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RESERVATION STORAGE POLICY FOR AS/RS AT AIR CARGO TERMINALS

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ABSTRACT

At air cargo terminals, the operations of an automatic storage and retrieval system (AS/RS) have certain special characteristics that both cargo arrival rates and storage duration are stochastic, and the probability distributions can only come from the empirical data. According to such particularities, this paper proposes a class-based *reservation storage policy* for AS/RS at air cargo terminals and an analytical model is developed. Two classes are investigated and a certain storage spaces are reserved for one priority class in such a way that the one-way travel time of S/R machine is minimized. The optimal reservation space is obtained by numerical searching. A simulation model is developed and the simulation results validate the optimal solution from the analytical model.

1 INTRODUCTION

Automated storage/retrieval systems (AS/RS) are broadly used in warehousing. A typical AS/RS is an automated warehousing system that comprises one or multiple parallel aisles with rack openings on both sides of the aisles. A Storage/Retrieval (S/R) machine in an AS/RS serves one or several aisles by carrying all the storage and retrieval orders. The S/R machine can travel horizontally and vertically simultaneously. Thus, the travel time between any storage location and the I/O point of an AS/RS is the maximum of the horizontal and vertical travel times; this is commonly called the Tchebychev metric. At air cargo terminals, AS/RS are also a key storage medium for cargo handling operations. Air cargo handling has an important requirement: swiftness. Thus, all operations, including AS/RS storage and retrieval, must be carried in the most efficient manner. In this paper, we focus on analyzing air cargo terminal AS/RS operations and developing an optimal storage policy.

In the literature three classical storage policies are broadly studied: randomized, class-based and dedicated (e.g. Hausman et al. 1976; Graves et al. 1977; Goetschalckx and Ratliff 1990; Pan and Wang 1996). With varying applications or assumptions, different analytical models are developed. Within these models, the travel time of S/R machine is the universal performance measure of AS/RS. Bozer and White (1984) developed an analytical model for the expected S/R machine travel time under randomized storage locations. Tompkins and White (1984) introduced a static analysis to estimate the utilization of S/R machines with the known number of requests. Kim and Seidmann (1990) derived general expressions for the expected travel time of S/R machines. Wen et al. (2001) proposed a travel time model for class-based storage assignment and full-turnover-based storage assignment which considered various travel speeds with known acceleration and deceleration rates. Ashayeri et al. (2002) presented a geometry-based analytical model to compute the cycle times for zone-based storage layouts.

All these models made a fundamental assumption that cargo (product) arrival rates and the storage duration in AS/RS are deterministic. This deterministic assumption can be reasonable in a production environment, because the production can be planned and controlled in advance. However, for the third-party warehousing, in retail operations, or at a seaport terminal, air terminal, etc, cargo arrival rates or requests can not be controlled. Cargo arrival time depends on flight schedules and retrieval requests can be made at any time by freight forwarders. The arrival rates or the storage durations in these systems are stochastic.

Some authors have considered such stochastic situations. In the shared storage policies developed by Goetschalckx and Ratliff (1990), an optimal policy with respect to travel time and storage space was developed first from a deterministic model, which assumed the input and output are perfect balance; however, for the actual problem with stochastic input and output, the authors proposed two heuristic policies without optimal solutions. Lee and Schaefer (1997) presented sequencing methods of storage and retrieval requests under static and dynamic approaches. Mahajan et al. (1998) developed a nearest-neighbour retrieval sequencing heuristic. Lee (1997) presented a stochastic analysis for performance evaluation of a unit-load AS/RS by using a single-server queuing model with two queues. Cycle times were assumed to follow exponential distributions. Thonemann and Brandeau (1998) applied the storage policies developed in Hausman et al. (1976) to a stochastic environment. They assumed the turnover rates followed the uniform and exponential distributions and developed an analytical expression of expected one-way travel time.

However these studies handle the stochastic situation by either heuristic approximation, or assuming a special probability distribution function (pdf). At import terminals, the storage duration of AS/RS cargo is the length of time between storage and retrieval. This can be regarded as a general definition for AS/RS cargo storage duration, and it is stochastic since forwarders collect cargo at their own convenient time. Based on historical data, we can treat storage duration as a random variable following a known probability distribution, which is shown by experience to be a general pdf rather than abovementioned special distributions. Another important variable affecting AS/RS operations is cargo volume. Many factors influence the volume of arriving cargo, such as flight type. We also derive the probability distribution of cargo arrival rate from historical data, rather than any assumed special pdf.

Whatever the assumption is deterministic or stochastic, and however accurate of the analytical models, simulation is an indispensable tool to validate the numerical results. That is because the actual behaviors of AS/RS are real-time operations; there are no analytical models that could capture all the details. Kulturel et al. (1999) used simulation to compare the two proposed shared storage assignment policies in Hausman et al. (1976) and Goetschalckx and Ratliff (1990). Elsayed and Unal (1989) proposed four heuristics to batch orders into tours instead of carrying orders one by one. Simulation was used to evaluate these four heuristics on the basis of minimizing total travel time. Randhawa et al. (1991) developed a simulation model to compare system performance of "square" in time AS/RS under different layout configurations and storage/retrieval rules. Van den Berg and Gademann (2000) presented a simulation study which examined a wide variety of control policies, including a new proposed continuous storage policy. They evaluated the trade-off between travel times and storage space requirements.

In this paper, we propose a new storage policy for AS/RS: *reservation storage policy*, due to the unique traits of air cargo terminals. The two input parameters, cargo arrival rates and storage durations, are both assumed to be stochastic and followed experienced general probability distributions. With the newly developed storage policy and the general pdf, an approximate analytical model is developed and solved. The results are validated by a simulation model. The remainder of this paper is organized as follows. Section 2 explains the details of the reservation storage policy, followed by the analytical model and solutions in Section 3. Section 4 describes the simulation model, followed by computational results in Section 5.

2 RESERVATION STORAGE POLICY

To minimize the expected travel time for an S/R machine, an obvious optimal storage policy is to store the cargo with shortest duration of storage in the locations with shortest travel time. One popular approach in literature is that all items are sorted by their turnover rates, the reciprocal of storage duration, and then assigned orderly. For air cargo terminal AS/RS, the storage duration is not known or constant, so we can sort and assign the cargo by their turnover rate; however, the same principle, improving utilization of storage locations with shorter S/R machine travel time, can be still followed. By this way, we newly propose the *reservation storage policy*: The storage locations with shorter S/R machine travel time are reserved for such cargo that has shorter storage duration. For air cargo terminals, all cargo are separated into two groups, one has shorter storage duration, and the other has longer storage duration. Such reservation storage policy reserves a certain storage spaces, which include the closest storage locations to I/O point, for the group that has shorter storage duration.

It is found that some forwarders have a large volume of cargo, thus they come to the terminal often. Other forwarders have smaller amounts of cargo and come to the terminal much less frequently. Therefore, we propose to divide all the forwarders into two groups: the forwarders whose cargo have shorter expected storage duration belong to "Big Group" (BG), and the forwarders whose cargo have longer expected storage duration belong to "Small Group" (SG). These two groups are independent. Note that this two-group separation does not guarantee all BG cargoes have shorter storage duration than SG cargo, but just guarantee the expected storage duration is shorter.

This reservation policy is employed together with the *closest-available-space policy*. That is, newly arriving cargo is always stored in the closest empty place. Under this policy, we reserve some spaces, s_r , exclusively for BG. Thus, when BG cargo arrives, it is stored in s_r if there is space available; otherwise, it is stored in the remaining area outside s_r , together with the arriving SG cargo. Cargo is always stored as close to the I/O point as possible within its assigned area. The AS/RS is represented by the two-dimensional area shown in Figure 1, with the maximum storage space labeled 'Max'.

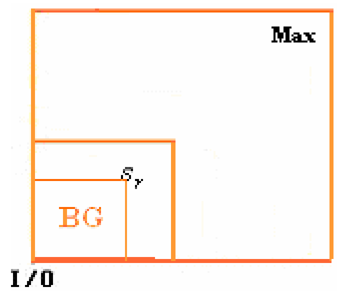

Figure 1: Reservation storage policy

Thus, we set our objective to identify, for BG cargo, the optimal amount of space that is reserved for BG group to minimize the expected S/R machine travel time. This *reservation policy* intends to increase the utilization of storage space with the shortest travel time. The following assumptions are made in this paper:

- Each bin can accommodate only one unit of cargo, and occupy exactly one storage position;
- The AS/RS has one aisle, which is served by one S/R machine;
- The I/O point of the AS/RS is located at the lower left-hand corner;
- Interleaving is ignored. The AS/RS is operating in "single command" mode only. For a storage order, the S/R machine picks up the bin at the I/O point, travels to the pre-assigned storage positions, puts the bin into that opening and returns to the I/O point. For a retrieval order, the S/R machine travels from the I/O point to the corresponding storage opening, picks up the bin and takes it to the I/O point. Both storage and retrieval orders begin and end at the I/O point;
- S/R machine loading and unloading times are constant and not included in the S/R machine travel time;
- The layout of the AS/RS, as well as the travel speeds of the S/R machine are known and constant;
- Travel time satisfies the Tchebychev metric;
- Storage duration and cargo arrival rate follow known distributions. Probabilistic density functions are derived from historical data.

3 SIMULATION MODEL

In the last section, we propose the analytical model and the solutions. The steady-state approximation is validated by comparing with the actual solutions on a small-size example. Such an approximating model can be employed to solve the real-size problems, but the solutions can not be validated by actual solutions, since the Markov Chain approach is impractical to solve the real-size problem. Alternatively, the popular validation of analytical models is simulation, which can simulate the detailed behavior of AS/RS. Besides for validating analytical model, the simulation can also compare different storage policies. Following the detail of the simulation model is described.

The simulation program is coded in VC++, organized by three modules: Initialization, Main and Output. In the first part Initialization, five parameters are determined: distributions of cargo arrival rate for BG and SG, distributions of storage duration for BG and SG, and one-way travel time of S/R machine from I/O point to each storage opening. In the Main part, each candidate number of reserved space is tested with 10 replications and for each replication, running period is set to be long enough to get accurate result. For different number of reserved space, same random number generator and seed are employed, which makes the result convincing. At last, simulation results are outputted into files. Three measures are provided to evaluate the system performance. The major measure is expected one-way travel time per storage order. Minimizing the major measure is the objective of this problem. Thus, from the result of this measure, optimal number of reserved space for Big Group can be identified. The minor measure is expected storage space requirement. During each period in the simulation, the storage space requirement of that period can be found by searching the furthest opening that is being occupied by any cargo. The average of storage space requirement during all periods is the minor measure. With increment of number of reserved space, the expected storage space requirement increases. The last measure is utilization of each opening. From this measure, the utilization of each individual opening is provided.

The simulation model captures the dynamic property, which means considering specific storage location for each cargo. The advantage of simulation is elimination of state explosion problem. Appropriate running periods and number of replications are tested to assure good enough results.

4 COMPUTATIONAL RESULTS

Two real-size problems are investigated by both steady-state approximating model and simulation. Case 1 and 2 are designed examples, and case 3 is a real problem of an international airport cargo terminal, which is also the motivation of this research. Furthermore, the current purely randomized storage policy is investigated, which shows the progress of the proposed reservation policy.

Case 1 BG and SG have the same probabilistic distribution of cargo arrival rates, which is an observed characteristic at the real airport terminals. It follows a uniform distribution. Also BG and SG have same number of possibilities of storage duration, but different probabilistic distributions, which make the expected storage duration time of BG is much shorter than SG. 5 possible values of cargo arrival rate and 4 possible values of storage duration are designed, shown in Table 1, and the computational results are shown in Figure 2. For the S/R machine travel time, we use

$$y_i = \left| \sqrt{i} \right|$$

where we consider the effect of the real two-dimension facility.

Table 1: Input Parameters in Case 1

Cargo arrival rate (/ hour)						
Probability	1	2	3	4	5	Expected
BG	0.2	0.2	0.2	0.2	0.2	3
SG	0.2	0.2	0.2	0.2	0.2	3
Storage duration (hour)						
Probability	1	2	3	4	Expected	
BG	0.6	0.2	0.1	0.1	1.7	
SG	0.4	0.2	0.2	0.2	2.2	

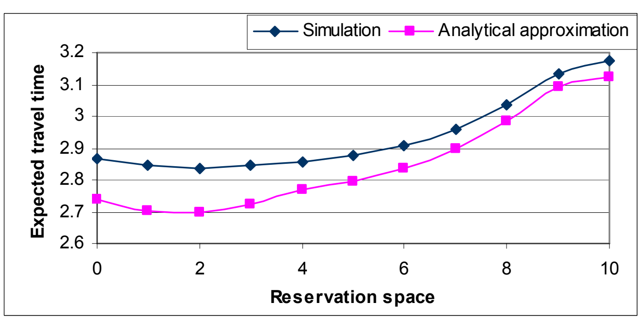

Figure 2: Results of Case 1

Case 2 Similar with case 1, but the distribution of arrival rate is general rather than uniform in case 1. We design 10 possible values for cargo arrival rate and 6 possible values for storage duration. Details are shown in Table 2, and the computational results are shown in Figure 3. For the S/R machine travel time, we use

$$y_i = \left| \sqrt{(i+1)/2} \right|$$

where we consider the effect of the real two-dimension and the both sides of aisles.

Table 2: Input Parameters in Case 2

Cargo arrival rate (/ hour)											
Probability	1	2	3	4	5	6	7	8	9	10	Expected
BG	0.18	0.16	0.14	0.12	0.1	0.1	0.08	0.06	0.04	0.02	4.1
SG	0.18	0.16	0.14	0.12	0.1	0.1	0.08	0.06	0.04	0.02	4.1
Storage duration (hour)											
Probability	1	2	3	4	5	6	Expected				
BG	0.5	0.2	0.1	0.1	0.05	0.05	2.15				
SG	0.3	0.2	0.2	0.1	0.1	0.1	2.8				

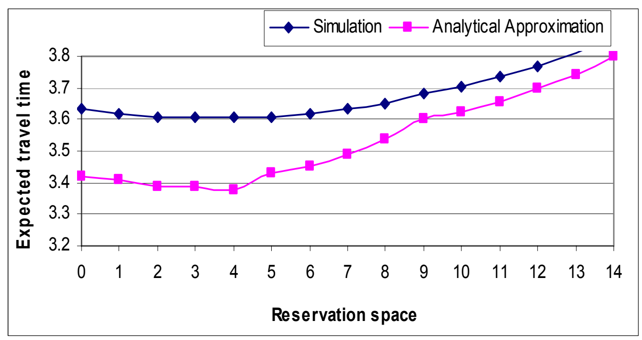

Figure 3: Results of Case 2

Case 3 According to the historical data collected from a real airport cargo terminal, BG and SG are separated, and the probabilistic distributions are empirically built up, shown in Figure 3 for arrival rate and storage duration, respectively. The computational results are shown in Figure 4. For the S/R machine travel time, the real facility layout based on the real dimension is counted in. However, since we just care the optimal reservation space, the exact number of travel time is trivial, if only they proportion the real data. Hence case 3 can be deemed as a real industrial problem.

From the computational results, the optimal reservation space is easily identified. In case 1, the optimal solution is 2, in case 2 it is 4, and in case 3 it is 8. All the simulation and the analytical approximation give the same optimal solutions. This coincidence validates the proposed steady-state approximating model. Note that the approximation results are always the lower than simulations results. As what we discuss in Section 4, the steady-state approximation provides a lower bound of the actual expected travel time.

At last, we estimate the expected travel time of the current operating storage policy, uniform storage policy. Unlike closest storage policy, which actually can reduce a lot of travel time for the proposed problem, uniform storage policy is the real randomized storage policy, i.e., any openings in the system have equal chance to be utilized. Then the expected travel time of uniform storage policy can be simply calculated as the average of one-way travel time of all storage openings to the I/O point. The simulation result is 12.65, which is nearly three times as the optimal one from the reservation storage policy.

5 CONCLUSION

In this paper, the AS/RS at air cargo terminals is studied. Unlike normal AS/RS which are operating based on inventory control policies, AS/RS cargo have stochastic storage durations and arrival rates. Different with the literatures, we propose a two-class-based reservation storage policy to minimize the expected S/R machine travel time. Both analytical and simulation model are developed. The Markov chain approach can capture the dynamic property accurately, but prohibitive to solve the real-size problem. Instead, the steady-state approximating model establishes the function between the reservation space and the expected travel time directly. By one-dimensional searching, the optimal solution can be found. Computational results show that the proposed reservation storage policy is helpful to reduce the expected S/R travel time, and the steady-state approximating model is effective to obtain the optimal reservation space.

Compared with a randomized storage policy, by which all cargo are stored randomly among the storage locations, the reservation storage policy assumes that cargo forwarders can be divided into groups by their historical data about demand information. Thus this policy requires additional data recording and tracking, which means more computerized efforts.

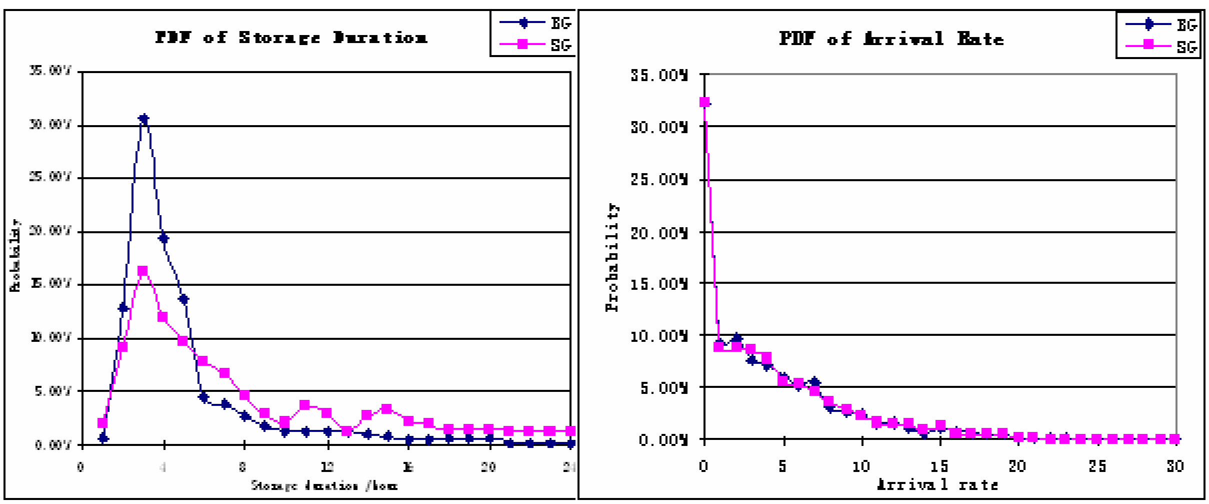

Figure 4: The Actual Probabilistic Distributions of the Storage Duration and Arrival Rate

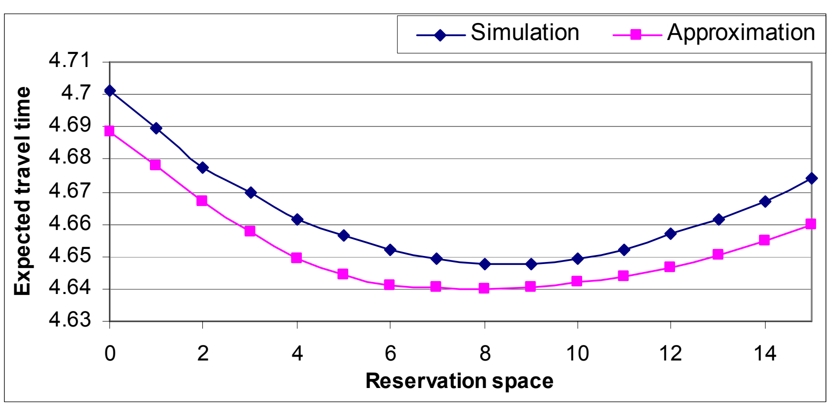

Figure 5: Results of Case 3

REFERENCES

Ashayeri, J., Heuts, R.M., Valkenburg, M.W.T., Veraart, H.C. and Wilhelm, M.R. 2002. A geometrical approach to computing expected cycle times for zonebased storage layouts in AS/RS, *International Journal of Production Research*, Vol. 40, No. 17, pages 4467-4483.

Bozer, Y.A. and White, J.A. 1984. Travel-time models for automated storage/retrieval systems, *IIE Transactions*, Vol. 16, No. 4, pages 329-338.

Elsayed, E.A. and Unal, O.I. 1989. Order batching algorithms and travel-time estimation for automated storage/retrieval systems, *International Journal of Production Research*, Vol. 27, No. 7, pages 1097-1114.

Goetschalckx, M. and Ratliff, H.D. 1990. Shared storage policies based on the duration stay of unit loads, *Management Science*, Vol. 36, No. 9, pages 1120-1132.

Graves, S.C., Hausman, W.H. and Schwarz, L.B. 1977. Storage-retrieval interleaving in automatic warehousing systems, *Management Science*, Vol. 23, No. 9, pages 935-945.

Hausman, W.H., Schwarz, L.B. and Graves, S.C. 1976. Optimal storage assignment in automatic warehousing systems, *Management Science*, Vol. 22, No. 6, pages 629-638.

Kim, J. and Seidmann, A. 1990. A framework for the exact evaluation of expected cycle times in automated storage systems with full-turnover item allocation and random service requests, *Computers and Industrial Engineering*, Vol. 18, No. 4, pages 601-612.

Kulturel, S., Ozemirel, N.E., Sepil,C. and Bozkurt,Z. 1999. Experimental investigation of shared storage assignment policies in automated storage/retrieval systems, *IIE Transactions*, Vol. 31, No. 8, pages 739-749.

Lee, H.F. 1997. Performance analysis for automated storage and retrieval systems, *IIE Transactions*, Vol. 29, No. 1, pages 15-28.

Lee, H.F. and Schaefer, S.K. 1997. Sequencing methods for automated storage and retrieval systems with dedicated storage, *Computers and Industrial Engineering*, Vol. 32, No. 2, pages 351-362.

Mahajan, S., Rao, B.V. and Peters, B.A. 1998. A retrieval sequencing heuristic for miniload end-of-aisle automated storage/retrieval systems, *International Journal of Production Research*, Vol. 36, No. 6, pages 1715-1731.

Pan, C.H. and Wang, C.H. 1996. A framework for the dual command cycle travel time model in automated warehousing system, *International Journal of Production Research*, Vol. 34, No. 8, pages 2099-2117.

Randhawa, S.U. and Shroff, R. 1995. Simulation-based design evaluation of unit load automated storage/retrieval systems, *Computers and Industrial Engineering*, Vol. 28, No. 1, pages 71-79.

Thonemann U.W. and Brandeau M.L. 1998. Optimal storage assignment policies for automated storage and retrieval systems with stochastic demands, *Management Science*, Vol. 44, No. 1, pages 142-148.

Tompkins, J.A. and White, J.A. 1984. *Facilities Planning*, John Wiley, New York.

Van den Berg, J.P. and Gademann, A.J.R.M. 2000. Simulation study of an automated storage/retrieval system, *International Journal of Production Research*, Vol. 38, No. 6, pages 1339-1356.

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