Maximizing the throughput capacity of mixed load multi-deep storage and retrieval systems

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Multi-deep storage systems are space efficient storage solutions for e-commerce and spare part logistics. Popular versions are robotic compact storage and retrieval (RCS/R) and multi-deep automated storage and retrieval (AS/R) systems. In such systems, multiple loads can be stored behind or above each other in a single lane, which leads to high space utilization. However, blocking loads must be reshuffled if they block a requested load. This increases the command cycle time. We present models to estimate the throughput capacity of these systems, which can be used in the design phase. We build these models using four different storage assignment strategies, three different load reshuffling strategies and two retrieval load selection strategies, incorporating the access frequency of products and allowing multiple stored loads per product for some strategies. Seven strategy combinations are analyzed which include among others the current AutoStore strategy and two state of the art strategies. The throughput capacity is determined using closed queuing networks and the model's quality is validated with simulation. We find that the class-based storage assignment strategy, where different classes share the same lanes, yields the highest throughput capacity and that relocation of reshuffled loads to other storage channels is superior to temporarily buffering and bringing back these loads. Furthermore, when information about the access frequency and number of loads per product is available, the throughput capacity can be increased significantly by properly storing and reshuffling loads to better positions. Based on the throughput model, we optimize the rack layout yielding maximum throughput capacity and provide the throughput capacity for a given industry rack layout. Furthermore, we provide managerial insights on storage assignment, reshuffle and retrieval load selection strategies for multi-deep storage systems.

Key words: Deep-lane storage; Multi-deep storage; Throughput capacity; RCSRS; AS/RS; travel time model; performance estimation

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1. Introduction

In recent decades, the introduction of various automated compact warehouse storage systems has transformed the logistics landscape. These storage systems employ multi-deep storage lanes to efficiently store products. Examples of these systems are multi-deep automated storage and retrieval (AS/R), robotic compact storage and retrieval (RCS/R), and multi-deep autonomous vehicle storage and retrieval (AVS/R) systems. A comprehensive overview of such systems is provided by Azadeh et al. (2019). Multi-deep (or deep-lane) storage systems are characterized by high space utilization and, for some systems, high throughput capacity. Consequently, they find applications in many distribution centers and spare part warehouses. In these systems, stored loads (totes, bins, pallets, containers) are arranged in multi-deep storage, either behind one another in a storage lane (as in AS/R and AVS/R systems), or they are stacked vertically (as in RCS/R systems or sea-container stacks). Load handling devices (cranes, robots, shuttles) cannot directly access each load. When a blocked load needs retrieval, the system must reshuffle the blocking storage loads, thereby adding to the command cycle time and decreasing system throughput capacity, a critical performance indicator.

The operator's challenge lies in efficiently storing and retrieving loads while minimizing the number of reshuffles. When a new system must be designed, it is important to estimate up front the impact of the design and operating strategies on the throughput capacity. Operating strategies include the storage assignment, reshuffle, and retrieval load selection strategy for a requested product, as well as channel (i.e. storage lane) policies such as shared storage of loads of different products in a channel or dedicated storage of only loads of the same product. When information on access frequency of different products and the number of loads per product in the system are known, more sophisticated storage assignment policies, like class-based storage or smart retrieval selection strategies can be used. However, storage planners have to lean on simulations and empirical data to devise new multi-deep storage systems, because analytic models for multi-deep storage systems employing these strategies are hardly available in literature. Additionally, comparisons between strategies have hardly been explored.

Therefore, in this paper we focus on RCS/R and multi-deep AS/R systems and address the following research question: How do the different storage assignment, reshuffle, and retrieval load selection strategies perform and which strategy combination maximizes the long-run throughput capacity? We also investigate the strategy used by the market leader for RCS/R systems (The AutoStore (2023) strategy is shown by Meller (2023)) and compare it to other strategies and investigate how information on the product access frequency and the stored number of loads per product can be used to improve the throughput capacity. We use this knowledge to find the optimal rack layout of a multi-deep RCS/R or AS/R system of a given storage capacity that maximizes the throughput capacity.

Our throughput models are applicable to two different multi-deep storage systems: RCS/R and multi-deep AS/R systems. We primarily focus on RCS/R systems. In the appendix, we illustrate how our results can also be applied to multi-deep AS/R systems.

2. Modeling Approach

To estimate the throughput capacity of a given RCS/R system, we use a closed queuing network (CQN) with two server nodes (see Figure 1). In a CQN, retrieval jobs are always available and robots

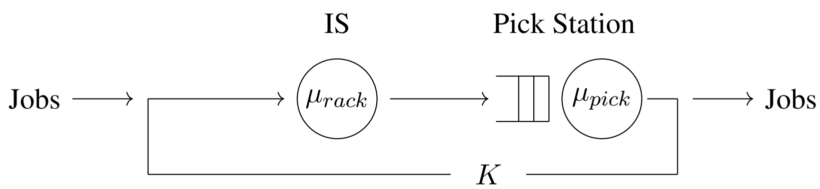

Figure 1. Closed Queuing Network with K Robots and two Server Nodes.

do not have to wait for new command cycles. The time needed for storage, reshuffles and retrieval of a command cycle is assumed to be an exponentially distributed delay process (an infinite server, denoted by IS). The service time of the pick station is assumed to be exponentially distributed and the queuing discipline is FCFS. Robots may have to queue at the pick station while the operator is still handling a previous load and there are K robots in the network.

3. Managerial Insights

The assessment of seven distinct operational strategies yields valuable insights for storage planners. Our findings demonstrate that the integration of supplementary data, including the number of loads per product and the frequency of access for products across different classes, significantly enhances the throughput efficiency of a given storage system. Notably, we conduct a comprehensive comparison and analysis of the prevailing AutoStore strategy against both random selection and a novel class-based approach. Our results reveal that while the AutoStore strategy performs comparably to random selection, the class-based approach demonstrates promising improvements. Moreover, we ascertain upper and lower bounds for the length-to-width ratio in RCS/R systems, along with identifying the optimal positioning for pick stations—preferably located at the midpoint of the longer side within an RCS/R system.

4. Conclusions

Our study introduces diverse models for calculating throughput capacity in multi-deep AS/R and RCS/R systems, offering practical utility during the design phase of new storage facilities. By comparing the AutoStore strategy with a newly proposed class-based alternative, we advocate for enhancements to the AutoStore approach based on our comparative analyses. Furthermore, our research lays the groundwork for developing throughput models applicable to other storage systems, such as the PowerCube (Jungheinrich 2023) or AVS/R systems, fostering broader insights into optimal storage system design and operational efficiency.

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