Proceedings of the 1988 Winter Simulation Conference
M. Abrams, P. Haigh, and J. Comfort (eds.)

Performance analysis of automatic storage and retrieval systems – A comparative approach

B. Mustafa Pulat
AT&T Network Systems
Oklahoma City Works
Oklahoma City, OK 73126-0060

P. Simin Pulat
Department of Industrial Engineering
University of Oklahoma
Norman, OK 73019

ABSTRACT

Performance analysis of a large man-machine system such as an Automatic Storage and Retrieval System (AS/RS) is a complex problem. Several approaches exist for carrying out such investigations. Frequently, a combination of these techniques is utilized. This paper presents a combinatorial approach to evaluating the performance of a mini-load system, with computer simulation as the primary tool of investigation.

1. INTRODUCTION

One of industry's most challenging problems is moving, buffering, and controlling material efficiently. This is especially evident in the electronics industry where material costs typically account for 60-80 percent of product cost.

Many technologies have emerged for efficient piece parts or bulk material handling in the last two decades. The AS/RS technology was developed in the 1960's with advancements in real time control of machines by computers. AS/RS's are highly specialized material handling systems which require considerable capital investment. Their speed, accuracy, and capacity must be adequate to justify the expenditures.

2. PROBLEM STATEMENT

Oklahoma City Works of AT&T Network Systems operationalized an AS/RS two years ago. This is a mini-load system with nine aisles and aisle captive S/R (storage and retrieval) machines (cranes). The system is responsible for receiving, buffering, selecting, and auditing of primarily circuit pack components.

Several studies prior to the development of the system established the expected capacity in terms of number of selects, audits, and stocking activities per shift. The first few MRP logical stores were loaded to the system on this basis. However, before proceeding any further, another and more comprehensive study of mechanical and software capability for increased load was carried out. This paper presents the details of the mechanical handling capacity studies.

3. AS/RS MATERIAL FLOWS

The AS/RS receives material from several sources (see Figure 1) including the receiving dock, the Integrated Circuit Test and Firmware shop, other shops and buffer zones, and areas within AS/RS control (accumulator aisles). At the receiving stations, material is either routed to stocking or shortage fill areas or both. Material to be buffered is eventually stocked into a bin and transported to an assigned rack location. Material routed to the shortage fill area is used to fill short selects and/or floor shortages.

Selecting and inventory audits are accomplished at the P/D (pick and delivery) stations. Complete selects are moved to the kit shops or other manufacturing shops. Short selects are staged until filled. They are then moved to the point-of-use.

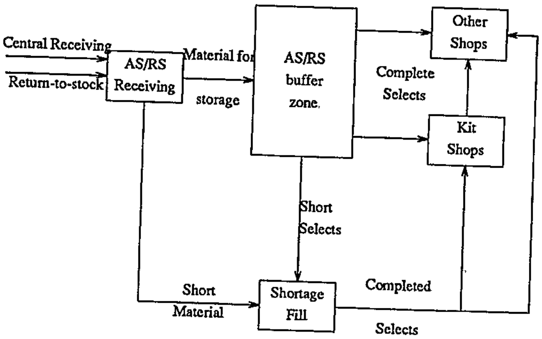

Figure 1. AS/RS Material Flow

4. P/D STATIONS

The P/D stations are located at the floor level. There are two I/O (input/output) points for each crane. One is the stocking station at the mezzanine level. The other is the P/D. Most of the crane activity (88 percent) is due to selecting and audit functions which take place at the P/D. Thus, it is important that the hardware and work flow at each P/D be reviewed.

4.1 P/D Hardware and Work Flow

Material flows in a horseshoe pattern through each station. Inbound bins are queued on an elevated roller conveyor. An elevator lowers the next bin in the work queue down to the operator level. The bin on which work has been completed is lowered to an outbound bin queue for crane pickup. The inbound bin queue length is controlled via photoelectric cells. When the queue length reaches four, bin delivery to that station stops. The process resumes with three or less bins in the queue. The outbound bin queue length limit is three. When this happens, the operator is blocked since no more bins can be processed. Each crane serves two P/D stations.

5. METHODOLOGY

Since the performance of the system largely depends on the activity level at the P/D, investigations concentrated on the output per station in terms of number of bins processed and load completion times. However, linearity assumption between one station's output and system output had to be justified with checks on level loadedness of aisles in terms of number of parts and their frequency of use, and long term randomization of load distribution between aisles. All checks proved that these assumptions were valid.

Three simultaneous investigations were carried out for process characterization (Rizo-Patron et. al, 1983). Simulation was the primary tool utilized. In addition, a queueing theoretic approach and intensive sampling of operator activity were employed.

5.1 Computer Simulation

A SIMAN model (see Pegden, 1984) was developed for simulation analysis. Figure 2 gives the block diagram model. In the model, entities representing bins in quantity equal to an average daily load are generated as the first step and placed in a queue. This is realistic since MRP download of daily work occurs each night in batch mode. Each entity is assigned an attribute code representing the type of activity to be performed (select or audit) on the bin. A bin is delivered to the P/D inbound bins queue only if there exists three or less entities in the queue.

Bins in the inbound queue are processed one at a time by the operator only if the system is not blocked. If so, the operator spends time in interference idleness. Each bin is processed according to the work type. Duty cycle time is drawn from an appropriate discrete probability distribution. In the mean time, the crane is performing dual command cycles.

Subsequent to bin delivery to the inbound queue, the crane is scheduled to move down to the outbound queue in order to pick a bin and deliver it to its assigned rack location. Then, the crane moves to the rack location where the next bin to be processed resides.

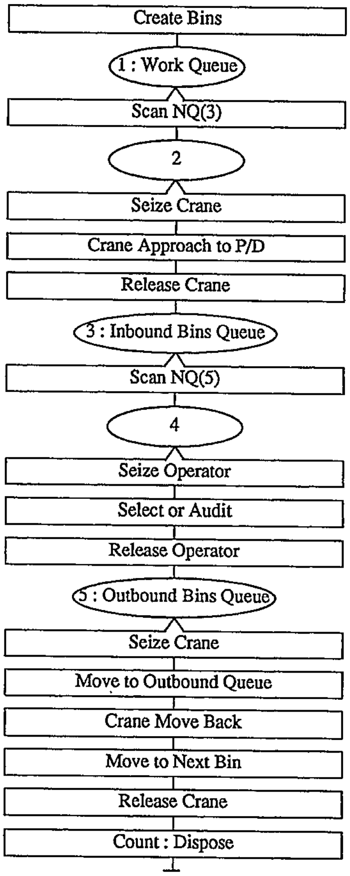

Figure 2. SIMAN Model for the P/D Process

A counter is incremented after returning a bin to its location and the entity is disposed. All crane move times are drawn from appropriate discrete probability distributions. Simulation ends when the scheduled load is processed.

5.2 Queueing Theory

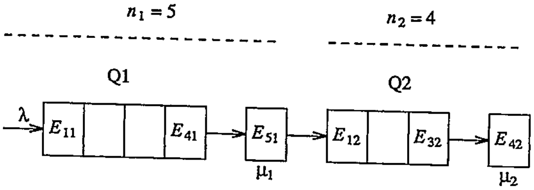

Figure 3. The P/D Process as a Queueing System

The queueing theoretic approach (see Gross and Harris, 1974) is explained via Figure 3. Consider a sequential two station single-server-at-each station model with n_1 and n_2 being the system capacity for the two stations. The first station is represented by the inbound bins queue coupled with the operator's work area. The second station is represented by the outbound bins queue and the crane pickup. In Figure 3, $n_1 = 5$ (queue length 4) and $n_2 = 4$ (queue length 3). If station two is full and service is completed at station one, the customer (a bin to be processed) must wait until service is completed at station two. During this time, the server (P/D operator) in station one remains idle. This case is referred to as station one being "blocked." Arrivals at station one are turned away (crane not delivering) when the station is full. Arrivals at station one are assumed to be Poisson distributed with parameter λ and service times are exponential with parameters μ_1, and μ_2, respectively. The states of the system are given in Table 1. The state definition indicates that there are $(n_1 + 1) \times (n_2 + 1)$ states where station one is not blocked and n_1 states where it is blocked. For this problem there exists 35 states. We wish to compute the steady state probabilities P_{i0k} and P_{ib4} for all i and k. Specifically, we are interested in P_{500} which represents crane idleness, and the total blockage probability P_b given by:

$$P_b = \sum_{i=1}^{5} P_{i,b,4}$$

Table 1. System States

State	Description	Limits on Subscripts
$i,0,k$	i customers in station 1 station 1 not blocked k customers in station 2	i=0,......,n_1 k=0,......,n_2
$i,0,k$	i customers in station 1 station 1 blocked 4 customers in station 2	i=1,......,n_1

Let i and k denote the number of customers in stations 1 and 2 respectively. Define,

$$\lambda_i = \begin{cases} \lambda & 0 \le i < 5 \\ 0 & i < 0, i = 5 \end{cases}$$

$$\mu_{1i} = \begin{cases} \mu_1 & 0 < i \le 5 \\ 0 & i = 0, i > 5 \end{cases}$$

$$\mu_{2k} = \begin{cases} \mu_2 & k > 0 \\ 0 & k = 0 \end{cases}$$

Steady state equations can then be written as follows:

$$(\lambda_i + \mu_{1i} + \mu_{2k})\, P_{i,0,k} = \lambda_{(i-1)}\, P_{(i-1),0,k} + \mu_{1(i+1)}\, P_{(i+1),0,(k-1)} + \mu_{2(k+1)}\, P_{i,0,(k+1)}$$

$$\text{for } i = 0,\dots,n_1$$

$$\text{for } k = 0,\dots,n_2-1$$

$$(\lambda_i + \mu_{1i} + \mu_{24})\, P_{i,0,4} = \lambda_{(i-1)}\, P_{(i-1),0,4} + \mu_{1(i+1)}\, P_{(i+1),0,3} + \mu_{2(i+1)}\, P_{(i+1),b,4}$$

$$\text{for } i = 0,\dots,n_1$$

$$(\lambda_i + \mu_{24})\, P_{i,b,4} = \lambda_{(i-1)}\, P_{(i-1),b,4} + \mu_{1i}\, P_{i,0,4} \qquad \text{for } i = 1,\dots,n_1$$

The above system of equations is linearly dependent. Any one of the equations can be eliminated while solving for the steady state probabilities. Hence, we have $(n_1 + 1) \times (n_2 + 1) + n_1 - 1$ equations and $(n_1 + 1) \times (n_2 + 1) + n_1$ unknowns. One can uniquely determine the steady state probabilities with the following additional equation:

$$\sum_{i=0}^{n_1} \sum_{k=0}^{n_2} P_{i,0,k} + \sum_{i=1}^{n_1} P_{i,b,4} = 1$$

The performance of the model and comparison with the other approaches are discussed in section 6.

5.3 Intensive Sampling

This leg of the research was conducted to cross check the simulation model and the queueing results. A completely randomized intensive activity sample was carried out within operational blocks by three different members of the material handling engineering department. The operational blocks in question are shifts (day and evening), P/D stations (one through eighteen), and finally four hour time blocks within a shift (first vs. second). All this effort was to account for possible sources of variation which may affect the percent time spent at various operating status by the operators. Fourteen such conditions were tracked, the most important being productive, blocked, starved, and avoidable delays.

6. RESULTS

Although the intensive sampling approach evaluated system status at various operating conditions, two are most important for system performance comparison purposes across the research tools. These are:

1. Operator interference idleness (system blocked).
2. Crane idleness.

In the optimal design of the system, neither should have a nonzero value. However, within the real life constraints of a manufacturing environment, one will. Table 2 gives the comparative results of the investigation across the two performance measures. Results in terms of "percent time spent in various operating conditions" have been adjusted in simulation and queueing approaches for realistic comparison with intensive sampling.

As can be observed, the bottleneck operation is crane handling of bins. This is evident in zero expected idleness (except for breakdown) on this resource. Thus, system output is

Table 2. Results (in percentages)

Performance Measures	Operation Type	Analysis Technique		
		Simulation	Queueing Theory	Intensive Sampling
Operator Interference Idleness (System Blocked)	Select	16	24	9
	Audit	47	46	55
	Mix	27	30	25
Crane Idleness	Select	0	0	0
	Audit	0	0	0
	Mix	0	0	0

determined by crane performance, including speed and mechanical availability. Operators on the other hand display various degrees of interference idleness which change by P/D operation type and analysis technique. Most idleness occurs when both sides of the P/D are scheduled with bin audits. This is a consistent result obtained across all approaches employed. It is a plausible outcome since when bin audits are scheduled for the P/D's, operators can process bins at a much higher rate than the crane can process bins. Thus, the outbound queue will fill fast and station one will be blocked most of the time.

Another consistent result across the analysis techniques is the fact that operators spend next most time in interference idleness when a mix of selects and audits is scheduled for the P/D's. In this case, aggregate operator bin processing rate gets closer to the crane bin processing rate. Least interference idleness occurs when all selects are scheduled. This is again a consistent result across all research tools, which can be explained by the fact that in this case, the processing rate difference between the two resources is minimum.

Although consistent trends have been observed in terms of results between the investigation approaches, one can also observe differences in numeric results between tools within a given performance measure. An example is that "percent operator interference idleness" ranges between 9 and 24 percent for selects between the scores obtained by using different tools. However, one more consistency may be observed even here. Always, simulation results are in between the queueing theoretic and the intensive sampling results. This may be attributed to the fact that the queueing approach assumes a poisson arrival process and exponential service process with random event occurances. These assumptions may not always hold since the AS/RS system administrator monitors and adjusts work mix and priorities throughout the day. Intensive sampling data have been collected over a considerable period, but may not have captured all sources of variation. Furthermore, event classification in terms of P/D operation type cannot be made in clear terms with sufficient number of data points. However, simulation data have been developed over a week's period across both shifts and several P/D's via two independent observers. Thus, we have more confidence in the simulation results. Hence, system capacity decisions in terms of number of bin pulls per shift have been based on the simulation results. Consistent trends in the behavior of the performance measures across the investigation tools give simulation the needed "feel" for predictive validity.

7. CONCLUSION

It is evident that computer simulation can be effectively utilized for AS/RS performance analysis. Throughput capacity may be determined by modeling operator and crane activity at the P/D with allowance for stocking station service.

Simulation is also an effective tool for identifying bottleneck operations which determine the system output capacity. The AS/RS crane mechanical uptime percentage is a variable that is very closely monitored at OCW. The AS/RS has a dedicated maintenance crew with software capabilities, including a pre-expert system for trouble-shooting.

8. REFERENCES

Gross, D. and Harris, C. M. (1974). *Fundamentals of Queueing Theory*. John Wiley and Sons, New York, NY.

Pegden, D. C. (1984). *Introduction to SIMAN*. Systems Modeling Corp. State College, PA.

Rizo-Patron, A., Bozer, Y. A., and McGinnis, L. F. (1983). *Analytic and Simulation Models for Advanced Automated Storage/Retrieval Systems*. Technical Report TR-82-03. Material Handling Research Center, Georgia Institute of Technology.

BIOGRAPHICAL NOTES

B. MUSTAFA PULAT received his B.Sc. and M.Sc. degrees in industrial engineering from the Middle East Technical University in Ankara, Turkey. His Ph.D in industrial engineering is from North Carolina State University, Raleigh, NC. He joined AT&T in 1985 after six years of full-time academic involvement. Currently, he is a senior engineer in the Material Handling Engineering department of AT&T Oklahoma City Works primarily involved with systems engineering, modeling, and ergonomics.

AT&T Technologies
7725 W. Reno Ave.
Oklahoma City, OK 73126-0060
(405) 491-3359

P. SIMIN PULAT received her B.Sc. degree in industrial engineering from the Middle East Technical University, Ankara, Turkey. Her M.Sc and Ph.D degrees in operations research are from North Carolina State University in Raleigh, NC. Dr. Pulat is currently an assistant professor of industrial engineering at the University of Oklahoma. Her research interests are in generalized networks, network reliability, and modeling.

Department of Industrial Engineering
University of Oklahoma
Norman, OK 73019
(405) 325-4310