European Journal of Operational Research 242 (2015) 72–87

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Production, Manufacturing and Logistics

Queuing models to analyze dwell-point and cross-aisle location in autonomous vehicle-based warehouse systems

Debjit Roy [a,*], Ananth Krishnamurthy [b], Sunderesh Heragu [c], Charles Malmborg [d]

[a] Production and Quantitative Methods Area, Indian Institute of Management, Ahmedabad, Gujarat 380015, India
[b] Department of Industrial and Systems Engineering, University of Wisconsin-Madison, Madison, WI 53706, USA
[c] School of Industrial Engineering and Management, Oklahoma State University, Stillwater, OK 74078, USA
[d] Department of Industrial and Systems Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180, USA

ARTICLE INFO

Article history:
Received 8 May 2013
Accepted 22 September 2014
Available online 2 October 2014

Keywords:
Logistics
Facilities planning and design
Queuing
Simulation

ABSTRACT

Technological innovations in warehouse automation systems, such as Autonomous Vehicle based Storage and Retrieval System (AVS/RS), are geared towards achieving greater operational efficiency and flexibility that would be necessary in warehouses of the future. AVS/RS relies on autonomous vehicles and lifts for horizontal and vertical transfer of unit-loads respectively. To implement a new technology such as AVS/RS, the choice of a design variable setting, interactions among the design variables, and the design trade-offs need to be well understood. In particular, design decisions such as the choice of vehicle dwell-point and location of cross-aisles could significantly affect the performance of an AVS/RS. Hence, we investigate the effect of these design decisions using customized analytical models based on multi-class semi-open queuing network theory. Numerical studies suggest that the average percentage reduction in storage and retrieval transactions with appropriate choice of dwell-point is about 8 percent and 4 percent respectively. While end of aisle location of the cross-aisle is commonly used in practice, our model suggests that there exists a better cross-aisle location within a tier (about 15 percent from end of aisle); however, the cycle time benefits by choosing the optimal cross-aisle location in comparison to the end of aisle cross-aisle location is marginal. Detailed simulations also indicate that the analytical model yields fairly accurate results.

1. Introduction

To achieve greater operational efficiency and drive competitive advantage, many distribution centers are increasingly interested in adopting automated technologies such as autonomous vehicle-based automated storage and retrieval systems (AVS/RS) for processing unit load transactions in their high density storage areas (Heragu, Cai, Krishnamurthy, & Malmborg, 2008). Savoye Logistics, a France-based equipment manufacturer, pioneered the development of Autonomous Vehicle-based Storage and retrieval system (AVS/RS) (see www.sayove.com). Today, there are more than 35 AVS/RS implementations in Europe and several implementations are currently being planned in USA. Further, several variants of AVS/RS are introduced by Vanderlande Industries and Nedcon.

An AVS/RS consists of autonomous vehicles, lifts, and a rail guide-path within the rack area. The empty or pallet-loaded vehicle navigates along the x-axis (depth of a tier) and the y-axis (width of a tier) using rail guide-paths and travels along the z-axis using lift mechanism. Autonomous vehicles transport pallets along z-axis (vertical direction) between tiers using lifts. A warehouse that uses AVS/RS in the high-density storage area is described in Fig. 1a. A portion of a multi-tier system that illustrates the vehicle-lift interface is depicted in Fig. 1b. Fig. 1c shows a vehicle unloading a pallet on a conveyor roller during the retrieval process. Fig. 2 illustrates the structural components of a multi-tier AVS/RS using a wire-frame model. A multi-tier system is composed of several single tiers. Each tier has a cross-aisle and several aisles. The storage locations, which are single-deep, are located on either side of the aisle. Using a combination of vehicle (horizontal) and lift (vertical) movement, the pallets are being transferred from the load/unload point (LU point) of the first tier to the rack location for processing storage requests or the pallets are being delivered from the rack location to the LU point for processing the retrieval requests.

Conceptualizing system designs using AVS/RS is a prohibitive task because a large number of operational and system design variables, and interactions among them affect the system performance. Design parameters such as location of cross-aisle and depth/width ($\frac{D}{W}$) ratio, vehicle dispatching policy, and dwell-point location have

* Corresponding author. Tel.: +91 7966324823; fax: +91 7966326896.
E-mail address: debjit@iimahd.ernet.in (D. Roy).

http://dx.doi.org/10.1016/j.ejor.2014.09.040
0377-2217/

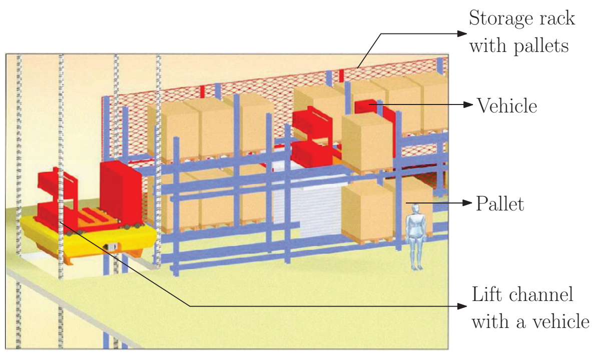

Fig. 1. Illustration of vehicle-lift interface in AVS/RS.

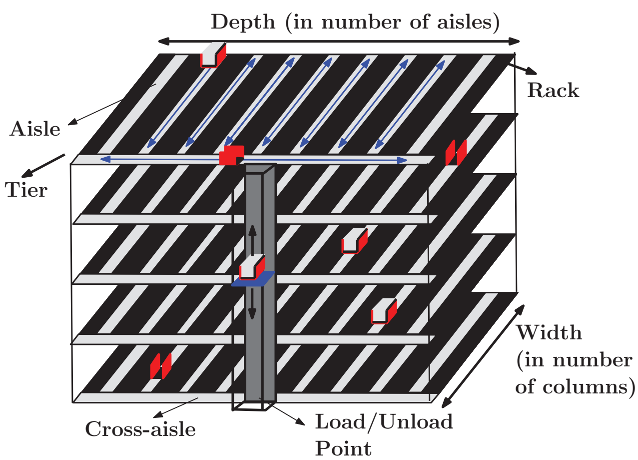

Fig. 2. Wire-frame model of a multi-tier AVS/RS.

performance implications on the system. In practice, the final design is typically obtained after simulating a few configurations in detail and selecting the best among them. The design is improved over time using the performance feedback from live implementations. Therefore, developing analytical models, which can rapidly explore the design space and identify the optimal set of design parameter combinations, can significantly mitigate the risks associated with investments in new technologies. By effectively leveraging advances in automation technology and system design principles, warehouses can achieve greater operational efficiencies.

The initial research focus in AVS/RS was to develop analytical models and obtain aggregate performance measures such as expected throughput times, resource utilization, and expected transaction waiting times (see Malmborg, 2002; Malmborg, 2003; Kuo, Krishnamurthy, & Malmborg, 2007; Fukunari & Malmborg, 2009; Zhang, Krishnamurthy, Malmborg, & Heragu, 2009). In these studies, the emphasis was on understanding the performance of systems with Point of Service Completion (POSC) dwell-point policy and end of aisle location of the cross-aisle.

The dwell-point of a vehicle denotes the location where a vehicle idles after processing a transaction. The choice of a dwell-point policy influences the travel time to process a subsequent transaction. For example, if a vehicle dwells at the point of service completion and the subsequent transaction involves retrieving a pallet from the same aisle, then the POSC dwell-point decision is an efficient choice. However, if the subsequent transaction is a storage transaction then LU dwell-point would have been a better dwell-point choice because the pallet (to be stored) is available at the LU point. Therefore, analytical models can help to arrive at an efficient choice of dwell-point policy.

In AVS/RS, cycle time savings may also be obtained by varying the location of the cross-aisle. The location of the cross-aisle influences the horizontal travel time along the direction of an aisle (y-axis). It is not apparent which location among the three choices: end of the aisle, center of the aisle, or somewhere in between is the best choice to place a cross-aisle. Analytical models can help to arrive at an efficient choice of placing the cross-aisle. Due to high-density storage space and additional cost associated with the placement of multiple cross-aisles, only one cross-aisle design is considered in this research.

Zhang (2008) showed that the travel time due to x- and y-axis movement of a vehicle within tiers is a substantial portion (typically between 25 percent and 45 percent) of the total cycle time. Therefore, this research focuses on optimizing the design policies for a single tier will improve the overall system performance.

First, a queuing model of a single tier is developed with LU dwell-point policy and cross-aisle located at the end of the aisle. This model is a multi-class semi-open queuing network model with class switching. The model precisely captures the transaction wait times at the transaction and vehicle synchronization station. The type of vehicle assigned to a transaction (for instance a vehicle situated in the racks versus a vehicle situated at the LU point) is represented with two classes and the vehicles switch their class using a class-switching rule. The queuing model has a non-product form structure, which would require complex analysis to solve in its original form. Therefore, a novel decomposition based approach is adopted to evaluate the model. A detailed simulation model is built and design of experiments is performed to validate the analytical model. The decomposition-based solution approach provides reasonable accuracy for all practical objectives of performance evaluation for a complex system (such as AVS/RS). This model provides the flexibility to analyze the effect of multiple design parameters. For instance, by altering the service time parameters of the analytical model with LU dwell-point policy, the system performance with varying cross-aisle location is evaluated. Numerical studies are performed to develop design insights.

The rest of this paper is organized as follows. Relevant literature is discussed in Section 2. The system description, design trade-offs, and queuing models to analyze the effect of dwell-point policies are presented in Section 3. Similarly, the queuing model to analyze the effect of cross-aisle location is described in Section 4. The solution approach to evaluate the queuing network models and the expressions to obtain the performance measures are included in Section 5. A detailed simulation model is used to study the efficacy of the analytical model. The model validation results and design insights are discussed in Section 6. The conclusions and possible extensions of this research are summarized in Section 7.

2. Literature review

We study relevant literature in three areas: dwell-point policies, cross-aisle location, and AVS/RS models.

1. *Dwell-point policies:* Design policies such as choice of resource dwell-point have been studied in the context of AS/RS using optimization and probabilistic models. In a typical AS/RS, there are multiple parallel aisles of racks with storage cells, a storage retrieval (S/R) machine for each aisle and a Load/Unload (LU) station at the end of the aisle (see Appendix A for basic differences between an AS/RS and an AVS/RS). Park (1999) showed that LU dwell-point policy is optimal for automated storage/retrieval systems with square-in-time racks and dedicated storage. van den Berg (2002) developed analytical expressions and a search routine for determining the optimal dwell-point in AS/RS with randomized and class-based storage policies. Ventura and Lee (2003) proposed an exact polynomial-time algorithm and illustrated that by placing dwell-points at certain pick-up station locations, the throughput time can be minimized in a unidirectional single-loop Automated Guided Vehicle (AGV) system. Meller and Mungwattana (2005)