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A Review of Analytical Travel Time Models in Automated Storage and Retrieval Systems

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Abstract—*Automated Storage and Retrieval Systems (AS/RS) are warehousing system that use mechanized devices to accomplish the repetitive task of storing and retrieving parts in racks. The (AS/RS) machine travels simultaneously horizontally and vertically as it moves along a storage aisle. The aspects include improving output/input rate, changing retrieval sequencing rules, using applying various dwell point policies and increasing the storage and retrieval machine capacity. As AS/RS machines include a considerable investment and operating costs they should be as efficient as possible. This paper presents analytical travel time models for the computation of travel time for automated warehouses with the aisle transferring S/R machine.*

Keywords*: Logistics, Automated Storage and Retrieval Systems, warehouse, system design, control policies.*

1. INTRODUCTION

Automated storage and retrieval systems have been widely used in material handling and production environments. An automated storage and retrieval system (AS/RS) usually consists of racks and cranes running through aisles between the racks. An AS/RS is capable of handling raw material or semi-finished products without the involvement of an operator and makes the system fully automated. Both in production and material handling environments AS/RSs are used for putting products (e.g., raw materials or semi-finished products) in storage and for retrieving those products from storage to fulfill an order. Over the years, there has been a significant increase in the number of AS/RSs used in distribution environments in the United States (Automated Storage Retrieval Systems Production Section of the Material Handling Industry of America, 2005). The usage of AS/RSs has many advantages over non-automated systems. Examples are reduction in labour costs and floor space requirement, increased reliability and reduction in error rates. Probable disadvantages are high investments costs, less flexibility and higher investments in control systems.

Due to the different AS/RS configurations possible and the high cost of these systems, particular attention has to be paid during the design process to present and future demand requirements in order to keep the system current and maximize its benefits. Several different models can help estimate the performance of the system during the feasibility design process, mostly based on Bozer and White formulations (Bozer & White, 1984).

2. ANALYTICAL TRAVEL TIME MODELS

Typically, AS/RSs are characterized by single-shuttle cranes that allow one load at the time. To have efficient performance, multi-shuttle AS/RS have been developed to increase the output/input rate, where each crane can transport more than one load at the time. Generally, increasing the number of shuttles increases performance because it decreases the number of empty trips. On the other hand, increasing the number of shuttles gives a higher investment cost. For these reasons, the applications of dual-shuttle AS/RSs are more common than other kinds of multi-shuttle AS/RSs.

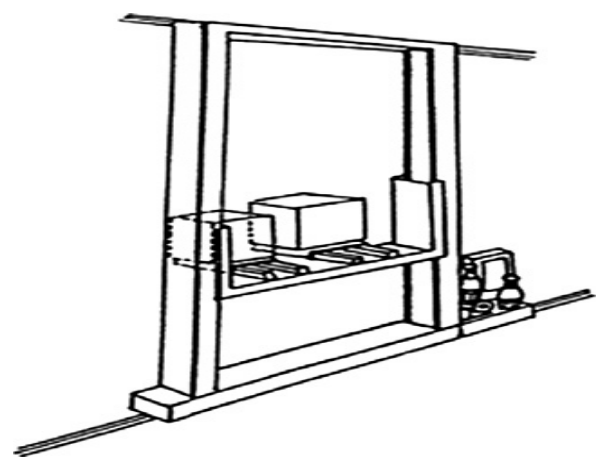

Fig. 1: Automated storage and retrieval system with dual-shuttles (Meller and Mungwattana, 1995, 1997).

2.1 Command Cycle of Stacker Crane

However, the stacker cranes capable of transporting more than two loads are still rarely seen and it is believed that there are no systems in practice with more than three shuttles.The storage (S) and retrieval (R) operations in an AS/RS rack for different command cycles are shown in Fig.2

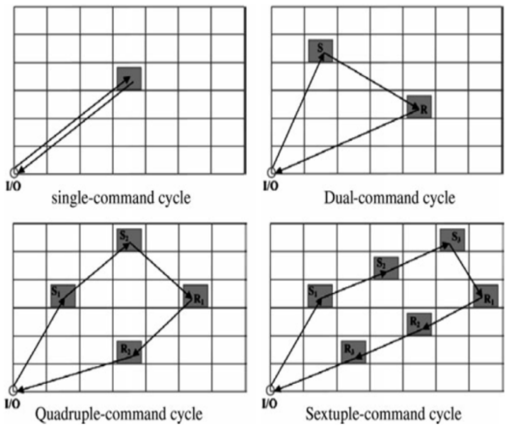

Fig. 2: Different command cycles of the stacker crane (M. R. Vasili et al)

Bozer and White (1984) presented expressions for the expected cycle times of an AS/RS performing single-command (SC) and dual-command (DC) cycles. The expressions are:-

$$\mathbf{E(SC) = \frac{1}{3}b^2 + 1} \qquad (1)$$

$$\mathbf{E(DC) = \frac{4}{3} + \frac{1}{2}b^2 - \frac{1}{30}b^3} \qquad (2)$$

As the value of b may represent the shape of a rack in terms of time, b was referred to as the ‘‘shape factor’’. In general throughput capacity of an AS/RS increases as the number of shuttles increases, since the amount of empty travel decreases correspondingly.

2.2 Dwell Point Policy

Another method is a dwell-point policy in an AS/RS which is the position where the stacker crane resides, or dwell, when the system is idle (Hu et al. (2005)) defined the dwell-point policy as the policy to decide where the stacker crane will stay when it becomes idle. The dwell-point is selected such that the expected travel time to the position of the first transaction after the idle period is minimized. For the dwell-point specification problem, the following static dwell-point rules were outlined by Bozer and White (1984), although they provided no quantitative comparison of their performance:

1. Return to the input station following the completion of a SC storage, remain at the output station following the completion of either a SC retrieval or DC cycle.
2. Remain at the storage location following the completion of a SC storage, remain at the output station following the completion of either a SC retrieval or a DC cycle.
3. Travel to a midpoint location in the rack following the completion of any cycle.
4. Travel to input station following the completion of Cycle.

2.3 Input/Output Position

The position of the I/O station(s) is also a factor that affects the AS/RS operation. Bozer and White (1984) analyzed and derived the expected travel time of the following alternative configurations for the I/O station:

1. Input and Output at opposite ends of the aisle.
2. Input and Output at the same end of the aisle, but at different elevations.
3. Input and Output at the same elevation, but at a midpoint in the aisle.
4. Input and Output elevated at the end of the aisle.

2.3.1 Input and Output at Opposite Ends of the Aisle

For this configuration, first assuming the dwell-point strategy (1) the expected travel time model per operation $E_1(T)$ is shown as :-

$$\boldsymbol{E_1(T) = E(V)(1+\alpha) + \frac{1}{2}E(TB)(1-\alpha) + \frac{1}{2}K\left[1-\frac{\alpha}{2}\right]}$$

Where α is percent of storages which are performed using SC cycles. E(V) is the expected travel time from any corner of the rack to a randomly selected point or vice versa. E(TB) is the expected travel time between two randomly selected points.

2.3.2 Input and Output at the Same End of the Aisle, but at Different Elevations.

Therefore, assuming the dwell-point strategy the expected travel time model per operation E2(T) for the this configuration was shown to be

$$\boldsymbol{E_2(T) = \frac{\alpha}{2}\{\alpha E(V) - \frac{1}{2}\alpha E(TB) + \frac{1}{2}[E(V)E(TB) + E_0(V)]\} +}$$

$$\boldsymbol{(1-\frac{\alpha}{2})\{\frac{1}{2}\alpha[E(V) - E(TB) + E_0(V)] + \frac{1}{2}\Big[E(V) + E(TB) + E_0(V) + \frac{1}{2}d^2\Big\}}$$

$E_0(V)$ as the expected travel time for returning to the output station. “d” is the distance between the Input and Output Position.

2.3.3 Input and Output at the Same Elevation, but at a Midpoint in the Aisle

The expected travel time model per operation $E_3(T)$ for the this configuration was shown to be

$$\boldsymbol{E_3(T) = \alpha[2E_M(V)] + (1-\alpha)[2E_M(V) + E(TB)]}$$

$E_M(V)$ as expected travel time from the center of rack to a randomly selected point.

2.3.4 Input and Output Elevated at the End of the Aisle

The expected travel times for Single and Dual Command cycles:

$$E(SC) = \frac{1}{3}b^2 + 1 - d(b - d)$$

$$E(DC) = \frac{4}{3} + \frac{1}{2}b^2 - \frac{1}{30}b^3 + d(b - d)$$

2.4 Storage Assignment

Hausman et al. (1976) investigated and compared the operating performance of the three storage assignment policies: randomized storage; class-based storage and full-turnover policy. It was observed that significant potential reductions in stacker crane travel times in automatic warehousing systems is possible based on class-based turnover assignment policies rather than closest open-location (essentially random) policies. Linn and Wysk (1987) presented a simulation study to consider the storage assignment rules similar to Hausman et al. (1976) but with other control decisions. Performance of different control algorithms for a unit-load AS/RS for various storage and retrieval rates under seasonal demand was analyzed. Furthermore, the effect of workload intensity on the control algorithms and the effect of product mix on the control algorithms were investigated. They used the following storage location assignment rules:

1. **Random assignment (RNDM):-** A location is randomly picked and assigned to the pallet to be stored if it is empty. Otherwise, another location will be picked.
2. **Pattern search, lowest tier first (LTF):-** The storage location is selected by searching for the closest open location in the lowest tier first. If no empty one is found, the next lower tier will be searched.
3. **Shortest processing time (SPT):-** The empty location with the minimum travel time from input station is assigned for next storage.
4. **Turnover rate based zone assignment (ZONE):-** The storage rack is partitioned into number of zones, which is equal to the number of product types. The zone closest to the I/O station is assigned to store pallets of highest turnover rate. When searching for an empty location, if an empty location cannot be found in its own zone, the next lower turnover zone will be searched. If all the lower turnover zones are full, then the next higher turnover zone is searched.

2.5 Request Sequencing

Linn and Wysk (1987) presented a simulation model to evaluate the following sequencing rules when the product demand shows seasonal trend:

1. **First-Come-First-Serve (FCFS):-** All the requests are served on FCFS basis.
2. **Shortest Completion Time (SCT):-** The request which needs the shortest completion time is served first.
3. **Shortest Completion Time with output priority (SCTop):-** This is a modified SCT rule, in which the retrieval requests have first priority, to clear the room for storage.
4. **Shortest Completion Time with controlled output priority (SCTcop):-** This is another modified SCT rule in which the retrieval requests would have the first priority only when the retrieval queue is longer than the storage queue.

The results indicated that, when arrival rate is such that the traffic intensity is low (below a critical value), the sequencing rules produce little improvement in system performance. When arrival rate increases until the traffic intensity goes beyond the critical value, job sequencing rules begin affecting the system performance.

3. CONCLUSIONS

From the discussions in this paper it can be seen that a considerable amount of research has been carried out over the years to evaluate, improve and optimize the operational features and control policies of the AS/RSs. Most of the existing studies only discuss a fraction of these AS/RS issues. Therefore, development of comprehensive evaluating and improving procedures would seem to be necessary in order to simultaneously address all these issues. In addition, regardless of the actual improving and optimisation procedures, a system of performance measurement is needed to evaluate the overall performance of the resulting system at every stage. In this regard, many publications have appeared on performance measurement. Most studies have analyzed the performance of AS/RSs under a balanced situation so that inbound work-flow is equal to the outbound work-flow. However, considering the dynamic nature and realistic operating characteristic of an AS/RS, during certain time slots, the system operates under an unbalanced situation. A perfectly balanced system is a very idealized situation which is unlikely to occur in real storage systems. Hence, the research in this field should move toward developing models, algorithms and heuristics that include the dynamic and stochastic aspects of current business. The performance of an AS/RS varies according to the definition of measure and the operating strategies. Performance measures for an AS/RS may include: system throughput, utilization of rack and stacker crane and expected travel time of stacker crane. Travel time estimates in different types of AS/RS configurations are appropriate analytical tools for evaluating and comparing the system performance.

In the preceding sections the existing travel time models on different aspects of the AS/RS, especially its control policies were investigated. Considering different control policies, dwell-point policy of the stacker crane is the strategy that can affect and contribute to the system response time of AS/RS. Several dwell-point policies for AS/RS have been introduced in the literature. Meanwhile, development of expected travel time (i.e., average travel time) models for AS/RS based on different dwell-point policies has been the subject in much research over the past several years. Although many dwell-point strategies have been suggested, and an optimal strategy defined, however for AS/RSs with high system utilizations, the dwell-point strategies may have no significant effect on the system response time, since the stacker crane will not be idle very often. Other control policies for AS/RSs that have received considerable attention in the literature are storage assignment and request sequencing. Majority of the literature addresses single aisle AS/RSs with single I/O station. Hence, storage assignment and request sequencing policies for other types of configurations (e.g., multiple I/O stations) or non-traditional AS/RSs (e.g., multiple shuttle AS/RSs) deserve further study.

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