idle.

The storage and retrieval requests represent entities in the system. Each entity has an associated set of attributes assigned to it. These attributes contain request specifics, such as the request arrival time, type of request (storage/retrieval), the cell location into or from which the request material has to be stored or retrieved and the travel time to a particular location in the aisle. The time events and their attributes are stored in the event calender, a system maintained file.

User-defined files or queues are used to keep track of storage and retrieval requests. The storage file maintaines entries on a first-come-first-serve basis. The one dock layout uses one storage file; for two dock layouts there are two such files representing two separate storage sources. Essentially, the transfer of pallet is equivalent to removing the first entity from the storage file. The crane cycle is then scheduled by changing the crane status from idle to busy. Similarly, a separate file is used for maintaining retrieval requests. When a retrieval request is completed, the entity stored in the retrieval file is removed and disposed (i.e., sent out of the system). The requests in the retrieval file are ordered either on the basis of travel time (e.g.., used by nearest neighbor policy) or the request arrival time(e.g., used for FCFS scheduling in relief nearest neighbor policy).

3.1.1 Model Structure

Figure 3.1 shows flow diagram for the basic logic used in developing the computer models. The SIMAN simulation language was used for developing the simulation models. Three different files are required to simulate the AS/RS under study, these are:

1. MODEL file (file extention MOD) - In discrete-event modeling, the model file represents the SIMAN network code. Since the models developed in this research did not use any network modeling, the model file is empty. However, a blank model file (with just BEGIN and END statements) is required to develop the executable program file linked with the experimental file.

EXPERIMENTAL file (file extention EXP) - This file is a specification of the experimental conditions for executing the model. The specification set includes: defining arrival distribution for storage and retrieval requests, the number of attributes for each entity, the maximum number of entities that can exist in the system at any given time, specification of the statistics to be collected during the simulation run, the length of simulation run and priority specifications on the queues.

FORTRAN file (file extention FOR) - This file contains the necessary logic (as user-written subroutines) required for modeling the system. Some subroutines are common to all of the models used in this study; others are designed for specific models. Each subroutine is referenced by a unique integer number assigned to it. A brief description of the program logic is presented below.

Subroutine EVENT maps the event number to the appropriate subroutine containing the logic for that event. Depending on the

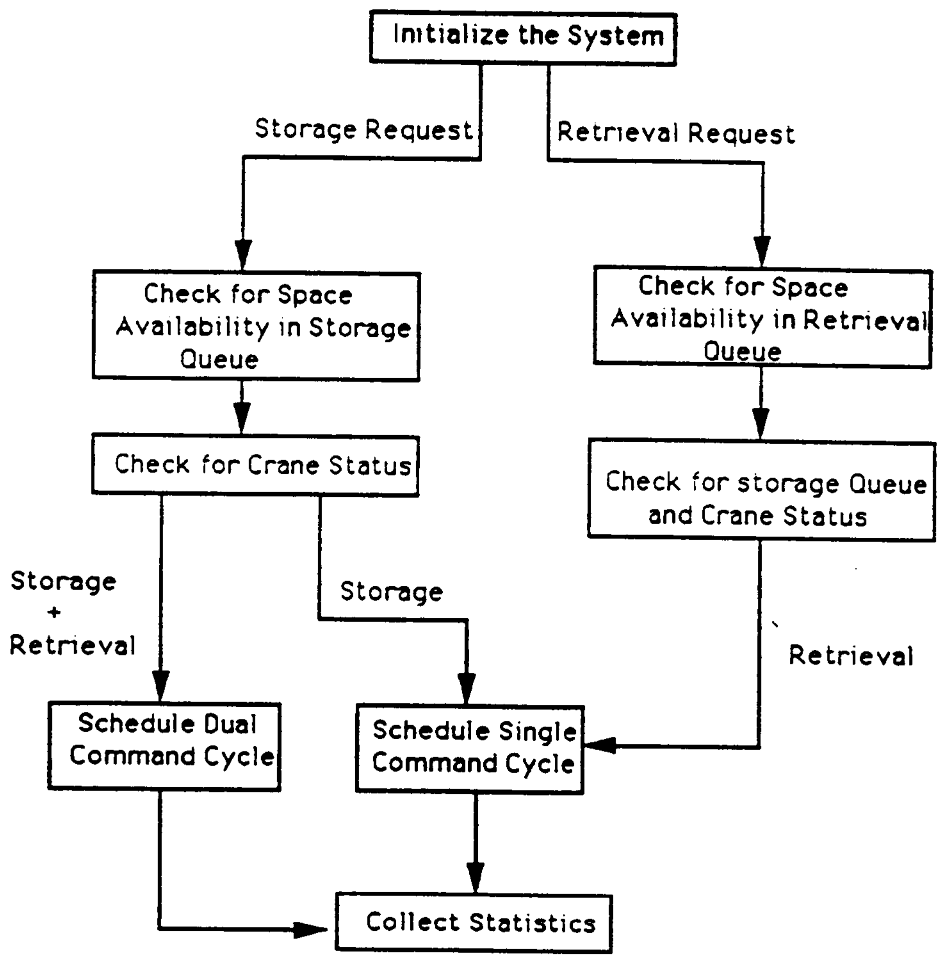


Figure 3.1. Logic Flow Diagram

value of the integer variable, it schedules the execution of the corresponding subroutine at the specified time. When the scheduled event in the event calender becomes active, the appropriate subroutine is invoked.

System status at the start of simulation is established in subroutine PRIME. This is a self-executable subroutine that is executed at the start of simulation. It initializes the variables and arrays. For example, it calculates the time distances and fills up each array elements with appropriate distances. Similarly, the rack is initially filled up randomly to reflect the 90% utilization level and the cell status array is updated. A link is developed between the cell status array and the distance array on the basis of the array element number. The distance arrays and the cell status array are sorted in the ascending order of distance. Each element of the cell status array stores either a zero or one, zero indicating that the cell is operating empty; 1 indicating that the cell is occupied. Subroutine PRIME also schedules the first arrival of storage and retrieval requests into the system.

Subroutine ARRST assigns different specifics such as the arrival time and the type of request to attributes of the storage requests arriving from either of the two departments. If the storage queue is not full, it stores the arriving request in the storage queue. It then schedules the arrival of the next storage request. Next, the crane status is checked. If the crane is idle, then the first entity (request) is removed from the storage queue and a crane cycle is initiated. The dual dock layouts and the class-based layouts have more subroutines performing the function of the ARRST subroutine.

Similar to subroutine ARRST, subroutine ARRRT handles the arriving retrieval requests. Upon arrival each request is assigned an open location. If none of the locations is available, then the request is rejected. The only difference between ARRST and ARRRT subroutines is that ARRST can schedule either a single command storage cycle or a dual command cycle, while ARRRT can only schedule a single command retrieval cycle, depending on the crane and storage queue status.

Subroutine SINDUL determines the type of cycle to be performed on the basis of storage and retrieval queue status. It finds the closest open location; while searching for the closest open location for storage, the cell status array is scanned sequentially and the first element with a zero entry is selected as the closest open location. Next, the corresponding array element number in the distance array (containing the time distance) is checked to determine the time required by the crane to reach its destination cell. Based on the storage location and the retrieval location (of the retrieval request), the total crane cycle time is calculated. In some models, this subroutine just determines the type of cycle to be performed, and rest of the task is shared by another subroutine called DCYCLE. This subroutine schedules the storage phase of the crane cycle by calling the subroutine CELBSY. Subroutine CELBSY contains necessary logic for changing cell status from open to occupied. The candidate cell location is obtained from one of the attributes of the entity arriving to this subroutine. In case of a dual-command cycle, this subroutine calls subroutine CELETY on the basis of the crane travel time from storage to retrieval location, while for a single-command storage cycle, it schedules the return phase of the cycle by calling subroutine ENDSV2. Subroutine CELETY changes the cell status from being occupied to open. It then schedules the return phase of either a single command retrieval cycle or a dual command cycle by calling subroutine ENDSV2.

Subroutine ENDSV2 contains logic for collecting statistics on the waiting time for retrieval request and crane cycle time. It also reinitializes some of the variables; the entities are then disposed, indicating that the requests have been satisfied.

The next crane cycle is then scheduled depending upon the queue status.

In addition to subroutine PRIME, there are two other self-executable subroutines used in the model. These are: subroutine WRAPUP and STATE. The Subroutine WRAPUP is called at the end of each simulation to collect statistics. Subroutine STATE is used to transfer the retrieval requests from the regular retrieval file to a special file that becomes active if the retrieval waiting time exceeds some specified time limit.

In addition to the user defined subroutines described above, the following SIMAN Subprogram Library subroutines were used in the simulation models (C. Dennis Pegden, 1989):

(a). CREATE(L): A request for either storage or retrieval is sent to the system by calling subroutine CREATE(L). This subroutine returns a pointer to an entity record as the value of the integer argument L.

(b). SCHED(L,N,DT): A request is scheduled on the event calendar by using subroutine SCHED(L,N,DT), where L is the entity record location, N is the event number to be executed, and DT is the time delay before executing the event. The scheduled events are automatically maintained in the event calendar.

(c). SETA(L,N,VAL): Subroutine SETA(L,N,VAL) sets the attribute number N of the entity with record location L to the real value specified by the argument VAL.

(d). INSERT(L,IFL): An entity in inserted into a file by calling subroutine INSERT(L,IFL). This subroutine causes the entity specified by the record pointer L to be inserted into file IFL. The relative position where the entity is placed in the file is determined based on the ranking rule specified in the experimental file.

(e). REMOVE(L,IFL): An entity that is a member of a file can be removed by using subroutine REMOVE(L,IFL). This subroutine causes the entity with record location L to be removed from file

IFL. The entity is unlinked from the other members of the file and the number of entities in the file is reduced by one.

(f). DISPOS(L): Once created, an entity may be disposed by calling subroutine DISPOS(L). The argument L is an integer FORTRAN variable that specifies the pointer to the data record of the entity to be disposed. This subroutine is usually called when either the requests are completed or the request files are completely occupied.

(g). TALLY(N,VAL): The tally N argument of subroutine TALLY refers to a tally register where the observation VAL is recorded. The tally register maintains a summary of the mean, standard deviation, minimum observation, maximum observation, and number of observations recorded for the tally variable. This subroutine is useful in collecting statistics like waiting times in the queue and crane cycle time for the system under study.

(h). COUNT(N,INC): Subroutine COUNT(N,INC) is used in a discrete event to increment the counter N by INC units. The counter N refers to a register to which a count increment is added at each execution of subroutine COUNT.

The following SIMAN Subprogram Library functions are also used in the simulation models (C. Dennis Pegden, 1989):

(a). LFR(N): This function returns the record location of the first record in file number N. A zero value indicates there is no entity in that file.

(b). LSUCC(L): This function returns the record location of the entity that is the successor of the entity with record location L. A value of zero indicates that the entity has no successor.

(c). NQ(N): This function returns the current number of entities in file number N.

(d). A(L,N): This function returns A as the value of attribute number N of the entity with record location L.

3.2 Design of Experiments

Experiments are carried out by investigators to study a particular process or to compare the effects of several factors on the performance of a system. Statistical design of experiments refers to the process of planning an experiment so that appropriate data can be collected and analyzed resulting in valid conclusions. The simulation experiment conducted for the Automated Storage and Retrieval System involves the study of the effects of two factors and their interaction. In each complete trial or replication of the experiment all possible combinations of the levels of the two factors were investigated. The effect of a factor is defined to be the change in the response produced by the change in the level of the factor. This is usually referred to as the main effect as it relates to the primary factors of interest in the experiment. In some experiments it is possible that the difference in response between the levels of one factor is not the same at all levels of the other factor. When this occurs, there is an interaction between the factors.

The two factors considered in this research were the rack or the layout arrangement (factor A) and the scheduling policies (factor B). In general, there were two factor levels for factor A. These levels are the two different rack arrangements such as single dock layout with the dock at the end and the single dock layout with the dock at the middle. Similarly, there were three levels for factor B. These levels were the three different scheduling disciplines or policies (the closest open location policy for storage with random retrieval, closest open location policy for storage with the nearest neighborhood retrieval and the closest open location policy for storage with relief nearest neighborhood retrieval).

For two levels of factor A and three levels of factor B, there were a total of six treatmets. The response id one of the performance measures such as throughput or mean storage waiting time. The experiment was designed for five replications. Different set of random number streams were used to take replications. The use of replication allows us to obtain an estimate of the experimental error which is a basic unit of measurement for determining whether observed differences in the data are really statistically different. Also, when the sample mean is used to estimate the effect of a factor in an experiment, then replication permits us to obtain more precise estimate of this effect. The ANalysis of VAriance (ANOVA) is used to analyze the results of the factorial experiment. Graphical and statistical analysis was done by using STATGRAPHICS.

Chapter 4

Analysis of Results

4.1 Introduction

The primary objective of this research was to evaluate the effect of scheduling policies on AS/R layout designs. The system performance was evaluated in terms of throughput, mean storage and mean retrieval waiting time, maximum retrieval waiting times, and the number of requests rejected due to the system being full. Simulation-based computer models were developed to model and analyze different layout and scheduling policy scenarios. The values for the performance measures were collected as system output at the end of each simulation run. To increase the accuracy of the system performance, each model was executed using five different sets of random numbers. The aggregate mean was used as an estimator for the population mean. The systems were analyzed using a load factor (initial rack utilization) of 90 percent and the queue capacities of 10 for both storage and retrievals. However, due to the nature of COL/RNN scheduling policy, there was no queue size limit when this policy was executed. Statistics were based on simulation run of 5000 time units, after the initial bias had been removed by running the system for 100 time units.

Table 2.1 that summarized the scheduling policies is reproduced in table 4.1 as the policies are referred to by their abbreviations shown in the table in the discussion that follows. Table 4.2 summarizes the layouts analyzed in this research. The abbreviation for layouts shown in Table 4.2 are used in subsequent discussion.

Scheduling Policy	Storage Rule	Retrieval Rule	Abbr.
1	First - Come - First - Serve Closest Open Location	Random Retrieval with Maximum waiting time limit of 60 minutes.	COL/RR60
2	First-Come-First-Serve Closest Open Location	Nearest Neighbor	COL/NN
3	First-Come-First-Serve Closest Open Location	Relief Nearest Neighbor	COL/RNN
4	First-Come-First-Serve Class Based Turnover	Random Retrieval with Maximum waiting time limit of 60 minutes.	COL/RR60 (within class)
5	First-Come-First-Serve Class Based Turnover	Nearest Neighbor	COL/NN (within class)
6	First-Come-First-Serve Class Based Turnover	Relief Nearest Neighbor	COL/RNN (within class)

Table 4.1: Scheduling Policies.

Layout Description				Abbr.
# of Docks	Dock Arrangement	Item Distribution	Rack Dimensions	
Single	End-of-Aisle	Uniform	5 x 20	Layout1
Single	Aisle-Mid-Point	Uniform	5 x 20	Layout2
Single	End-of-Aisle	Class-Based	5 x 20	Layout3
Single	End-of-Aisle	Uniform	10 x 10	Layout4a
Single	End-of-Aisle	Uniform	4 x 25	Layout4b
Single	End-of-Aisle	Uniform	2 x 50	Layout4c
Dual (hybrid)	Two-ends-of-Aisle	Uniform	5 x 20	Layout5
Dual (dedicated)	Two-ends-of-Aisle	Uniform	5 x 20	Layout6

Table 4.2: Layout Arrangements.

The results are organized in two major sections: comparison across schedules and comparison across layouts.

The primary statistical techniques used for analyzing the results are the Box and Whisker plots, Bar graphs and Analysis of Variance.

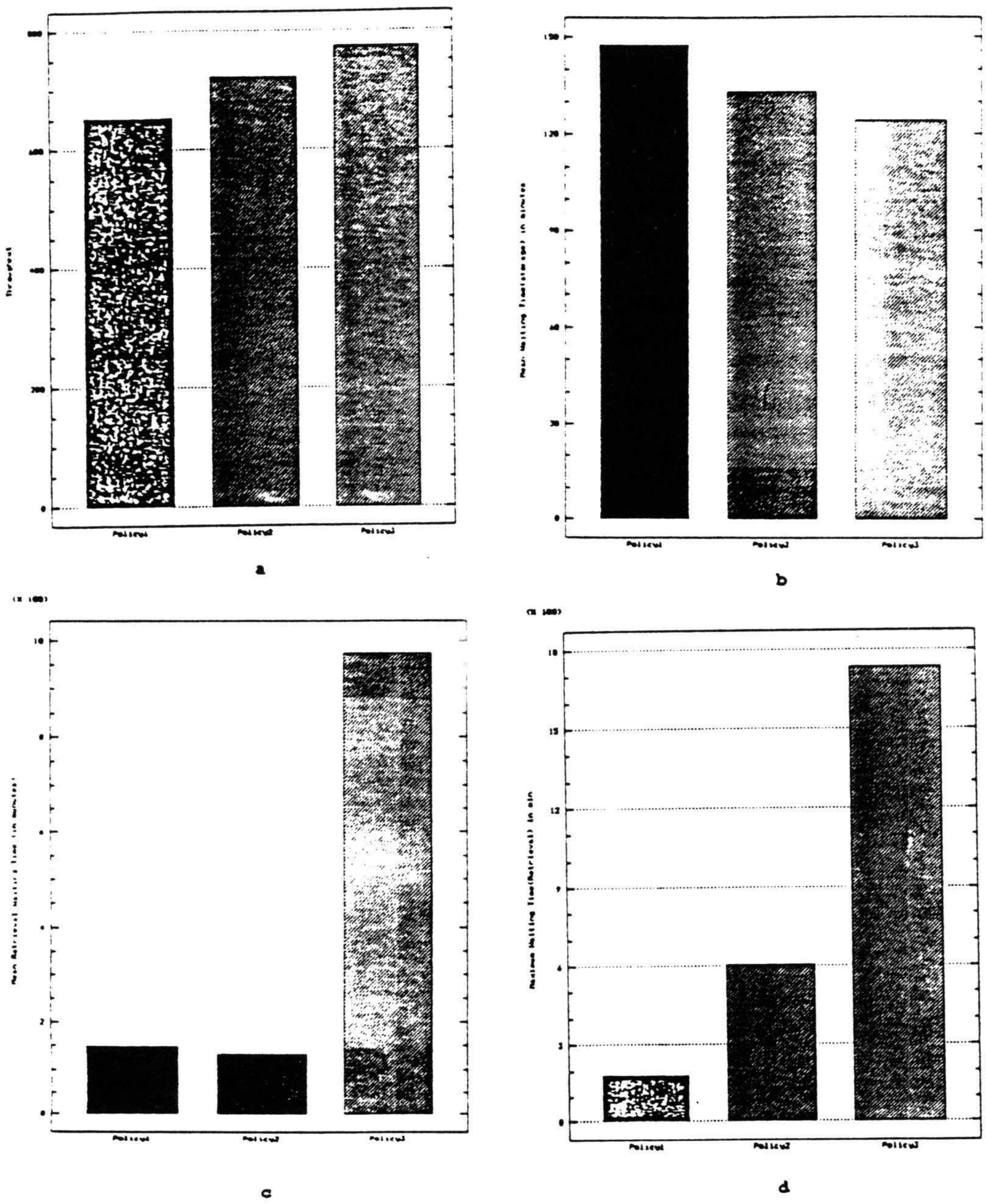
In the Box and Whisker plots (shown in Figures 4.6, 4.8,4.10 and 4.14), the central "Box" covers the middle 50 percent of the data values, between the lower and upper quartiles. The "Whisker" extend out to the extremes (minimum and maximum values), while the central line is at the median. Each of the horizontal lines of the central box represents the mean of a performance measure being plotted. The bar graphs (shown in Figures 4.1, 4.2, 4.3, 4.4,4.11 and 4.12) plot the mean performance of a performance measures under different scheduling policies. The statistical comparison of different combinations of layouts was accomplished using ANOVA (shown in Figures 4.5, 4.7, 4.9 and 4.13).

4.2 Comparison Across Schedules (Single-dock)

4.2.1 Layout1

Figure 4.1 shows the four basic performance measures for the End-of-aisle single dock layout under the three different scheduling policies.

Throughput - Figure 4.1(a) shows that COL/RNN had the highest throughput of the three scheduling policies. COL/NN produced approximately 10 percent higher throughput as compared to COL/RR60. The throughput for COL/RNN was 6.5 percent higher than COL/NN and 16 percent higher than COL/RR60.



policy1 -> COL/RR60
policy2 -> COL/NN
policy3 -> COL/RNN

Figure 4.1: Comparison Across Scheduling Policies for Layout1.

Mean Storage Waiting Time - Figure 4.1(b) shows that the storage waiting times were the least under COL/RNN. COL/RR60 rule produced 10 percent and 16 percent higher waiting times than COL/NN and COL/RNN,respectively. The waiting time under COL/NN was found to be 7 percent higher than the COL/RNN.

Mean Retrieval Waiting Times - It is not compatible to compare the retrieval waiting times for COL/RNN with COL/NN and COL/RR60. The reason is that for COL/NN and COL/RR60 requests are rejected from the system if the queue size exceeds the prespecified critical length. In contrast, for COL/RNN the queue size is infinite. Therefore, requests wait until served rather than rejected from the system. Comparing COL/NN and COL/RR60, there is no statistical difference in retrieval waiting times. However, there is a longer variance associated with COL/NN and COL/RR60.

Maximum Retrieval Waiting Times - Due to the nature of the COL/NN and COL/RNN policy, retrieval requests may be excessively delayed if the assigned location is at the far end of the storage rack. The maximum waiting time values have been plotted in Figure 4.1(d). The figure shows that COL/RR60 resulted in the least maximum waiting time for the retrieval requests. This is obvious since under COL/RR60 rule a retrieval request waiting for more than 60 minutes is given higher priority as compared to other requests waiting to be served. Due to high arrival rate of the retrieval requests, a number of requests were found to be waiting for more than 60 minutes which resulted in the maximum waiting time being more than 60 minutes. COL/NN performed 69 percent worse than COL/RR60. For the COL/NN policy relatively higher maximum waiting times were recorded because no matter how long a request had to wait, it would only be served if the retrieval location assigned to it resulted in the least cycle time. COL/RNN produced disproportionately bad results (as compared to the other two policies) because of the increased queue length.

Storage and Retrieval Rejects - Rejects for the storage queue are defined as the number of requests that are denied service due to the storage queue being full. Due to high arrival rates the crane performed dual command cycles most of the time. Given a fixed queue size, the number of rejects depends on the arrival rate and the cycle time. COL/RNN resulted in the least number of rejects for most of the single dock layouts due to the reduced cycle time for the COL/RNN policy and infinite queue size. The implication of an infinite queue was that the number of available alternatives for the selection of retrieval location was more as compared to that of during COL/RR60 and COL/NN where queue size was limited. The COL/RNN produced 6 percent and 3 percent less storage rejects as compared to COL/RR60 and COL/NN, respectively. The COL/NN produced 5 percent less rejects as compared to COL/RR60.

The retrieval rejects can be defined as the number of retrieval requests denied from being served. Similar to the storage rejects, the number of retrieval rejects were also a function of the crane cycle time and the retrieval queue size. For COL/RR60 and COL/NN polices a queue size of ten was used. Even though no queue limit was specified for COL/RNN, practically it was equal to the total number of cells in the storage rack. The COL/RNN produced the least number of retrieval rejects due to reduced cycle time and increased queue length. The increase in queue length allowed more requests to become potential candidates to be served, resulting in less number of rejects. COL/RNN produced 11 percent and 14 percent less rejects as compared to COL/NN and COL/RR60. COL/NN produced 4 percent less rejects as compared to COL/RR60.

4.2.2 Layout2

The performance measures obtained for the single-dock layout with the dock at the middle are plotted in Figure 4.2. The results show that the COL/RNN again generated the best results for system throughput. The relative performance of the layout under different scheduling policies is similar to end-of-aisle single-dock layout. The reasons for these performance are also similar, as discussed in the previous section.

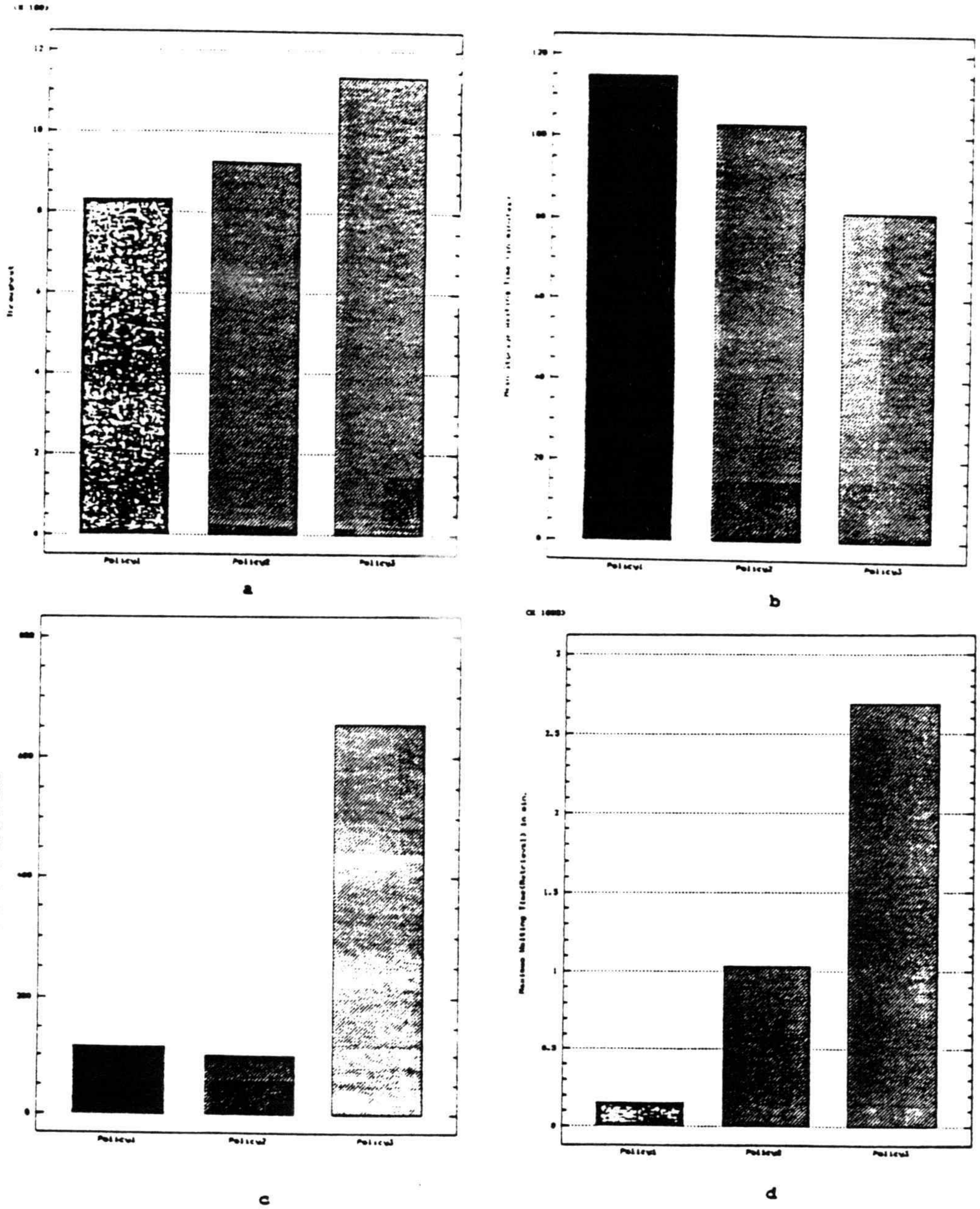
Throughput - COL/RNN produced 19 percent and 27 percent higher throughput as compared to COL/NN and COL/RR60, respectively. COL/NN produced 10 percent higher throughput than COL/RR60.

Mean Storage Waiting Times - Figure 4.2(b) shows that COL/RR60 resulted in 10 percent and 28 percent higher waiting time as compared to COL/NN and COL/RNN, respectively. The COL/RNN performed 21 percent better than COL/NN.

Mean Retrieval Waiting Times - The mean retrieval waiting times have been plotted in figure 4.2(c). COL/NN performed 85 percent and 13 percent better than the COL/RNN and COL/RR60. COL/RR60 performed 82 percent better than COL/RNN.

Maximum Retrieval Waiting Times - COL/RNN performed 61 percent and 94 percent worse as compared to COL/NN and COL/RR60. COL/NN generated 84 percent higher waiting time as compared to COL/RR60.

Storage and Retrieval Rejects - COL/RNN produced 23 percent and 18 percent less storage rejects as compared to COL/RR60 and COL/NN, respectively. COL/NN rejected 7 percent less storage rejects as compared to COL/RR60.



policy1 -> COL/RR60
policy2 -> COL/NN
policy3 -> COL/RNN

Figure 4.2: Comparison Across Scheduling Policies for Layout2.

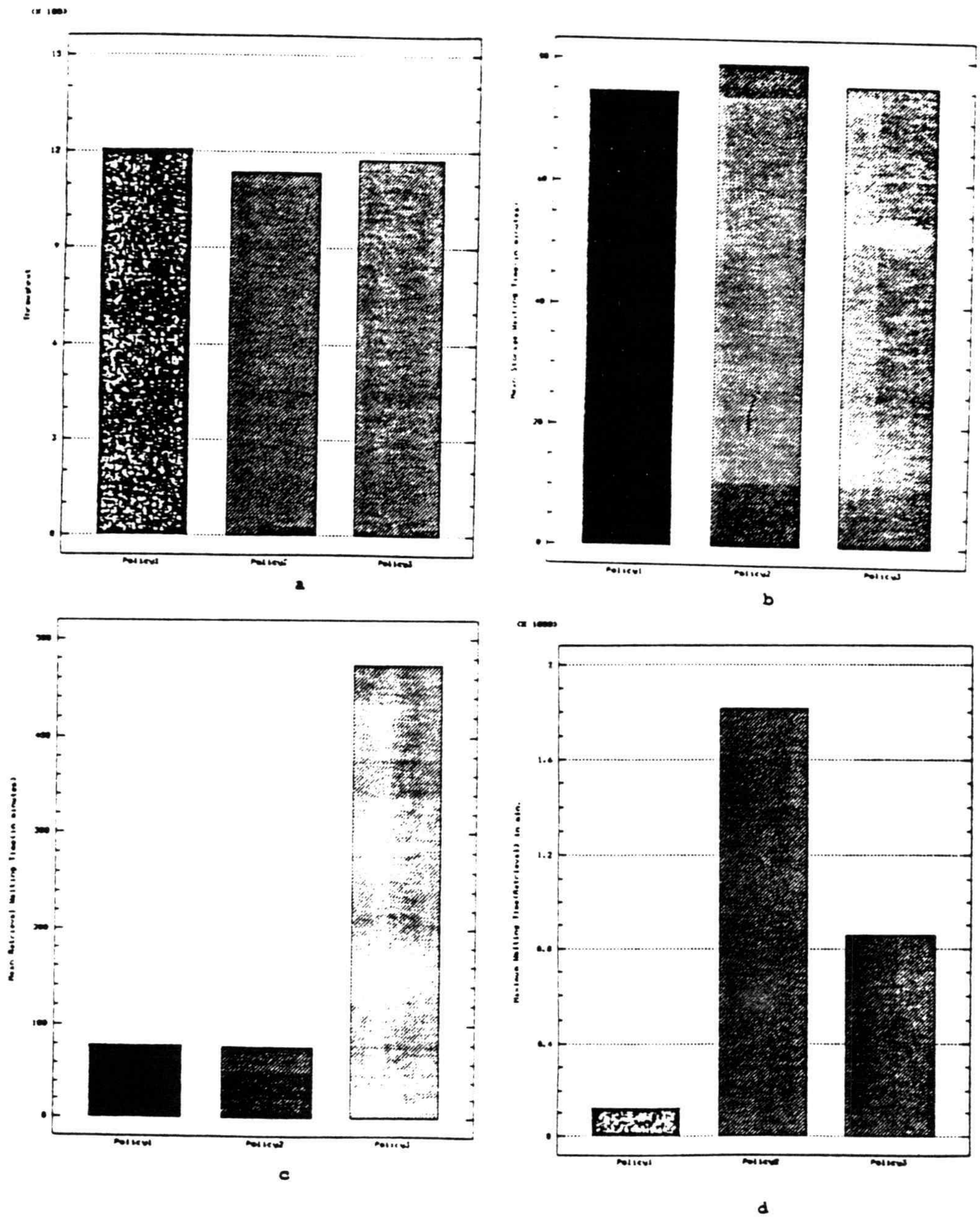
Similarly, for the retrieval rejects, the COL/RNN rejected 24 percent and 29 percent less requests as compared to COL/NN and COL/RR60, respectively. COL/NN rejected 7 percent less requests as compared to COL/RR60.

4.2.3 Layout3

The statistics obtained from this arrangement are plotted in the Figure 4.3.

Throughput - Statistics indicate that the random retrieval rule was the most efficient as far as throughput is concerned. This can be attributed to the fact that due to high load factor and arrival rate, the crane cycle time increased and hence the throughput declined for the other two policies. A partial success might have been obtained while minimizing the crane travel time from storage location to the retrieval location, with increase in travel time during the return phase. Under this system, COL/RR60 performed 6 percent and 3 percent higher than COL/NN and COL/RNN, respectively. COL/RNN produced 3 percent higher throughput as compared to COL/NN.

Mean Storage Waiting Times - COL/RNN showed the worst performance in case of the class-based arrangement for a single dock layout(Figure 4.3(b)). This can be due to the rack's operating at a very high load factor. Hence, it might not have been possible to generate a random retrieval location close to the current crane location at such a high arrival rate. This resulted in higher crane cycle time, which subsequently increased the storage queue waiting time due to the crane's being unavailable for a longer time. The storage waiting time for COL/RNN was 42 percent and 45 percent higher than COL/NN and COL/RR60,respectively. The waiting time was found to be approximately 6 percent higher for COL/NN as against the random retrieval rule.



policy1 -> COL/RR60
policy2 -> COL/NN
policy3 -> COL/RNN

Figure 4.3: Comparison Across Scheduling Policies for Layout3.

Mean Retrieval Waiting Times - Figure 4.3(c) compares the results generated by different scheduling policies. The COL/NN produced 83 percent and 3 percent less waiting time as compared to that of COL/RNN and COL/RR60, respectively. The COL/RR60 resulted in 83 percent less waiting time as compared to COL/RNN.

Maximum Retrieval Waiting Times - Figure 4.3(d) plots the maximum retrieval waiting time for each of the scheduling policies. It was found that COL/NN performed 52 percent and 93 percent worse than COL/RNN and COL/RR60, respectively. COL/RR60 produced 85 percent better waiting time as compared to COL/RNN.

Storage and Retrieval Rejects Comparison - Of the three scheduling policies, COL/RR60 policy produced the least rejects. This can be attributed to the higher load factor for the storage rack. Therefore, during the execution of either COL/NN or COL/RNN, the crane also performed single command cycles for some percentage of time, resulting in increased total cycle time. COL/RR60 policy performed 5 percent and 8 percent better than COL/RNN and COL/RR60, respectively. COL/RNN produced 3 percent less storage rejects as compared to COL/NN.

Again, COL/RNN produced the best results for retrieval rejects; it produced 17 percent and 8 percent less retrieval rejects as compared to COL/NN and COL/RR60, respectively. COL/RR60 produced 9 percent better results than COL/NN.

4.2.4 Layouts 4a, 4b and 4c

Figures 4.4.1 through 4.4.3 show results obtained for the non-square rack arrangements.

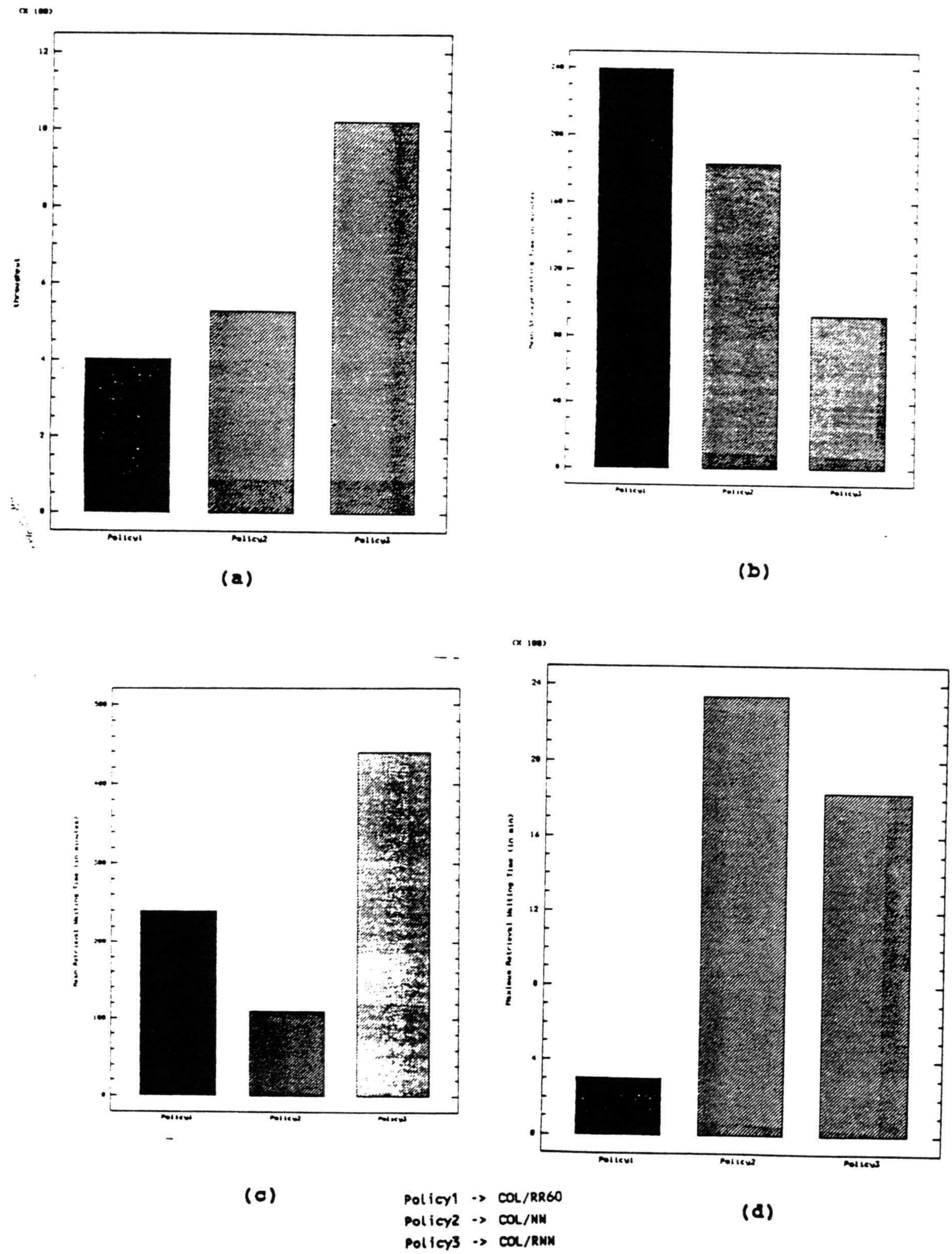


Figure 4.4.1: Comparison Across Scheduling Policies for Layout4a.

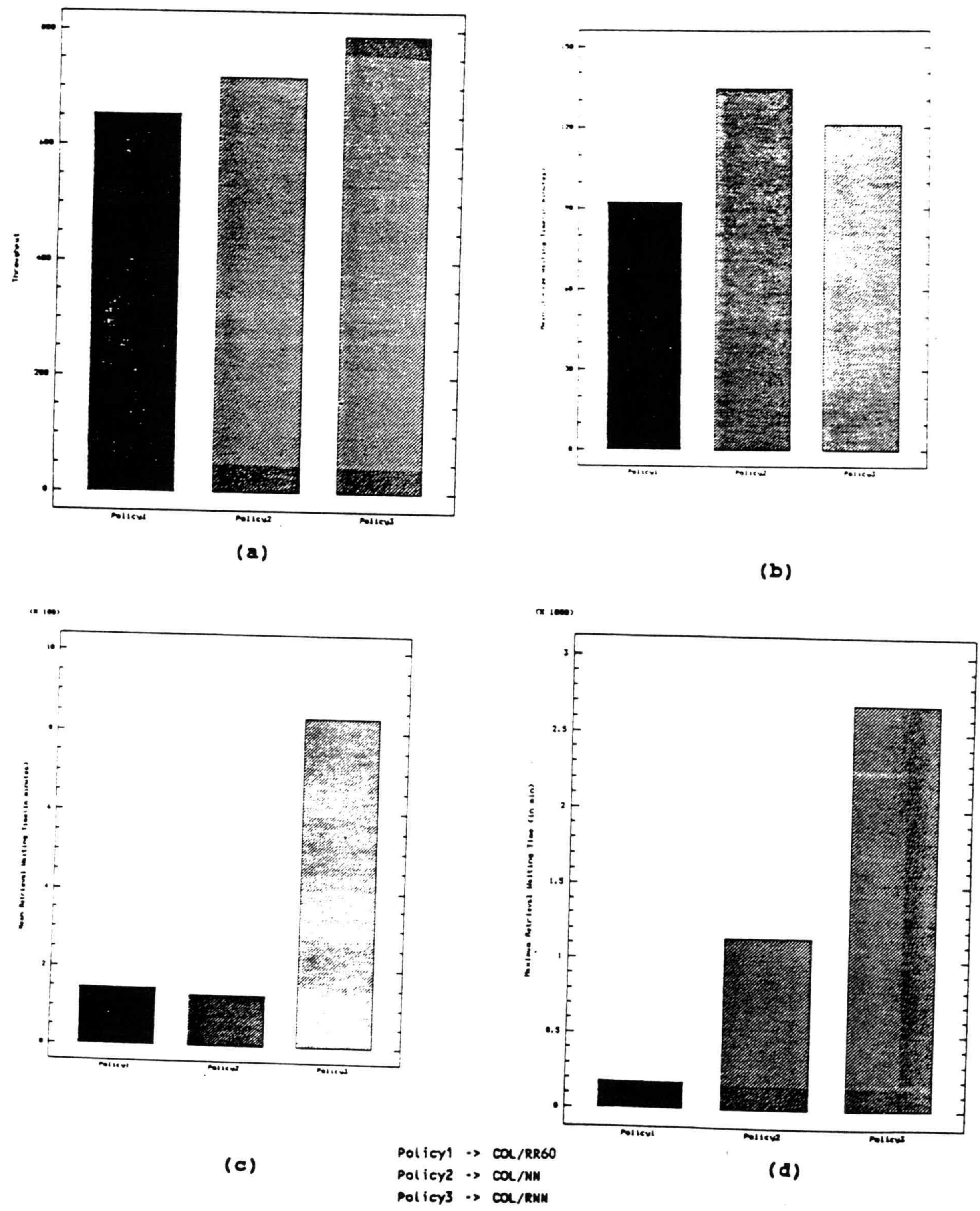


Figure 4.4.2: Comparison Across Scheduling Policies for Layout4b.

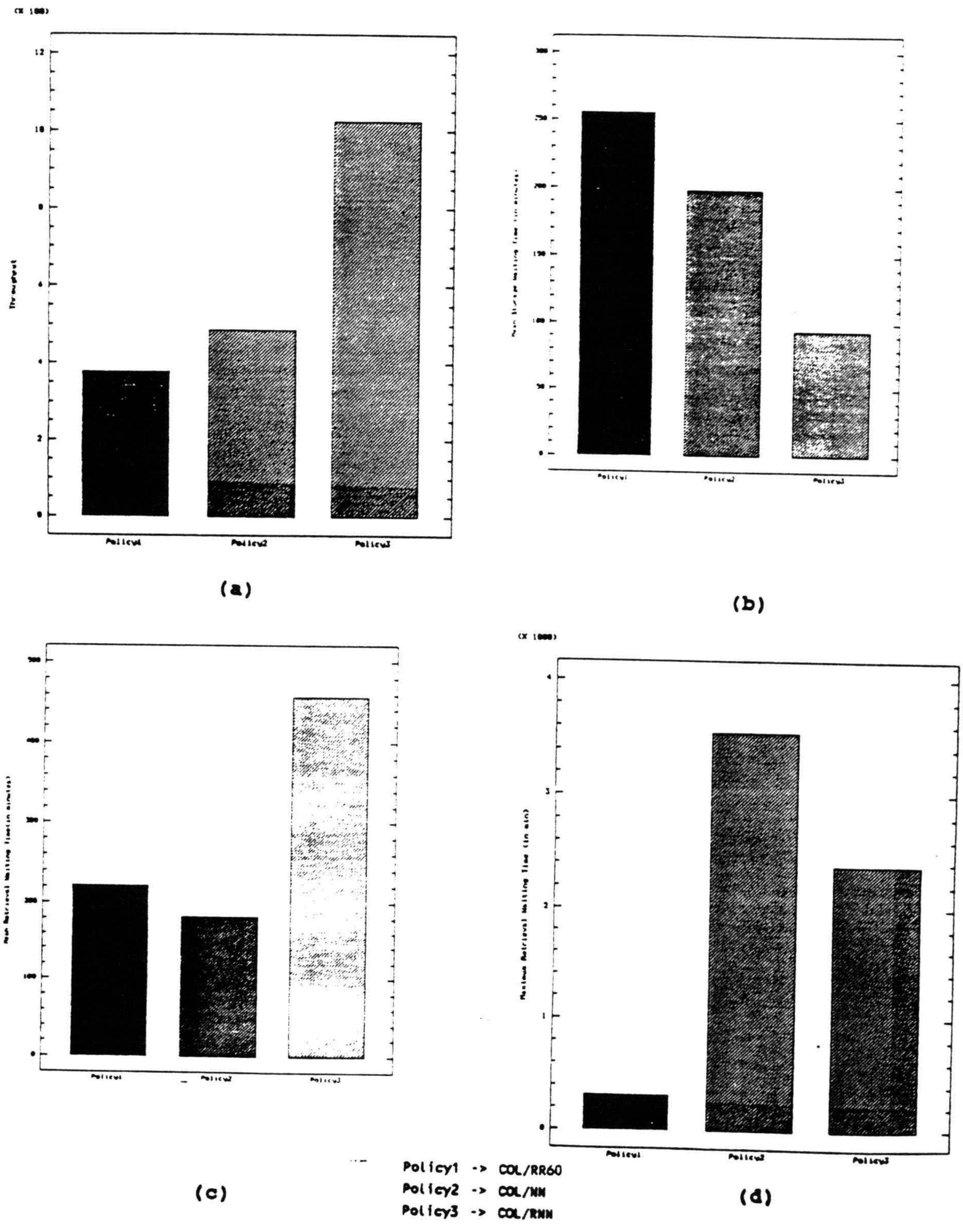


Figure 4.4.3: Comparison Across Scheduling Policies for Layout4c.

Throughput - The non-square rack arrangement for a single dock layout was simulated by using three different sets of rack dimensions. For all rack dimensions considered, the COL/RNN policy produced the best throughput result. From the analysis, it can be inferred that initially the throughput increased as the number of rows decreased and the number of columns increased(to keep the same number of openings). This behavior can be explained by considering the crane travel patterns. It has been assumed that the crane travels diagonally and the time taken by the crane to go from one location to the other is the maximum of the horizontal travel time(column) and the vertical travel time (row). By decreasing the number of rows, it was possible to reduce the crane travel time. However, decreasing rows resulted in increasing the number of columns, which had an effect of increasing the crane cycle time. For the non-square (10 x 10) rack arrangement, COL/RNN performed 48 percent and 68 percent better than the COL/NN and the COL/RR60 policies, respectively; for the same system, COL/NN performed 23 percent better than the COL/RR60. For the system with 4 x 25 rack dimensions, the COL/RNN produced 9 percent and 17 percent better throughput as compared to the COL/NN and COL/RR60. Under the same system the COL/NN performed 9 percent better than the COL/RR60. For the system with 2 x 50 rack dimensions, the COL/RNN produced 52 percent and 63 percent higher throughput than the COL/NN and the COL/RR60 rule. The COL/NN produced 22 percent higher throughput as against the COL/RR. The system with rack dimensions of 4 X 25 was found to be the best amongst the non square rack dimensions considered with the implementation of COL/RR60 and COL/RN. The COL/RNN generated the best results for the rack with 2 x 50 dimensions.

Mean Storage Waiting Times - From the non-square rack dimensions considered, the rack with 4 x 25 dimensions was found to be the best performer. For the 4 x 25 rack, COL/RR60 performed 32 percent and 24 percent better than COL/NN and COL/RNN, respectively.

Mean Retrieval Waiting Times - For the non-square rack dimensions, the least mean waiting time was obtained with 10 x 10 rack dimensions under the COL/NN policy.

Maximum Retrieval Waiting Times - COL/RNN produced the worst results for 4 x 25 rack dimensions. For 10 x 10 rack dimensions, COL/NN performed 21 percent and 86 percent worse than that of COL/RNN and COL/RR60, respectively. The waiting time was found to be 83 percent lower for COL/RR60 as compared to COL/RNN. With 4 x 25 rack dimensions, COL/RNN produced 58 percent and 93 percent higher waiting time as compared to COL/NN and COL/RR60. COL/RR60 resulted in 83 percent less waiting time as against COL/NN. With 2 x 50 rack dimensions, COL/NN resulted in the highest waiting time. The results indicate that the performance of COL/NN was 32 percent and 91 percent lower than COL/RNN and COL/RR60. The COL/RNN gave 87 percent higher waiting times as compared to COL/RR60. Hence, the layout with 4 x 25 rack dimensions produced the least maximum waiting times in two out of three scheduling policies.

Storage and Retrieval Rejects - The rack with 2 x 50 dimensions and COL/RNN scheduling policy resulted in the least number of storage rejects among the non square rack dimensions considered. COL/RNN produced the least number of storage rejects for all the rack dimensions while comparing all the scheduling policies. As a whole, the rack with 4 X 25 dimensions produced the least storage rejects in two out of three scheduling policies.

Among the non-square rack dimensions considered, the layout with 2 x 50 rack dimensions and COL/RNN scheduling policy produced the least number of retrieval rejects.

4.3 Comparison Across Layouts (Single-Dock)

The following section consists of two different parts. In the first part, the different single-dock layouts with different I/O point (dock) and rack arrangements are compared. In the second part, dual-dock layouts with different input-output relationships are compared. Multivariate Analysis of Variance (ANOVA) was performed on different sets of layouts to substantiate the inferences drawn from the analysis of graphical results. The ANOVA was based on two factors, each with two levels. The two factors were layouts and scheduling policies. The objective was to analyze the effect of these two independent factors on the performance measures.

4.3.1 Single Dock Layouts

4.3.1.1 Layout1 versus Layout2

In Layout1, the I/O point is located at one end of the aisle whereas for Layout2, the dock is located in the middle of the aisle. In both cases the rack was assumed to be square-in-time and the total number of locations was the same for both layouts. In layout2, the horizontal travel time to go to a certain location from the I/O point would be half the distance expected in Layout1. The vertical travel time will be the same for both layouts. The ANOVA results (Figure 4.5) show that the interaction between the two factors was significant for all performance measures at significant level of 5 percent, except for the maximum retrieval waiting times. This means that both layout configurations and the scheduling policies affect system performance.

Analysis of Variance for TH1.THRUPUT

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	687271.20	3	229090.40	237.580	.0000
TH1.FT_A_LVL	459298.13	1	459298.13	476.319	.0000
TH1.FT_B_LVL	227973.07	2	113986.53	118.211	.0000
2-FACTOR INTERACTIONS	49841.867	2	24920.933	25.844	.0000
TH1.FT_A_LTH1.FT_B_L	49841.867	2	24920.933	25.844	.0000
RESIDUAL	23142.400	24	964.26667		
TOTAL (CORR.)	760255.47	29			

0 missing values have been excluded.

(a)

Analysis of Variance for TH1.MEAN_W1_

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	13313.605	3	4437.8685	316.630	.0000
TH1.FT_A_LVL	9307.590	1	9307.5899	664.071	.0000
TH1.FT_B_LVL	4006.016	2	2003.0078	142.909	.0000
2-FACTOR INTERACTIONS	214.05902	2	107.02951	7.636	.0027
TH1.FT_A_LTH1.FT_B_L	214.05902	2	107.02951	7.636	.0027
RESIDUAL	336.38288	24	14.015953		
TOTAL (CORR.)	13864.047	29			

0 missing values have been excluded.

(b)

Analysis of Variance for TH1.MEAN_W2_W3

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	3303677.5	3	1101225.8	936.017	.0000
TH1.FT_A_LVL	123395.1	1	123395.1	104.883	.0000
TH1.FT_B_LVL	3180282.4	2	1590141.2	1000.000	.0000
2-FACTOR INTERACTIONS	138047.91	2	69023.956	58.669	.0000
TH1.FT_A_LTH1.FT_B_L	138047.91	2	69023.956	58.669	.0000
RESIDUAL	28236.041	24	1176.5017		
TOTAL (CORR.)	3469961.4	29			

0 missing values have been excluded.

(c)

Analysis of Variance for TH1.MAX_W2_W3_

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	23258177	3	7752726	22.344	.0000
TH1.FT_A_LVL	1523352	1	1523352	4.390	.0469
TH1.FT_B_LVL	21734826	2	10867413	31.321	.0000
2-FACTOR INTERACTIONS	1200803.8	2	600401.91	1.730	.1986
TH1.FT_A_LTH1.FT_B_L	1200803.8	2	600401.91	1.730	.1986
RESIDUAL	8327318.5	24	346971.60		
TOTAL (CORR.)	32786299	29			

0 missing values have been excluded.

(d)

Figure 4.5: ANOVA Results for Layout1 versus Layout2 Comparison.

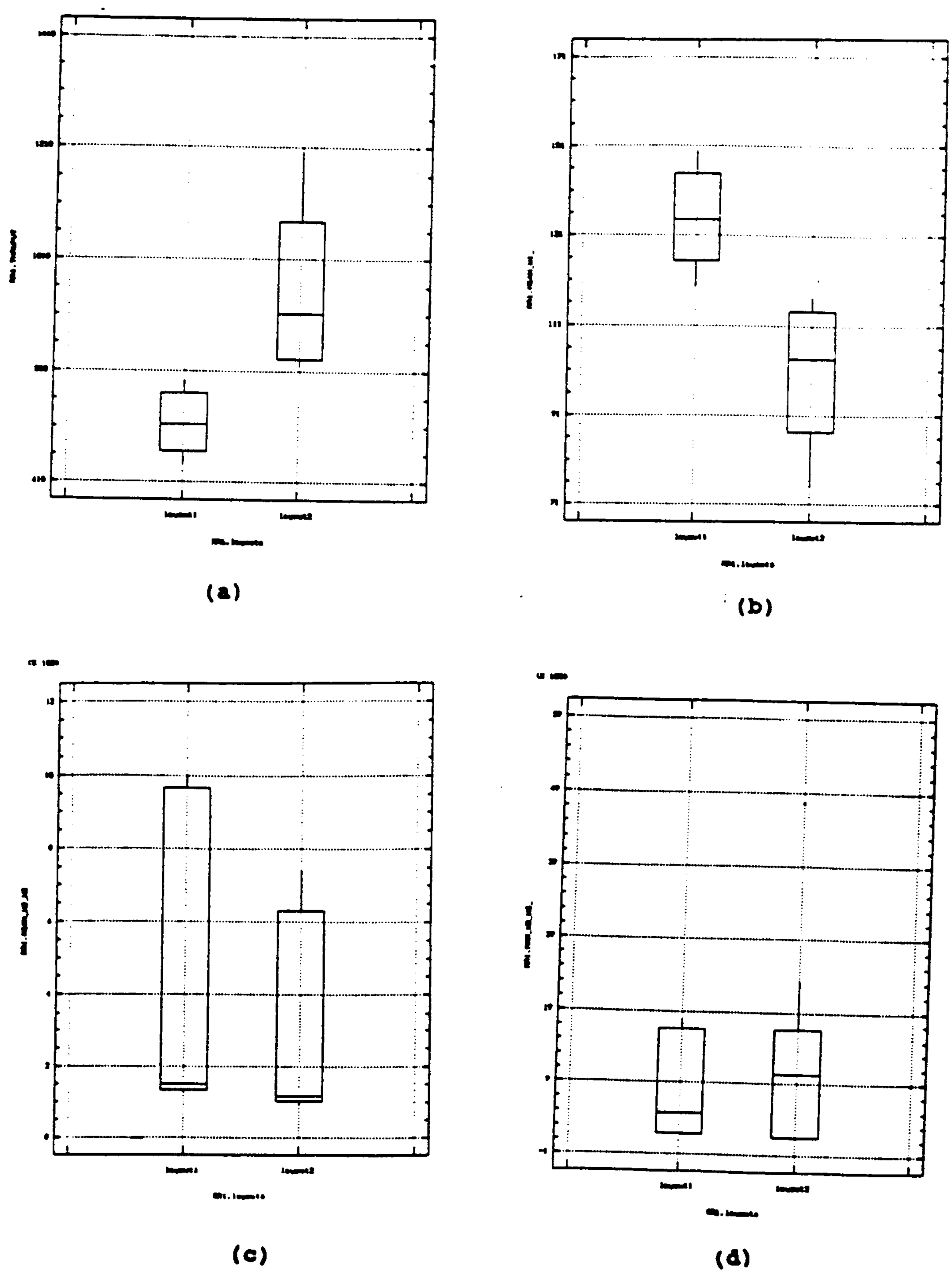
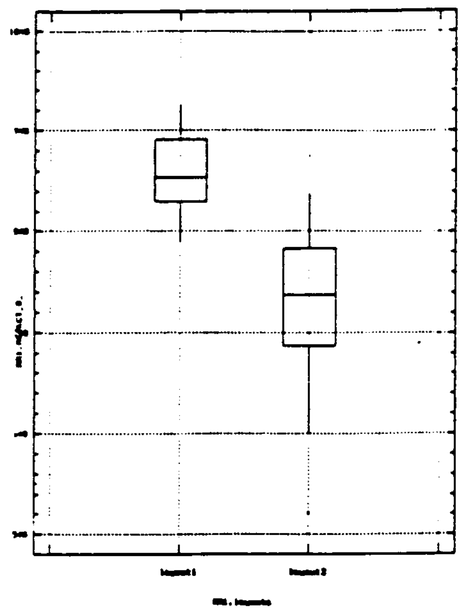
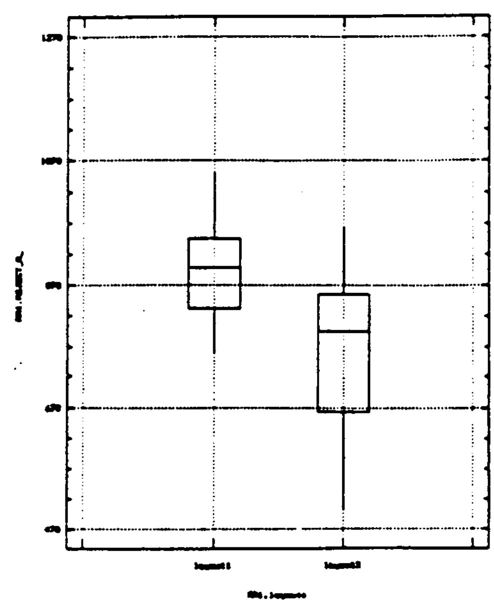


Figure 4.6: Box and Whisker Plots for Layout1 versus Layout2 Comparison.



(e)



(f)

Figure 4.6(Continued...): Box and Whisker Plots for Layout1 versus Layout2 Comparison.

Throughput - Due to the reduction in total travel time the dock at the aisle mid-point serves more requests than when the dock is located at the end of the aisle. Even though the horizontal crane travel time for Layout2 is half that of Layout2, the throughput increment was not doubled. This is because at times, the vertical travel distances are also used in computing the crane travel path. With reference to Figure 4.6(a), the throughput for Layout1 was observed to vary between 644 and 794, and between 820 and 1204 for Layout2. COL/RNN produced the best results for both layouts. The variation in throughput was higher in Layout2 as compared to Layout1. Overall, the throughput performance of Layout2 was significantly better than that of Layout1. The throughput for Layout2 exceeded that of Layout1 by 21, 22 and 32 percent than that of Layout1 while implementing COL/RR60, COL/NN and COL/RNN, respectively.

Mean Storage Waiting Times - The results obtained from the simulation runs for Layout1 and Layout2 are compared in the Figure 4.6(b). Due to increased travel distances for Layout1, the storage requests had to wait longer to be served as compared to Layout2. The minimum waiting time for Layout1 was higher than the maximum waiting time for Layout2. For Layout1 the mean storage waiting time varied between 120 and 150 minutes. The COL/RNN policy was found to be the best for both layouts, in terms of the least storage waiting times. For Layout2, it varied between 75 and 116 minutes. Layout2 produced 34.3, 23 and 22 percent less waiting time as compared to that of Layout1 under COL/RRN, COL/NN and COL/RR60, respectively.

Mean Retrieval Waiting Times - Figure 4.6(c) compares the mean retrieval waiting times results obtained for the two layouts. The variation in the mean waiting times for retrieval requests were found to be larger in Layout1 as compared to Layout2. This was primarily due to high waiting time encountered while implementing COL/RNN under Layout1 (caused by infinite queue length). The waiting time was considerably higher with COL/RNN for both layouts, and the difference in the retrieval waiting time between COL/RR60 and COL/NN was not very significant for the two layouts. It was observed that the mean retrieval waiting time varied between 127 minutes and 1002 minutes for Layout1 and between 95 minutes and 742 minutes for Layout2. For each layout, the best results were produced under COL/NN scheduling policy. Layout2 produced 24, 22 and 33 percent less waiting time compared to Layout1 under COL/NN, COL/RR60 and COL/RNN, respectively.

Maximum Retrieval Waiting Times - The COL/RR60 produced the least maximum waiting time for each of the layouts. The results have been plotted in the Figure 4.6(d). In COL/RR60 policy, a retrieval request waiting for more than 60 minutes had to be served. The presence of this constraint limited the maximum waiting time a request had to wait before being served. Under COL/NN and COL/RNN a retrieval request assigned a location far away from the I/O point might have to wait longer before being served, resulting in higher maximum waiting time. The maximum waiting time for Layout1 was found to vary between 179 minutes and 1810 minutes and between 151 minutes and 4755 minutes for Layout2. The whiskers in Box and Whisker plot extend to points which are within 1.5 times the interquartile range. When unusual values occur far away from the bulk of the data, they are plotted as separate points. An extreme value of 4754 minutes obtained with COL/RNN policy has been plotted as a separate point in figure 4.6(d). The graph shows that under COL/RR60, the difference between the maximum waiting times of Layout1 and Layout2 was small due to the 60 minute limit. The difference was higher under COL/NN and COL/RNN. Layout2 resulted in 15 percent less maximum waiting times under COL/RR60. However, for COL/NN and COL/RNN Layout1 resulted in 41 and 35 percent lower maximum waiting time as compared to Layout2. The ANOVA table in Figure 4.5(d) indicates that the interaction between the two factors is not significant. The main effects show that the scheduling policies have a greater effect on maximum retrieval time than does the layout configuration.

Storage and Retrieval Rejects - Due to the reduced crane travel time and increased throughput for Layout2, the number of rejects was lower than for Layout1 for all scheduling policies. These storage and retrieval rejects are plotted in Figures 4.6(e) and 4.6(f). The number of rejects was minimum under COL/RNN in both the layouts for both request types. The number of storage rejects varied between 829 and 967 for Layout1 as against 561 to 881 for Layout2. From this variation it is clear that the scheduling policies have a larger impact under Layout2 as far as the storage rejections are concerned. It was found that Layout2 rejected 10, 11 and 25 percent less storage requests under COL/RR60, COL/NN and COL/RNN scheduling policies, respectively, as compared to Layout1. The number of rejects for the retrieval requests varied between 768 and 1017 in Layout1 and between 501 and 963 in Layout2. Layout2 produced 9, 12 and 25 percent less rejects under COL/RR60, COL/NN and COL/RNN scheduling polices, respectively, as compared to Layout1.

4.3.1.2 Layout1 versus Layout3

In Layout1 (uniform rack arrangement) the storage and retrieval requests were assigned locations at random. There was no distinction between the item classes. In Layout3 (class-based rack arrangement), the storage rack was divided into two sections, each section responsible for a particular class of items (i.e., the items were also divided into two distinct classes). For both layouts, the dock was located at one end of the aisle. The ANOVA results show that the

Analysis of Variance for TH2.THRUPUT

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	1587164.7	3	529054.9	777.888	.0000
TH2.FT_A_LVL	1567738.8	1	1567738.8	1000.000	.0000
TH2.FT_B_LVL	19425.9	2	9712.9	14.281	.0001
2-FACTOR INTERACTIONS	40666.400	2	20333.200	29.897	.0000
TH2.FT_A_LTH2.FT_B_L	40666.400	2	20333.200	29.897	.0000
RESIDUAL	16322.800	24	680.11667		
TOTAL (CORR.)	1644153.9	29			

0 missing values have been excluded.

(a)

Analysis of Variance for TH2.MEAN_W1_

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	26513.366	3	8837.789	1000.000	.0000
TH2.FT_A_LVL	25701.811	1	25701.811	1000.000	.0000
TH2.FT_B_LVL	811.555	2	405.777	79.061	.0000
2-FACTOR INTERACTIONS	985.36861	2	492.68431	95.994	.0000
TH2.FT_A_LTH2.FT_B_L	985.36861	2	492.68431	95.994	.0000
RESIDUAL	123.17916	24	5.1324651		
TOTAL (CORR.)	27621.914	29			

0 missing values have been excluded.

(b)

Analysis of Variance for TH2.MEAN_W2_W3

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	2731081.7	3	910360.6	1000.000	.0000
TH2.FT_A_LVL	305983.5	1	305983.5	1000.000	.0000
TH2.FT_B_LVL	2425098.2	2	1212549.1	1000.000	.0000
2-FACTOR INTERACTIONS	287451.68	2	143725.84	513.090	.0000
TH2.FT_A_LTH2.FT_B_L	287451.68	2	143725.84	513.090	.0000
RESIDUAL	6722.8323	24	280.11801		
TOTAL (CORR.)	3025256.3	29			

0 missing values have been excluded.

(c)

Analysis of Variance for TH2.MAX_W2_W3_

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	8133022.9	3	2711007.6	39.635	.0000
TH2.FT_A_LVL	87140.6	1	87140.6	1.274	.2702
TH2.FT_B_LVL	8045882.4	2	4022941.2	58.816	.0000
2-FACTOR INTERACTIONS	6439781.3	2	3219890.6	47.075	.0000
TH2.FT_A_LTH2.FT_B_L	6439781.3	2	3219890.6	47.075	.0000
RESIDUAL	1641569.1	24	68398.713		
TOTAL (CORR.)	16214373	29			

0 missing values have been excluded.

(d)

Figure 4.7: ANOVA Results for Layout1 versus Layout3 Comparison.

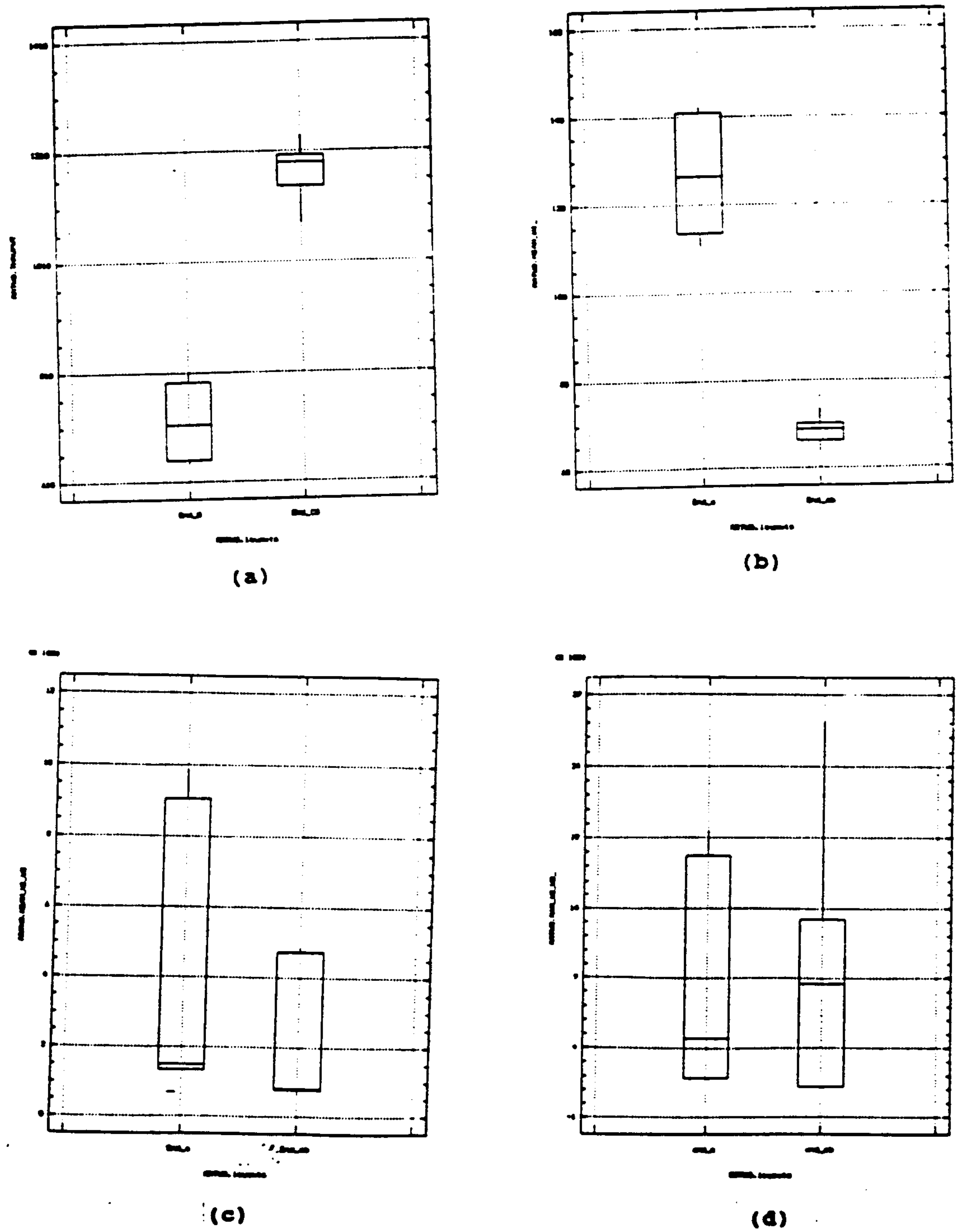
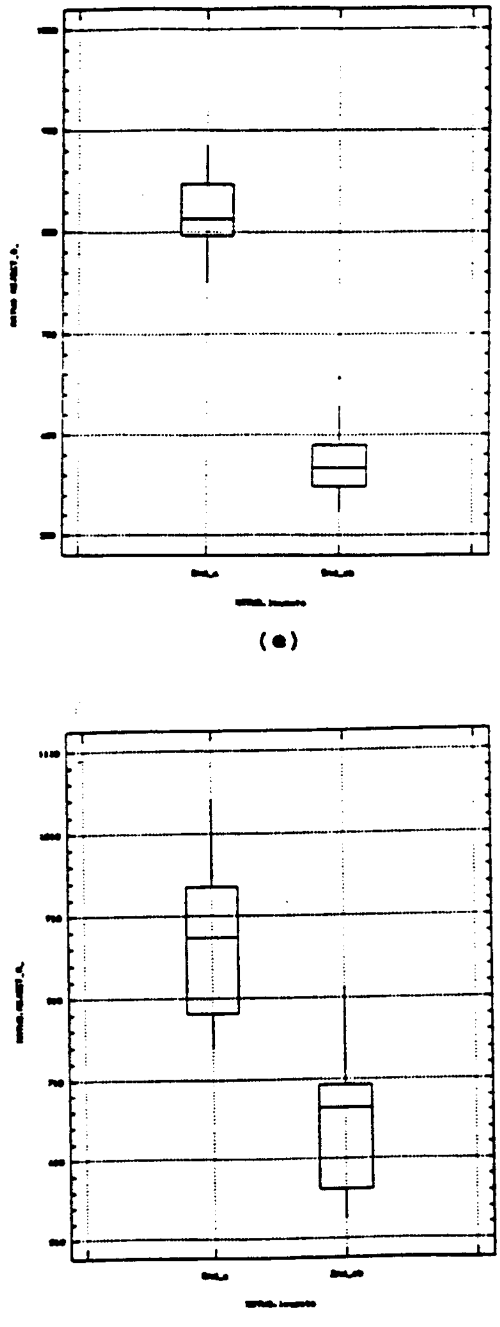


Figure 4.8: Box and Whisker Plots for Layout1 versus Layout3 Comparison.



(e)

(f)

Figure 4.8 (Continued....): Box and Whisker Plots for Layout1 versus Layout3 Comparison.

interaction between the two factors is highly significant for all performance measures at significance level of 5 percent. Hence, it is inferred that the combination of the rack arrangement and the scheduling policies do affect the performance measures.

Throughput - In Layout1, COL/RNN policy served the maximum number of requests(Figure 4.8(a)). However, in Layout3 the COL/RR60 policy maximized throughput. The throughput was considerably higher in Layout3 as compared to Layout1. The throughput varied between 644 and 810 for Layout1 as compared to between 1082 and 1238 for Layout3. The increase in throughput is due to the reduced cycle time in the class-based arrangement. Locating class I items close to the dock produced smaller crane travel time; as the class I items were expected to be stored and retrieved 80 percent of the time, the throughput goes up substantially. Layout3 produced 46, 37 and 33 percent higher throughput under COL/RR60, COL/NN and COL/RNN policies, respectively as compared to Layout1.

Mean Storage Waiting Time - The mean waiting time for Layouts 1 and 3 are compared in Figure 4.8(b). The mean waiting time was significantly higher in Layout1. Also, The variation in the mean waiting time was comparatively higher in Layout1. The mean waiting time varied between 118 and 150 minutes for Layout1 as against between 72 and 82 minutes in Layout3. Reduction in the crane cycle time produced lower waiting time for Layout3. Layout3 performed 50, 41 and 38 percent better under COL/RR60, COL/NN and COL/RNN policies, respectively, as compared to Layout1. COL/RNN resulted in the least waiting time for Layout1. For Layout3, the least waiting time was obtained through the application of COL/RR60.

Mean Retrieval Waiting Times - Figure 4.8(c) represents the mean retrieval waiting time comparison between the two layouts. The COL/NN scheduling policy produced the least mean retrieval waiting time for both layouts. The mean retrieval waiting time was considerably higher for COL/RNN for both layouts. This is due to the increased queue size in the implementation of COL/RNN forcing more retrieval requests to wait for longer duration. Due to higher arrival rates the retrieval queue could hardly be expected to operate below the queue size threshold of ten requests. Hence, it was rare to implement the FCFS policy for the retrieval requests. Layout3 always performed better than Layout1. Statistics indicate that the waiting time varied between 132 and 989 minutes for Layout1 as compared to between 76 to 492 minutes for Layout3. Layout3 generated 47, 43 and 50 percent less waiting time in COL/RR60, COL/NN and COL/RNN policies respectively than Layout1.

<u>Maximum Retrieval Waiting Times</u> - The maximum waiting time for Layouts 1 and 3 have been compared in Figure 4.8(d). The observations show that the two layouts yielded the least maximum waiting time under COL/RR60 policy. This is expected because of the 60 minutes waiting time limit. However, the highest waiting time was recorded under COL/RNN policy for Layout1, while the highest waiting time for Layout3 resulted under COL/NN policy. The waiting time varied between 179 and 1810 minutes for Layout1, whereas for Layout3 it varied between 112 and 2707 minutes. It was also observed that COL/NN produced comparatively less waiting time for the Layout1. Layout1 produced 34 and 52 percent higher waiting time under COL/RR60 and COL/RNN policies, respectively as compared to Layout3. Layout1 produced 73 percent less waiting time under COL/NN policy as compared to Layout3.

<u>Storage and Retrieval Rejects</u> - The storage and retrieval rejects for Layout 1 and 3 have been compared in Figures 4.8(e) and 4.8(f). Due to increased throughput, both storage and retrieval rejects were significantly smaller for all the

scheduling policies under Layout3. The number of storage rejects varied between 831 and 964 for Layout1 as compared to 604 to 708 in Layout3. Layout3 rejected 34, 25, and 24 percent, less rejects under COL/RR60, COL/NN and COL/RNN policies, respectively as compared to Layout1. The resultant increase in the throughput in Layout3 also had a considerable impact on the number of retrieval rejects. Statistics indicate that Layout3 outperformed Layout1 for all the scheduling policies. The number of retrieval rejects varied between 751 and 1051 in Layout1 as compared to 536 to 823 in Layout3. Layout3 produced 31, 21, and 26 percent less rejects under COL/RR60, COL/NN and COL/RNN policies respectively as compared to Layout1.

4.3.1.3 Layout1 versus Layouts 4a,4b and 4c

This section compares the end-of-aisle square rack arrangement with the non-square rack arrangements. On the basis of the analysis made in the comparison across layouts, it can be concluded that, the non-square rack with the 4 x 25 dimensions outweighed the other two rack dimensions for four out of six performance measures in two out of three scheduling policies.

Throughput - Of the three non-square layouts, Layout4b produced the maximum throughput. The throughput results indicate that Layout1 and Layout4b performed quite close to each other under COL/RR60 and COL/NN. Layout4b produced only 0.12 percent higher throughput than that of Layout1. For COL/NN policy, Layout1 served 0.83 percent more request than that of Layout4b. On the other hand, Layout4b generated 2 percent better results than Layout1 for COL/RNN. The throughput in Layout1 varied between 644 and 1188 as compared to 642 to 830 in Layout4b. Figure 4.9 shows the ANOVA for Layout1 versus Layout4b (the best of non-square arrangements). From the ANOVA results in table 4.9(a), it is

Analysis of Variance for TH4.THRUPUT

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	81544.400	3	27181.467	68.698	.0000
TH4.FT_A_LVL	97.200	1	97.200	.246	.6299
TH4.FT_B_LVL	81447.200	2	40723.600	102.924	.0000
2-FACTOR INTERACTIONS	634.40000	2	317.20000	.802	.4602
TH4.FT_A_LTH4.FT_B_L	634.40000	2	317.20000	.802	.4602
RESIDUAL	9496.0000	24	395.66667		
TOTAL (CORR.)	91674.800	29			

0 missing values have been excluded.

(a)

Analysis of Variance for TH4.MEAN_W1_

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	3755.5821	3	1251.8607	57.315	.0000
TH4.FT_A_LVL	2704.0811	1	2704.0811	123.803	.0000
TH4.FT_B_LVL	1051.5010	2	525.7505	24.071	.0000
2-FACTOR INTERACTIONS	4902.0958	2	2451.0479	112.218	.0000
TH4.FT_A_LTH4.FT_B_L	4902.0958	2	2451.0479	112.218	.0000
RESIDUAL	524.20516	24	21.841882		
TOTAL (CORR.)	9181.8830	29			

0 missing values have been excluded.

(b)

Analysis of Variance for TH4.MEAN_W2_W3

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	4522617.9	3	1507539.3	1000.000	.0000
TH4.FT_A_LVL	423.2	1	423.2	1.056	.3143
TH4.FT_B_LVL	4522194.7	2	2261097.4	1000.000	.0000
2-FACTOR INTERACTIONS	801.80429	2	400.90214	1.001	.3824
TH4.FT_A_LTH4.FT_B_L	801.80429	2	400.90214	1.001	.3824
RESIDUAL	9614.1305	24	400.58877		
TOTAL (CORR.)	4533033.8	29			

0 missing values have been excluded.

(c)

Analysis of Variance for TH4.MAX_W2_W3_

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	23100790	3	7700263	73.265	.0000
TH4.FT_A_LVL	1839504	1	1839504	17.502	.0003
TH4.FT_B_LVL	21261286	2	10630643	101.147	.0000
2-FACTOR INTERACTIONS	1141117.4	2	570558.69	5.429	.0114
TH4.FT_A_LTH4.FT_B_L	1141117.4	2	570558.69	5.429	.0114
RESIDUAL	2522433.0	24	105101.38		
TOTAL (CORR.)	26764340	29			

0 missing values have been excluded.

(d)

Figure 4.9: ANOVA Results for Layout1 versus Layout4b Comparison.

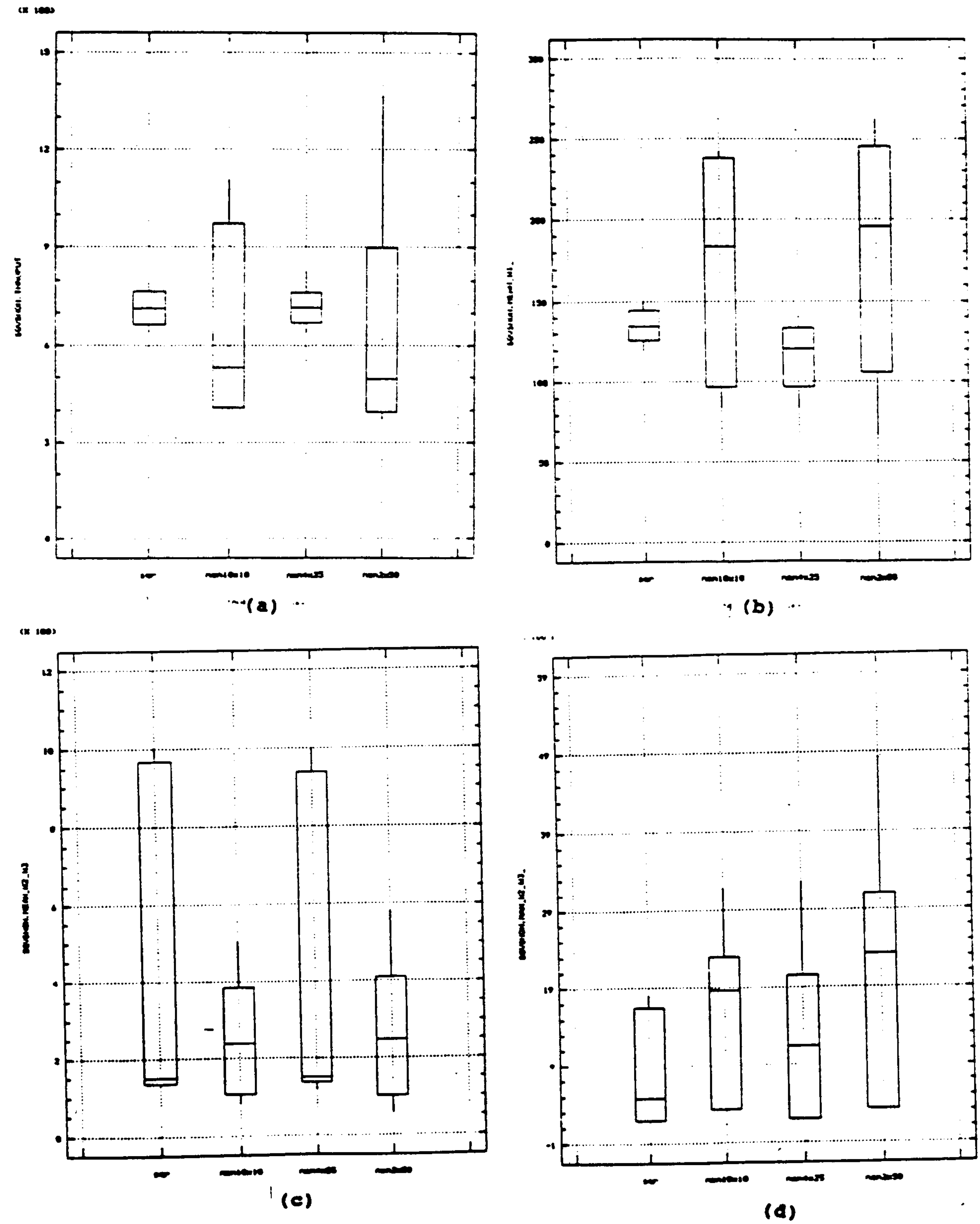
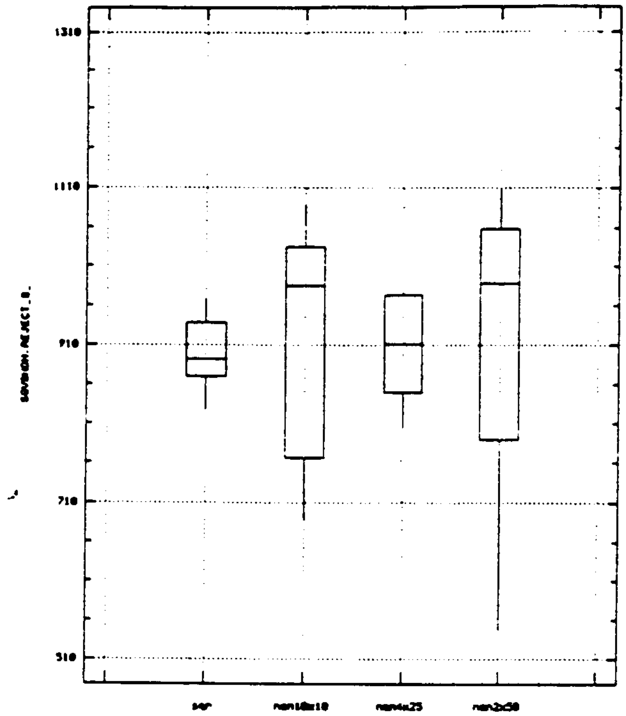
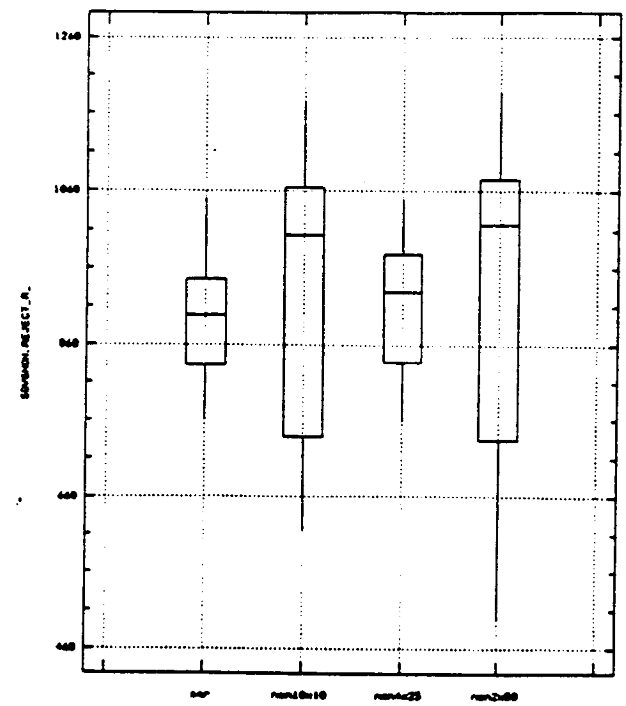


Figure 4.10: Box and Whsiker Plots for Layout1 versus Layout4b Comparison.



(e)



(f)

Figure 4.10 (Continued..): Box and Whisker Plots for Layout1 versus Layout4b Comparison.

clear that the interaction between the two factors is not significant. Thus, analysis of the main effects becomes imperative. From the ANOVA table it can be concluded that the throughput primarily appears to depend only on the scheduling policies.

Mean Storage Waiting Times - Layout4b was found to perform better in two of three scheduling policies as compared to Layout1. Under COL/RR60 and COL/RNN policies, Layout4b produced 37 and 3 percent less waiting time for the storage requests. Under the COL/NN scheduling policy, both the layouts produced fairly close results. The waiting time in Layout1 varied between 119 and 150 minutes as compared to between 83 to 135 minutes in Layout4b. The ANOVA results in table 4.9(b) indicate that the interaction between the two factors significantly affects the mean storage waiting time.

Mean Retrieval Waiting Times - (Figure 4.10(c)) In COL/RR60 and COL/NN scheduling policies Layout1 and Layout4b produced identical average waiting times for the retrieval requests. With the COL/RNN policy, Layout4b produced 14 percent less waiting times as compared to that of Layout1. Layout4b was slightly worse than that of Layout1. The mean waiting time in Layout1 varied between 126 and 1003 minutes as compared to 117 to 1000 minutes in Layout4b.

Maximum Retrieval Waiting Times - (Figure 4.10(d)) Layout1 performed better than Layout4b for all the scheduling policies. Under COL/RR60 policy both the layouts generated very close maximum waiting times for the retrieval requests. The results indicate that Layout1 produced 0.17, 47 and 35 percent less maximum waiting time under COL/RR60, COL/NN and COL/RNN scheduling policies, respectively, as compared to that in Layout4b. The waiting time varied between 179 and 1810 minutes in Layout1 as against 180 and 3200 minutes in Layout4b.

clear that the interaction between the two factors is not significant. Thus, analysis of the main effects becomes imperative. From the ANOVA table it can be concluded that the throughput primarily appears to depend only on the scheduling policies.

Mean Storage Waiting Times - Layout4b was found to perform better in two of three scheduling policies as compared to Layout1. Under COL/RR60 and COL/RNN policies, Layout4b produced 37 and 3 percent less waiting time for the storage requests. Under the COL/NN scheduling policy, both the layouts produced fairly close results. The waiting time in Layout1 varied between 119 and 150 minutes as compared to between 83 to 135 minutes in Layout4b. The ANOVA results in table 4.9(b) indicate that the interaction between the two factors significantly affects the mean storage waiting time.

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Maximum Retrieval Waiting Times - (Figure 4.10(d)) Layout1 performed better than Layout4b for all the scheduling policies. Under COL/RR60 policy both the layouts generated very close maximum waiting times for the retrieval requests. The results indicate that Layout1 produced 0.17, 47 and 35 percent less maximum waiting time under COL/RR60, COL/NN and COL/RNN scheduling policies, respectively, as compared to that in Layout4b. The waiting time varied between 179 and 1810 minutes in Layout1 as against 180 and 3200 minutes in Layout4b.

Storage and Retrieval Rejects (Figure 4.10(e,f))- The results showed that Layout1 produced less storage rejects under two of three scheduling policies as compared to that of Layout4b. Layout1 rejected 0.57 and 5 percent less rejects under COL/RR60 and COL/NN policies as compared to that of Layout4b. Under COL/RNN policy, Layout4b resulted in 3 percent less storage rejects as compared to that of Layout1. In Layout1, the storage rejects varied between 829 and 967 as compared to 805 to 978 in Layout4b. For retrievals, Layout1 produced 2, 5 and 1 percent less rejects under COL/RR60, COL/NN and COL/RNN scheduling policies as compared to that of Layout4b. The number of retrieval rejects varied between 762 and 1051 in Layout1, and between 759 and 1051 in Layout4b.

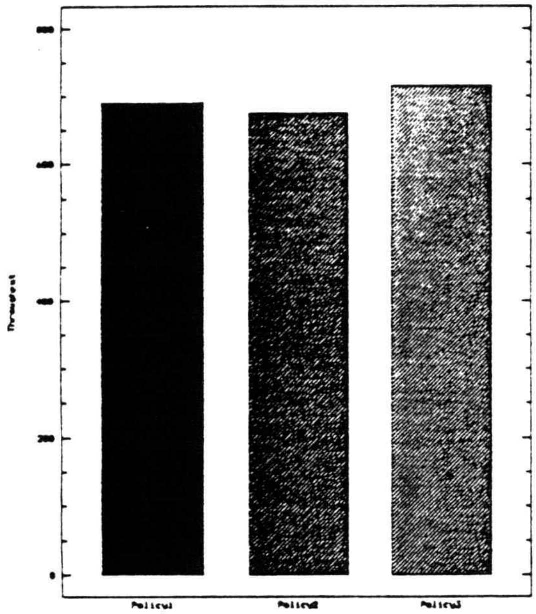
4.4 Comparison Across Schedules (Dual-Dock)

4.4.1 Layout5

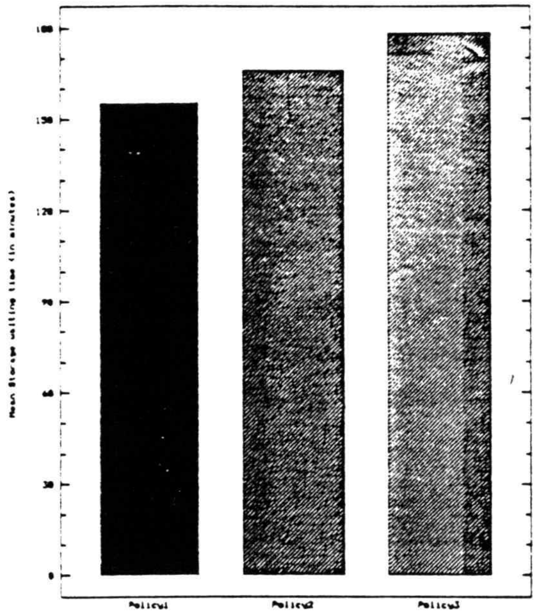
Figure 4.11 shows the four basic performance measures for the Two-Ends-of-Aisle dual-dock layout with the hybrid arrangement.

Throughput - Figure 4.11(a) shows that there was not much difference among the throughput generated by the three scheduling policies. COL/RNN produced the highest throughput of the three scheduling policies. COL/RNN produced 6 and 3 percent higher throughput as compared to COL/NN and COL/RR60, respectively. The throughput for COL/RR60 was about 3 percent higher than COL/NN.

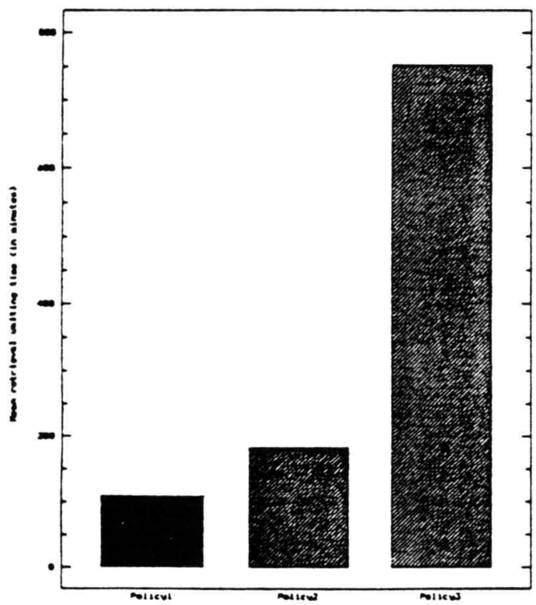
Mean storage Waiting Times - The storage waiting times were the least under COL/RR60. COL/RR60 produced 15 and 7 percent lower waiting times as compared to COL/RNN and COL/NN, respectively. COL/RNN produced 7 percent lower waiting times as compared to COL/NN.



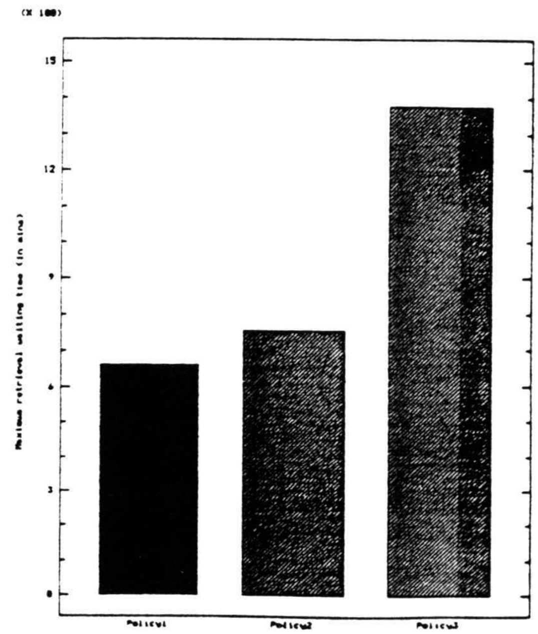
(a)



(b)



(c)



(d)

Policy1 -> COL/RR60
Policy2 -> COL/NN
Policy3 -> COL/RNN

Figure 4.11: Comparison Across Scheduling Policies for Layout5.

Mean Retrieval Waiting Times - It is not compatible to compare the retrieval waiting times for COL/RNN with COL/NN and COL/RR60 due to difference in the queue size. However, for COL/NN, the waiting times were 40 percent higher than COL/RR60.

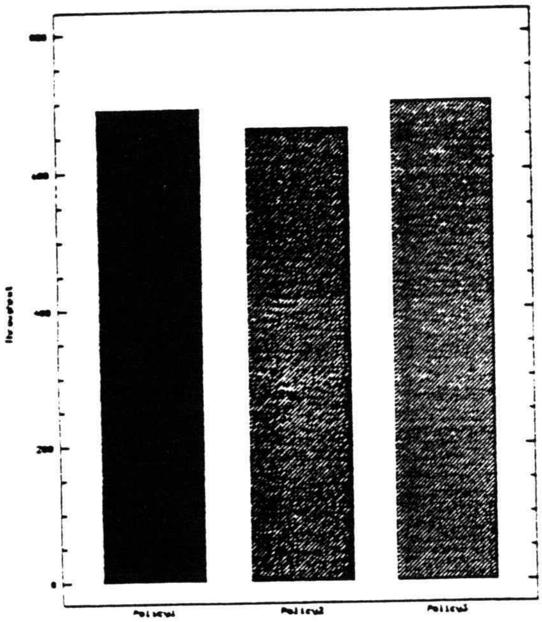
Maximum Retrieval Waiting Times - Figure 4.11(d) shows that COL/RR60 resulted in the least maximum waiting times. The reasons for COL/RR60 producing the least waiting time are similar to those discussed for the single-dock layouts. COL/RR60 produced 12 percent lower waiting times as compared to COL/NN. Due to increased queue size COL/RNN resulted in the worst waiting times.

Storage and Retrieval Rejects - COL/RNN produced the least number of storage rejects due to reduced cycle time. COL/RNN resulted in 1 percent and 3 percent lower storage rejects as compared to COL/NN and COL/RR60, respectively. COL/NN produced 2 percent higher storage rejects as compared to COL/RR60.

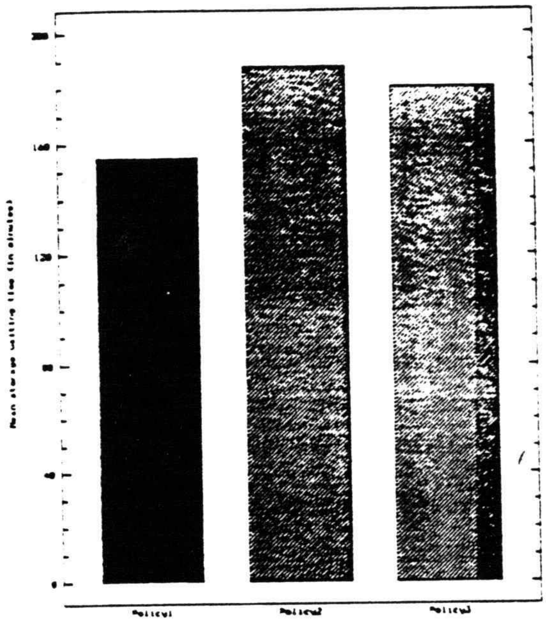
COL/RNN produced the least number of retrieval rejects due to larger queue size (as compared to COL/RR60 and COL/NN) which allowed more retrieval requests to wait in the queue before service. COL/RNN produced 4 percent and 8 percent less retrieval rejects as compared to COL/RR60 and COL/NN. COL/RR60 produced about 5 percent less retrieval rejects as compared to COL/NN.

4.4.2 Layout6

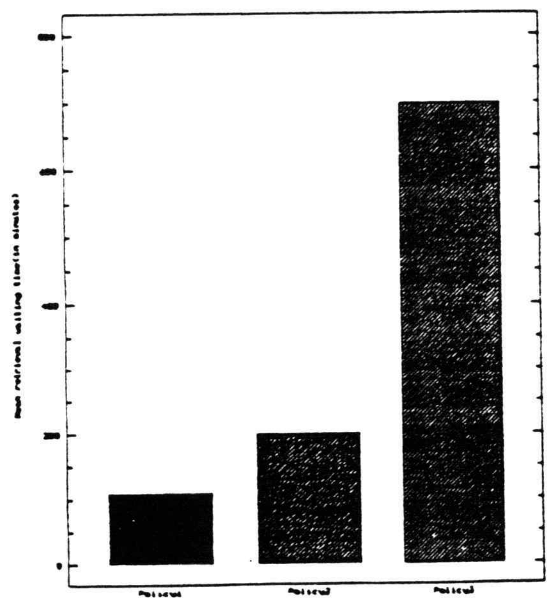
The performance measures for Layout6 have been plotted in Figure 4.12.



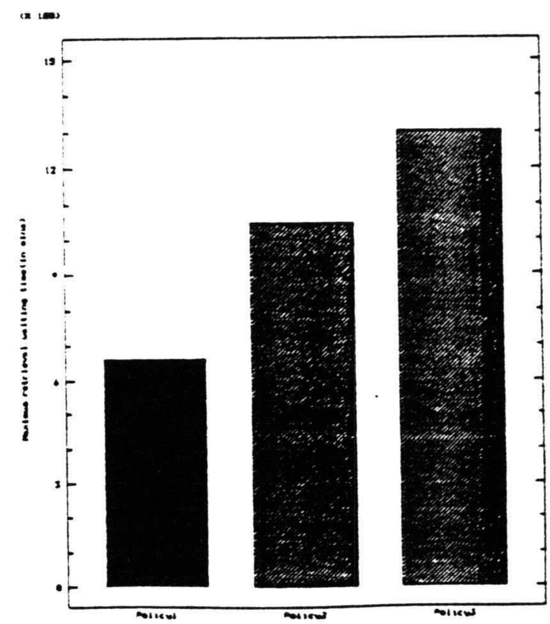
(a)



(b)



(c)



(d)

Policy1 -> COL/RR60
Policy2 -> COL/NN
Policy3 -> COL/RNN

Figure 4.12: Comparison Across Scheduling Policies for Layout6.

Throughput - COL/RNN produced the highest throughput for Layout6. There was not much of a difference between COL/RR60 and COL/RNN. However, throughput generated by COL/NN was approximately 4 percent and 5 percent lower than COL/RR60 and COL/RNN, respectively.

Mean Storage Waiting Times - COL/NN produced the maximum storage waiting times. COL/NN produced 17 percent and 4 percent higher storage waiting times as compared to COL/RR60 and COL/RNN. COL/RNN produced 14 percent higher storage waiting times as compared to COL/RR60.

Mean Retrieval Waiting Times - Due to increased queue size, COL/RNN produced the maximum waiting times. COL/RNN produced 5 percent and 71 percent higher retrieval waiting times as compared to COL/RR60 and COL/NN. COL/NN produced 69 percent lower retrieval waiting times as compared to COL/RR60.

Maximum Retrieval Waiting Times - COL/RNN performed 49 percent and 20 percent worse than COL/RR60 and COL/NN. COL/NN resulted in approximately 37 percent higher maximum retrieval waiting times as compared to COL/RR60.

Storage and Retrieval Rejects - COL/RR60 resulted in the least number of storage rejects. For COL/RR60, the retrieval rejects were 4 percent and 6 percent lower as compared to COL/RNN and COL/NN. For COL/RNN the storage rejects were approximately 2 percent lower than COL/NN.

The retrieval rejects were the least under COL/RNN. COL/RNN produced approximately 2 percent and 10 percent less rejects as compared to COL/RR60 and COL/RNN. COL/NN produced approximately 8 percent higher retrieval rejects as compared to COL/RR60.

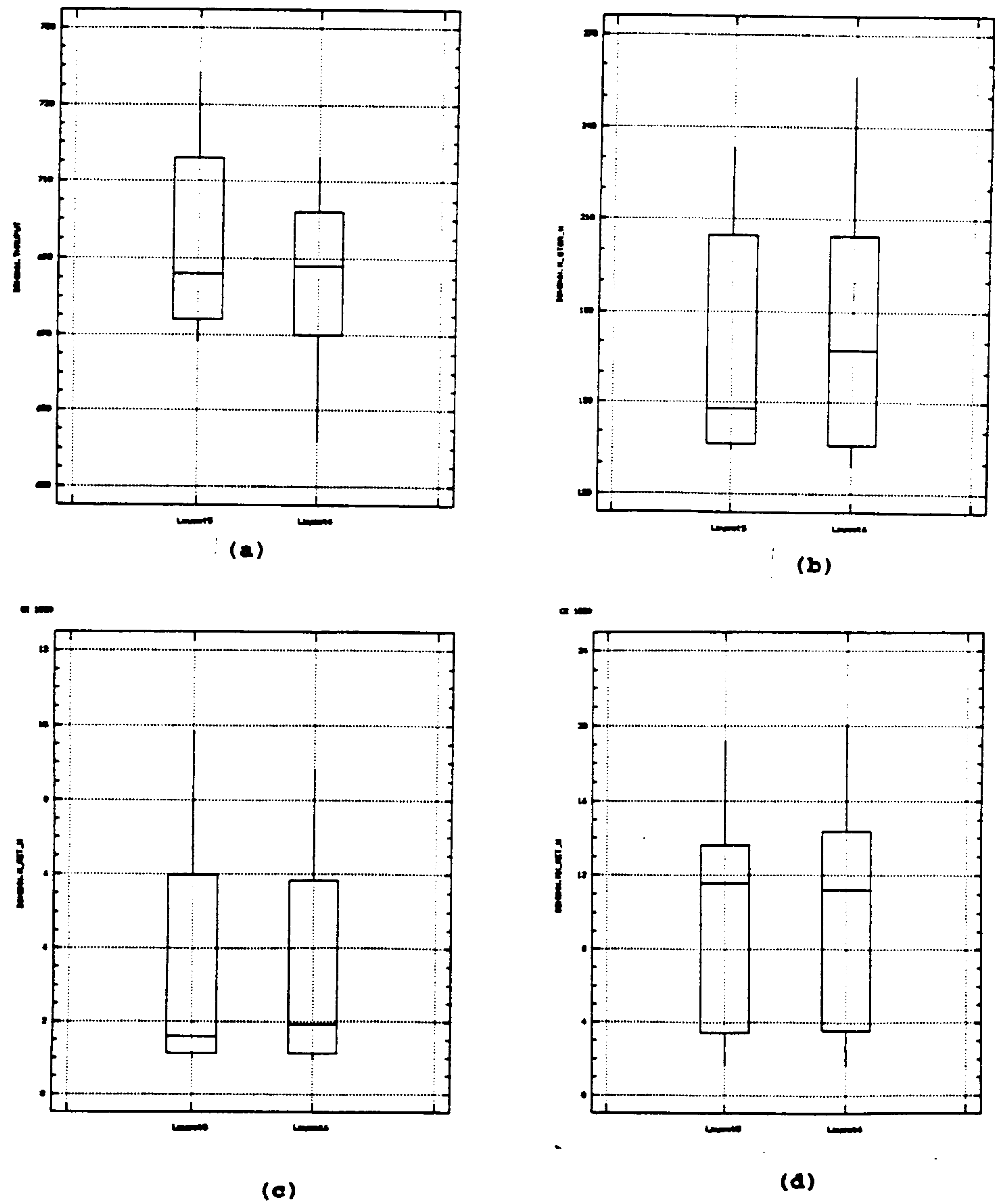
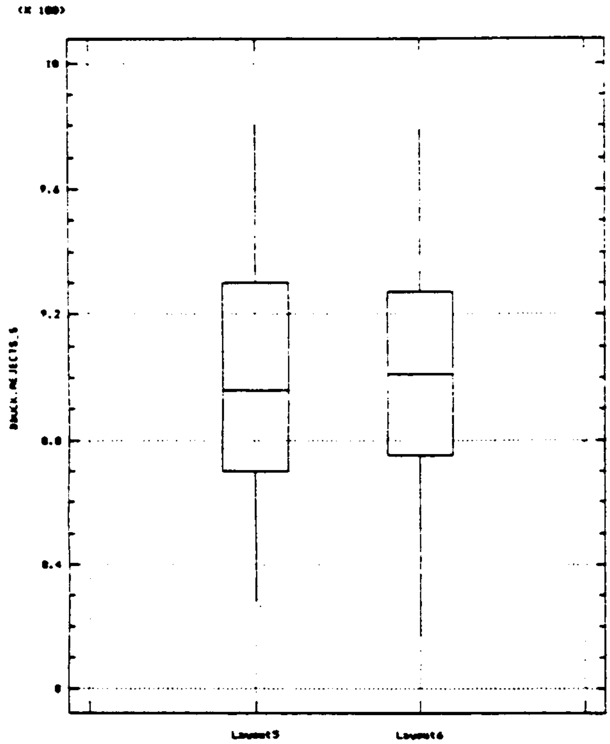
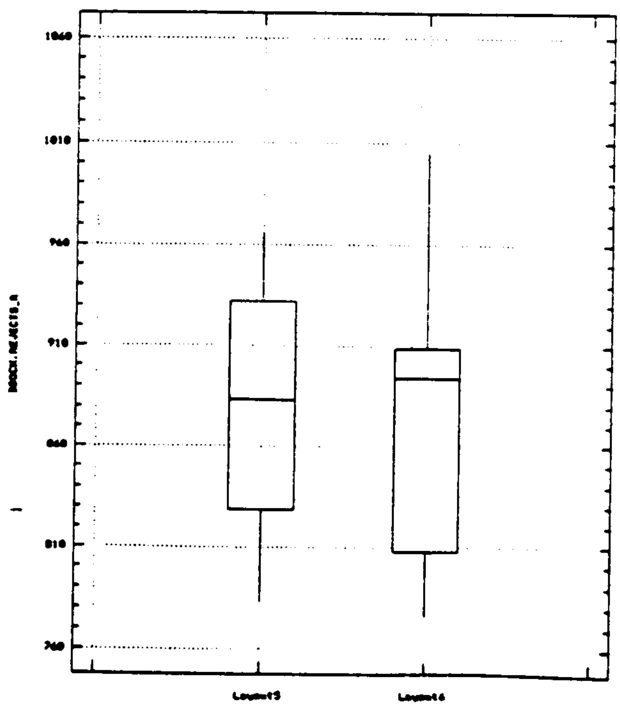


Figure 4.13: Box and Whisker Plots for Layout5 versus Layout6 Comparison.
(Arrival Rate = EX(8))



(e)



(f)

Figure 4.13 (Continued..): Box and Whisker Plots for Layout5 versus Layout6 Comparison. (Arrival Rate = EX(8))

Analysis of Variance for DDHBXW.THRUPUT

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	8157.2000	3	2719.0667	11.342	.0001
DDHBXW.FACTOR_A	634.8000	1	634.8000	2.648	.1167
DDHBXW.FACTOR_B	7522.4000	2	3761.2000	15.689	.0000
2-FACTOR INTERACTIONS	327.20000	2	163.60000	.682	.5149
DDHBXW.FACDDHBXW.FAC	327.20000	2	163.60000	.682	.5149
RESIDUAL	5753.6000	24	239.73333		
TOTAL (CORR.)	14238.000	29			

0 missing values have been excluded.

(a)

Analysis of Variance for DDHBXW.M_STOR_W

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	4084.6943	3	1361.5648	.827	.4919
DDHBXW.FACTOR_A	494.3050	1	494.3050	.300	.5946
DDHBXW.FACTOR_B	3590.3893	2	1795.1946	1.091	.3521
2-FACTOR INTERACTIONS	739.33332	2	369.66666	.225	.8005
DDHBXW.FACDDHBXW.FAC	739.33332	2	369.66666	.225	.8005
RESIDUAL	39505.080	24	1646.0450		
TOTAL (CORR.)	44329.108	29			

0 missing values have been excluded.

(b)

Analysis of Variance for DDHBXW.M_RET_W

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	2248351.2	3	749450.4	76.111	.0000
DDHBXW.FACTOR_A	1186.0	1	1186.0	.120	.7352
DDHBXW.FACTOR_B	2247165.2	2	1123582.6	114.106	.0000
2-FACTOR INTERACTIONS	7203.7035	2	3601.8518	.366	.6975
DDHBXW.FACDDHBXW.FAC	7203.7035	2	3601.8518	.366	.6975
RESIDUAL	236323.50	24	9846.8124		
TOTAL (CORR.)	2491878.4	29			

0 missing values have been excluded.

(c)

Analysis of Variance for DDHBXW.MX_RET_W

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	2419652.4	3	806550.8	2.945	.0533
DDHBXW.FACTOR_A	40214.3	1	40214.3	.147	.7090
DDHBXW.FACTOR_B	2379438.0	2	1189719.0	4.344	.0245
2-FACTOR INTERACTIONS	185260.84	2	92630.422	.338	.7164
DDHBXW.FACDDHBXW.FAC	185260.84	2	92630.422	.338	.7164
RESIDUAL	6572670.4	24	273861.27		
TOTAL (CORR.)	9177583.6	29			

0 missing values have been excluded

(d)

Figure 4.14: ANOVA Results for Layout5 versus Layout6 Comparison (Arrival Rate = EX(8)).

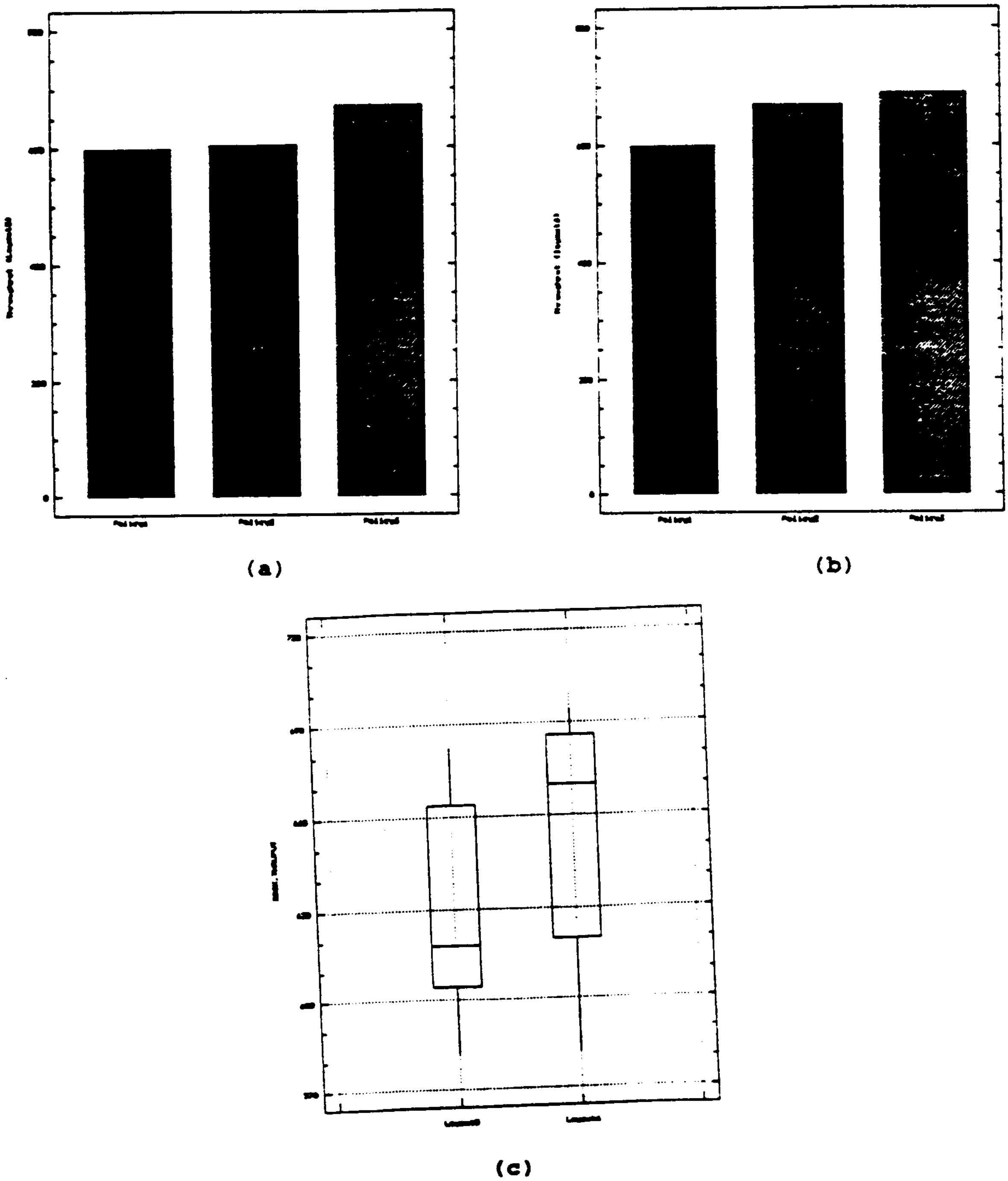


Figure 4.15: ANOVA Results for Layout5 versus Layout6 Comparison (Arrival Rate = EX(16)).

Analysis of Variance for DDOK.THRUPUT

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	23564.619	4	5891.1548	39.022	.0000
DDOK.FACTOR_A	3059.286	2	1529.6429	10.132	.0032
DDOK.FACTOR_B	18278.119	2	9139.0595	60.536	.0000
2-FACTOR INTERACTIONS	3328.7143	2	1664.3571	11.024	.0024
DDOK.FACTODDOK.FACTO	3328.7143	2	1664.3571	11.024	.0024
RESIDUAL	1660.6667	11	150.96970		
TOTAL (CORR.)	28554.000	17			

0 missing values have been excluded.

Figure 4.16: ANOVA Results for Layout5 versus Layout6 Comparison. (Arrival Rate = EX(16))

4.5 Comparison Across Layouts (Dual-Dock)

4.5.1. Layout5 versus Layout6

In Layout5, the crane can handle requests from either department, irrespective of the crane's location, whereas in Layout6, each dock is dedicated to one specific department. Both layouts generated very close results, with Layout5 being slightly better than Layout6, when the arrival rate was EX(8) for both storage and retrieval requests (Figure 4.13). The performance of both layouts was found to be identical under COL/RR60 scheduling policies. However, when the inter arrival time was increased with a difference of arrival time between the storage and retrieval requests, Layout6 generated higher throughput as compared to Layout5 for COL/RR60 policy. ANOVA results in Figure 4.14 for an arrival rate of EX(8) show that the difference between the two layouts is insignificant. The ANOVA results also show that the scheduling policies have significant effect at 90 percent rack utilization with the arrival rates equal to EX(8) for both request types. Figure 4.15 compares the throughput results obtained when the arrival rate was lowered to EX(16). The ANOVA table (shown in Figure 4.16) shows that there is a significant difference in the throughputs obtained in the layouts using the three scheduling policies.

At lower arrival rate Layout6 performed better than layout5. In Layout5, the storage pallets from S1 and S2 could be retrievec by either R1 or R2. In Layout6, the S1 storage pallets were retrieved only by R1, while S2 pallets were retrieved only by R2. Based upon identical space utilization (90 percent) and the closest-open-location storage rule, R1 or R2 retrieval requests ir Layout5 could be selected from any pallet in the storage rack. However, in Layout6, the R1 retrieval requests could be selectec from only the one-half of the palletsin the storage rack which were located in the area closest to dock 1; the situation for R2 paralleled that for R1. Thus, the expected crane cycle time in Layout6 must be lower than for Layout5. Hence, the throughput for Layout6 was found to be higher than Layout5.

CHAPTER 5

CONCLUSIONS

5.1 General Conclusions

The primary objective of this research was to evaluate single and dual-dock AS/RS layouts and the effect of scheduling policies on AS/RS layout designs. Microcomputer based simulation models were developed to evaluate different unit load AS/R systems. Analysis of the data obtained for the performance measures under steady state conditions show that the accuracy of the single dock AS/R system can be substantially increased by the introduction of class based arrangement when the input pallets are stored in the closest open location and the output pallets are retrieved using random retrieval rule. For a two dock layout, the statistics indicate that at high arrival rates both hybrid and dedicated arrangements perform very close to each other. However, at lower arrival rates dedicated arrangement produced significantly better results. The important results (Table 5.1) from the simulation and statistics analysis are summarized below :

1. End-of-aisle, uniform, square-in-time one dock layout: This layout arrangement produced the best throughput results under relief nearest neighbor (RNN) retrieval policy while storing the pallets based on the closest open location. Due to the nature of queuing involved, it is not compatible to compare the retrieval waiting times for COL/RNN with COL/NN and COL/RR60 scheduling policies. However, comparing COL/NN and COL/RR60, there is no statistical difference in retrieval waiting times. The storage waiting times were lower under COL/NN policy as compared to that of COL/RR60.

	Hybrid			Dedicated		
	ARRIVAL RATES			ARRIVAL RATES		
	ex(8)	ex(16)	ex(24)	ex(8)	ex(16)	ex(24)
COL/NN	737	611	484	660	674	700
COL/RNN	706	672	546	695	690	608

Table 5.1: Throughput Comparison for Dual-Dock Layouts

2. Mid-aisle, uniform, square-in-time, one dock layout: The performance of the mid-aisle arrangement can be substantially improved by using COL/RNN scheduling policy.

3. Class-based, square-in-time, one dock layout: Statistics indicate that the random retrieval rule was the most efficient with reference to all the performance measures.

4. End-of-aisle, uniform, non-square-in-time, one dock layout: For all the rack dimensions considered, the COL/RNN policy produced the best throughput results. From the analysis, it can be inferred that throughput is higher for designs that are close to the square-in-time design. COL/RR60 produced the least storage waiting times for the 4 x 25 rack. The least retrieval waiting time was obtained with 10 x 10 rack dimensions.

5. Hybrid, square-in-time, dual dock layout: There was not much difference among the throughput generated by the three scheduling policies, with COL/RNN performing slightly better than the other two scheduling policies. The waiting times were the least under COL/RR60 scheduling policy. COL/RNN produced the least number of rejects due to reduced cycle time.

6. Dedicated, square-in-time, dual dock layout: Again, the COL/RNN produced the highest throughput. The waiting times were lower with COL/RR60 scheduling policy.

7. Uniform versus class based, square-in-time, one dock layouts: The throughput for the class based layout was higher than that of the uniform arrangement for all the scheduling policies with the relief nearest (RNN) producing consistently better results. The increase in throughput in the class based arrangement is due to the reduced cycle

time. Locating items with high turnover (class I) items close to the dock produced smaller crane travel time; as the class I items were expected to be stored and retrieved 80 percent of the time, the throughput went up substantially.

8. End-of-aisle versus mid-aisle, uniform, square-in-time, one dock layouts: The RNN scheduling policy produced the best throughput results with the mid-aisle being superior arrangement. Due to the reduction in total travel time the dock at the aisle-mid-point serves more requests than when the dock is located at the end of the aisle. The waiting times and rejects for end-of-aisle layout were comparatively higher than that of mid-aisle layout.

9. Square-in-time versus non-square-in-time layouts: In comparing square-in-time with a number of non-square-in-time configurations, the overall trend showed the square arrangement producing the best combination of results.

10. Dedicated versus hybrid arrangement: In comparing the dual dock layouts, the dedicated arrangement produced better results than the hybrid arrangement at lower arrival rates. This is because in the hybrid arrangement retrieval requests could be selected from any pallet in the storage rack, whereas in the dedicated arrangement the retrieval requests could be selected from only the one-half of the pallets in the storage rack which were located in the area closest to the corresponding dock. As arrival rates increase with the dedicated layout item stored and retrieved are close to the rack mid-area, resulting in deterioration of throughput performance.

The performance of AS/RS is a function of several variables or system specifications. The choice of a single or dual dock layout is dependent on the level of activity demanded by the system and the structure of the production facilities. For a one-dock layout, a balance of improved throughput and reduced waiting times can be achieved by sequencing of retrieval requests using the relief nearest neighbor rule. For a system with two storage and two retrieval sources, substantial increase in system throughput can be achieved using a two dock layout to handle independent storage and retrieval source.

5.2 Recommendations for Further Research

Following are some of the suggested areas in which this research work can be extended -

1. Some of the assumptions used in this study can be relaxed, and additional factors may be considered. These include: crane capacity per trip (storing or retrieving more than one item in one trip), crane acceleration/deceleration and and pallet pickup and deposit times.

2. The effect of using more complex scheduling rules (as used in machine scheduling) on system performance can be evaluated and compared with results obtained in this research.

3. The unit load AS/R systems are only one type of material handling systems available in the industry. Scheduling of different material handling systems for storage/retrieval can be studied to improve the performance of the system.

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