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# COORDINATED CONTROL OF MULTI-ZONE AVS/RS, CONVEYORS AND PICK-UP OPERATIONS IN WAREHOUSE SYSTEM

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## ABSTRACT

During recent years, Autonomous Vehicle Storage and Retrieval Systems (AVS/RS) have been widely applied to meet the increasing demand for rapid and flexible large-scale storage and retrieval tasks. This paper focuses on the control strategies for coordinating the subsystem operations with regard to the conveyor system, rack storage system and pick-up system in order to maximize the system's throughput capacity and minimize the storage/retrieval times of items in an e-commerce picking warehouse. The study is based on a large-scale shoe manufacturer's warehouse with an eight-zone AVS/RS. We describe a simulation model that was built to validate the proposed control strategies and thus provides insights for system management.

## 1 INTRODUCTION

During the past decade, autonomous vehicle storage and retrieval system (AVS/RS) technology has been widely applied to automated production and warehouse control, and has proven successful especially for use with relatively lightweight loads. These systems facilitate rapid storage and retrieval and also improve overall system flexibility. An AVS/RS typically uses both vertical machines (lifts) and horizontal machines (vehicles) for items' in-store and out-store operations to and from locations in storage racks. In addition to the rack, lifts, and vehicles, the warehouse system needs other subsystems to support those in-store and out-store operations, for example a conveyor system responsible for controlling SKUs' inflow and outflow to/from the storage, as well as a pick-up system responsible for picking up SKUs and returning container units. To improve overall system performance, coordination among these subsystems is necessary.

This paper focus on improving the overall performance of the AVS/RS based warehouse system through coordination of the conveyor system as well as pick-up system with the rack storage system. Such warehouse system is first viewed as a Semi-Open Queuing Network (SOQN) which could be parameterized by arrival rates of new SKUs and out-store requests, storage and retrieval service times of the rack system, and pick-up pattern. Then the system is further analyzed by taking into account practical constraints including conveyors lengths, container unit dimensions, buffers capacities, and also transient effects including blocking on conveyor system and unbalanced inventories. With such considerations, a simulation model is developed to explore interactions between subsystems and system control polices. We use the simulation to study the coordination between the rack system and the conveyor system in particular. We also conduct an experiment to compare results of different coordination policies based on different throughput and pick-up assumptions. Recommendations are made for improving system performance under high throughput levels.

This paper is organized as follows. The next section provides a brief review of relevant literature involving design and control of AVS/RS based warehouses. Section 3 describes the subsystem

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configuration and workflows of a typical AVS/RS-based warehouse. In sections 4 and 5 further system analysis is conducted, and decisions and methods regarding to coordinated control of the subsystems are discussed. The simulation model is introduced in section 6 and an experiment comparing control methods and the statistical results are described in section 7.

## 2 LITERATURE REVIEW

Ever since its first conceptualization by Malmborg (2002), the autonomous vehicle storage and retrieval system (AVS/RS) has gained vast research interests from practitioners. An AVS/RS is characterized by horizontally operating vehicles sharing a fixed number of lifts for vertical movement (Malmborg 2002). Comparing with its traditional counterparts like crane-based automated storage and retrieval system (CBS/RS), AVS/RS provides user more flexibility in system design and assets configuration. Variations to further improve system performance and reduce costs are studied. Two configurations of AVS/RS are introduced by Marchet et al. (2013), namely tier-captive and tier-to-tier. Unlike the tier-captive configuration where each tier has one vehicle, in the tier-to-tier configuration vehicles ride lifts to move between tiers, and thus less number of vehicles are needed and costs are reduced. Hu et al. (2005) introduced split-platform storage and retrieval system (SP-AS/RS), where the same tiers in two adjacent racks share a shuttle. Carlo and Vis (2012) introduced a variation to AVS/RS and named it shuttle-based storage and retrieval system (SBS/RS). Two non-passing lifts and buffer conveyors are used in a SBS/RS.

Design and control methods to optimize the performance of the AVS/RS are widely discussed, where queuing analysis and/or simulation technique are typically used. Fukunari and Malmborg (2009) estimated the throughput of an AVS/RS based on a network queuing approach. Heragu et al. (2011) developed effective travel time models for the vehicles and lifts as in AVS/RS and also for cranes as in traditional AS/RS, based on which system performance with different lift machines configurations are analyzed. Erken et al. (2015) presented simulation analysis for SBS/RS and explored the effects of various design assumptions. Tappia et al. (2016) develop queuing models which can handle both specialized and generic shuttles and both continuous and discrete lifts of multitier shuttle-based compact storage systems, and validated their models using simulation. Ha and Chae (2019) developed a decision model to determine number of shuttles of the SBS/RS.

Approaches for improving the overall performance of the warehouse system are studied by fewer researchers. Amato et al. (2005) suggested a control architecture for management of automated warehouses. De Koster et al. (2007) investigated different methodologies of design and control of warehouse order picking, multiple aspects the systems are discussed for both picker-to-order and order-to-picker systems.

## 3 SYSTEM DESCRIPTION

A typical AVS/RS based warehouses could be viewed as three consisting subsystems: a Rack Storage System, a Conveyor System, and a Pick-up System (Figure 1).

In this study, the following definitions are used: a basic item of customer goods (e.g. a box of shoes in shoe industry case) is referred as a **Stock Keeping Unit (SKU)**. Such basic items are usually packed in, transported in, and picked up from container units. A **Bin** is a container unit for SKUs (e.g. a large paper box which contains multiple boxes of shoes). It is the basic unit for all storage and retrieval operations in the Rack Storage System. It is also the smallest unit for all transportation operations in the Conveyor System. After all SKUs in the bin container are picked up, the empty bin generally leaves the system (abandoned or goes for recycling).

New SKUs typically come in batches of bins, they arrive to the warehouse, then enter the Conveyor System and finally enter the Rack Storage System. When a SKU in storage is called by an out-store request, its bin is retrieved from storage, conveyed to the Pick-up Stations, and finally the requested SKU is picked out, while the remaining SKUs together with the bin is conveyed back to the storage.

### 3.1 Rack Storage System

The Rack Storage System consists of a number of AVS/RSs, each is defined as a **zone**. Each AVS/RS has multiple **levels** (tiers), and each **level** has multiple **cells** (storage locations). Each AVS/RS has its own set of **vehicles** responsible for storing a bin to a cell or retrieving a bin from a cell. Although two non-passing lifts and buffer conveyors are used in a SBS/RS (Carlo and Vis, 2012), in this study we assume that a single **Lift** is supporting the elevation and taking-down operations with regard to the AVS/RS(s) in its zone. As showed in Figure 2, the elevation and taking-down operations are mutually exclusive in the single-lift case. It is also assumed here that each zone has a single AVS/RS. Further, all AVS/RSs are assumed to be tier-captive (thus vehicles are not moving across levels).

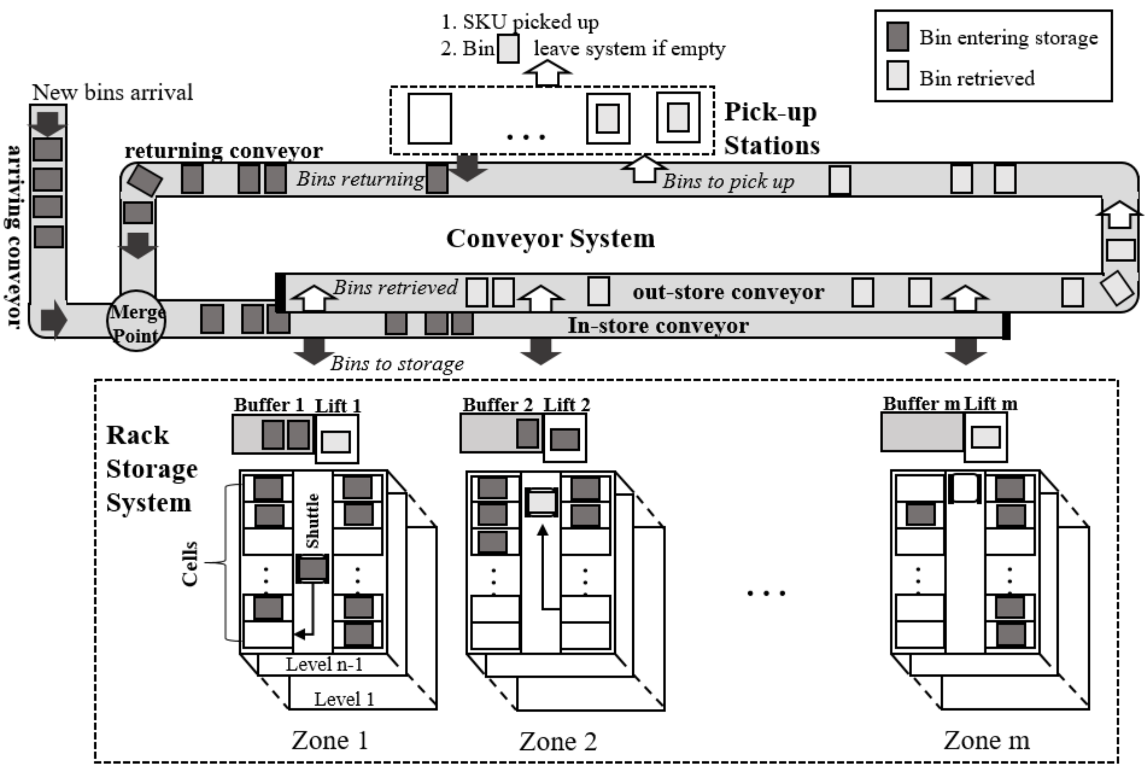


Figure 1: Illustration of an AVS/RS-based warehouse system.

### 3.2 Conveyor System

The transportation of bins is typically facilitated by a unidirectional **roller-type** conveyor system. A roller-type conveyor is accumulating, which means if a bin stops on the conveyor, the bins behind it will continue to be conveyed until the first of them reached the position right after the stopped one. This is different from the belt-type conveyors, on which a stopped bin will immediately stop all other bins as well.

**Merge point** is the point on the conveyor system where the arriving conveyor and returning conveyor merges to the in-store conveyor. Dynamic priority rules may apply here to control the flow of the two different types of bins in order to maximize the overall flow speed of the system. In this study the scope is limited to the First-come-first-serve (FCFS) rule.

Bins trying to enter the rack storage system are transported by a single in-store conveyor. When arriving at the **Enter point** in front of the assigned zone, the bin either waits to be taken off the conveyor and enter the zone or continue to be conveyed towards the next zone (Figure 2). For each zone, a **Lift buffer** at ground floor is set as the waiting area for a lift machine's elevation services. It is typically a short conveyor in-between the main conveyor and the lift. Bins left the rack storage system will be placed on a single out-store conveyor and then conveyed to the pick-up stations.

### 3.3 Pick-up System

The pick-up system consists of one or more pick-up station(s). According to out-store request, one or more SKUs will be removed from the bin. If the bin becomes empty after the removal, the bin will leave the system. Otherwise the bin is routed to the returning conveyor to be put back into storage by the lift/vehicle system.

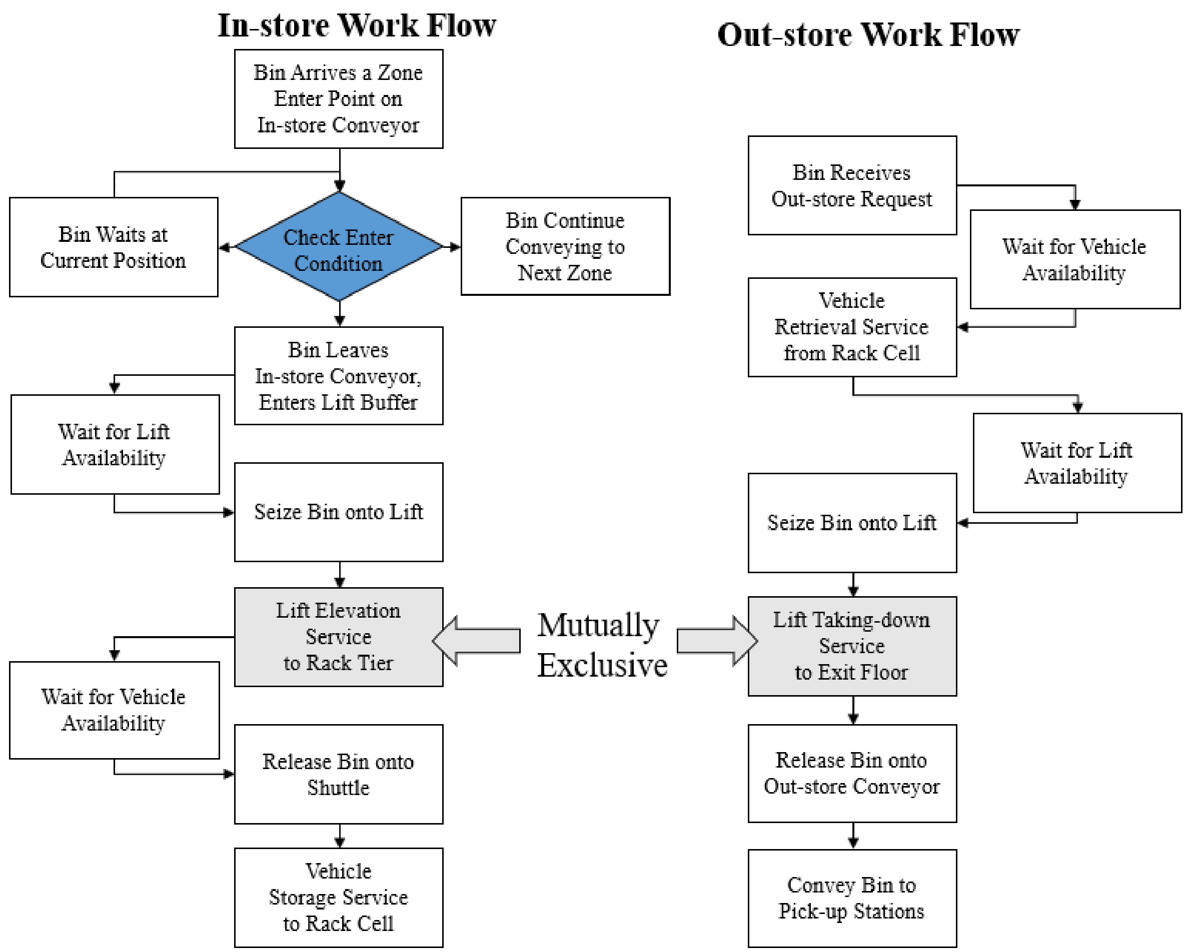


Figure 2: In-store and out-store work flows of an AVS/RS-based warehouse system.

## 4 SYSTEM ANALYSIS

The purposes of the system control could be viewed in two related aspects: to improve the maximize system throughput of customer goods (SKUs), and to improve the fulfillment performance of out-store requests.

### 4.1 Notation and Assumptions

In this study, each AVS/RS in the rack storage system is assumed to be tier-captive and supported by a single lift. The lift is assumed to follow a simple policy: the lift will stay idle at its current location until called by the next task request. When the lift has completed an elevation task, if there exist any taking-down request, the lift will always go for this taking-down task first. Similarly, when completed a taking-down task and there exist any elevation request, the lift will always go for the elevation task first.

The AVS/RSs in the rack storage system are assumed identical in terms of size and capacity. Lifts, lift buffers and vehicles are also assumed identical for all AVS/RSs. It is also assumed that the expected service times of the lift transactions ($\tau\_L_{in}$, $\tau\_L_{out}$) are larger than those of the vehicle transactions ($\tau\_V_{in}$, $\tau\_V_{out}$) and pick-up transactions (τ_P), so that the lift service times become the only rigid bottlenecks that constraint the system's maximum theoretical throughputs ($T_{Bin}$, $T_{SKU}$).

It is assumed that each out-store request only calls on a single bin randomly selected from inventory bins with equal probabilities, and a random quantity of SKUs in this bin are decided to be picked-up. This request is viewed as fulfilled once the pick-up transaction of its bin is completed.

Table 1: Parameters definition of a typical AVS/RS based warehouse system.

| **Parameter** | **Description** |
|---|---|
| $M$ | Number of zones (thus number of AVS/RS and also number of in-store conveyor sections) in the rack storage systems |
| $N$ | Number of pick-up stations |
| $B$ | Batch size of arriving bins |
| $Q$ | Capacity of number of SKUs in a bin |
| $P$ | Average number of SKUs requests call from a bin |
| $P_i$ | Number of SKUs a request *i* call from a bin |
| $k$ | Bin return rate after pick-up operation, defined as (Q-P)/Q |
| $CB_m$ | Capacity of lift buffer m |
| $CC_m$ | Capacity of in-store conveyor section m |
| $\lambda_{in}$ | Arrival rate of new bins |
| $\lambda_{out}$ | Arrival rate of out-store requests, assuming each request calls on one bin |
| $\tau\_L_{in}$ | Expected travel time a lift takes for a storage transaction |
| $\tau\_L_{out}$ | Expected travel time a lift takes for a retrieval transaction |
| $\rho_L$ | Expected utilization of lift |
| $\tau\_V_{in}$ | Expected travel time a vehicle takes for a storage transaction |
| $\tau\_V_{out}$ | Expected travel time a vehicle takes for a retrieval transaction |
| $\tau\_P$ | Processing time in a pick-up station |
| $T_{Bin}$ | Throughput (Bins) |
| $T_{SKU}$ | Throughput (SKUs) |
| $FT$ | Requests' average fulfillment time |
| $fT_i$ | Request i's fulfillment time |

## 4.2 Steady-state Analysis

Consider the pick-up and return process described in section 3. When the system is in steady state, the SKUs' expected throughput $E(T_{SKU})$ should be a constant multiplier to the bins throughput $T_{Bin}$:

$$E(T_{Bin}) = \frac{P}{Q}E(T_{SKU}).$$

For the system to be in steady state, two conditions should hold:

1) For the overall system, overall bin inflow and outflow should be equal.
2) For all AVS/RSs, the bin inflow and outflow should be equally divided by number of zones from the total inflow and outflow of the overall system.

From Figure 3, the following equation must stand:

$$E(T_{Bin}) = \lambda_{out} = (B\lambda_{in} + k\lambda_{out}), \text{ thus:}$$

$$\lambda_{in} = (1-k)\frac{\lambda_{out}}{B}, \text{ where } k = \frac{Q-P}{Q}.$$

Based on the two steady-state conditions, it is reasonable to define expected lift service time $\tau_L = \tau_{L_{in}} = \tau_{L_{out}}$, the expected lift utilization $\rho_L$ could be computed as:

$$\rho_L = \tau_L\left(\frac{(B\lambda_{in}+k\lambda_{out})+\lambda_{out}}{M}\right).$$

this equation could be rewritten as:

$$\rho_L = \frac{2\tau_L \cdot \lambda_{out}}{M}.$$

The equation above indicates that, for a system of $M$ AVS/RSs each supported by a lift with expected service time $\tau_L$, the system's expected lift utilization rate $\rho_L$ could be obtained by just knowing the requests arrival rate $\lambda_{out}$ (which is equal to system throughput $E(T_{Bin})$). The theoretical maximum system throughput could be computed given $\rho_L$ = 100%.

The requests fulfillment time is the main indicator measuring the system's performance. The fulfillment time $f_i$ of an request *i* is defined as:

$$ft_i = c_i - p_i.$$

where $p_i$ is request placement time, and $c_i$ is request pick-up completion time. The computation of requests' average fulfillment time $FT$ is weighted based on the SKU quantity in each request:

$$FT = \frac{\sum_i P_i \cdot fT_i}{\sum_i P_i}.$$

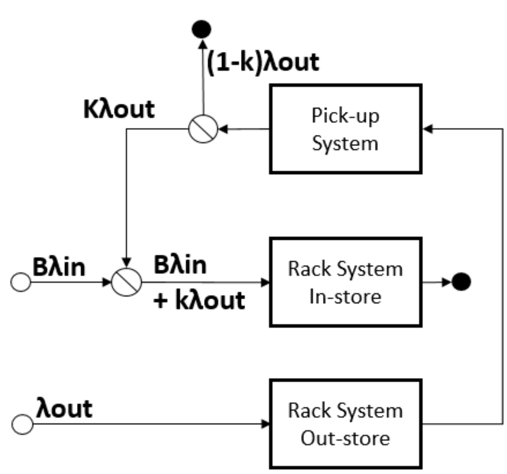


Figure 3: Steady-state Analysis of an AVS/RS-based warehouse system.

The two conditions for steady-state system are for ideal situation and do not always hold in practical implementations. The practical system does not allow for infinite queues anywhere, thus the theoretical maximum throughput could never be achieved due to physical constraints including footprint of the zones, capacity of each conveyor section, capacity of lift buffers, capacity and instantaneous inventory level of each AVS/RS and so on.

Furthermore, two effects would further deteriorate the system performance: unbalanced machine utilization due to unbalanced bin flows, as well as blocking effects on the conveyor system. Lessening these two effects are the main targets of the coordinated controlling studied here.

## 4.3 Unbalanced Utilization Effects due to Unbalanced Inventory Levels

Define $I_m$ as the instantaneous bins inventory of rack storage $m$. Define $I$ as the instantaneous total bins inventory in the rack storage system. As assumed in section 4.1 that an out-store request calls on an bin from all inventory bins with equal probability, the "transient" requests arrival rate to zone $m$ is approximately:

$$\lambda_{out_M} = \lambda_{out} \frac{I_m}{I}.$$

While a zone has higher inventory level $I_m$ in its AVS/RS than other zones, this zone is expected to receive more requests arrivals, and thus introducing heavier retrieval workload to its lift. The end result of this is not just deterioration of requests fulfillment times, but also negative effects on the service for in-store transactions. In order to keep the inventory levels balanced, bin inflows need to be controlled wisely.

## 4.4 Blocking Effects on Conveyor System

As the in-store bin flow is conveyed by a single in-store conveyor, a single bin could block all the following bins in the flow. Two blocking cases are possible and are shown in Figure 4. Both cases would deteriorate the system throughput and lower machine utilization and should be avoided as much as possible.

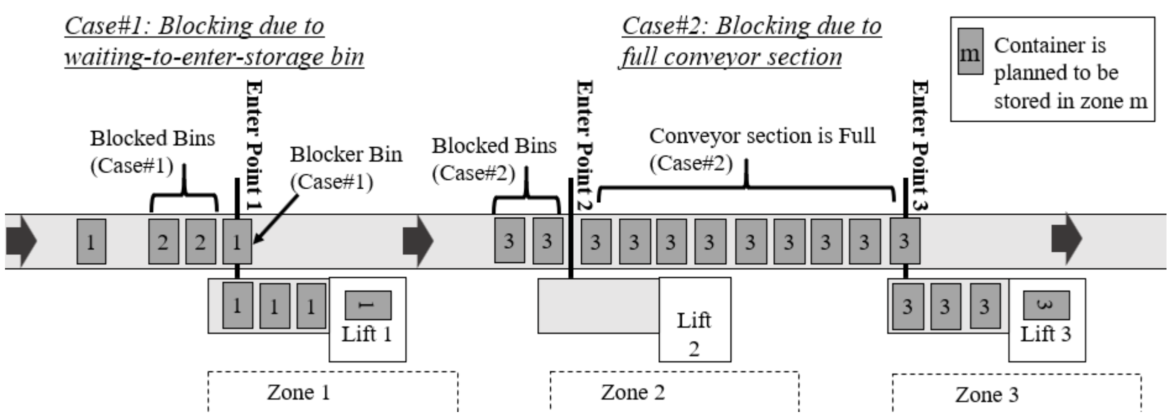


Figure 4: Illustration of blocking effects on conveyor.

Consider the case where a bin is trying to enter a zone for lift service while the lift buffer is full. In this case the bin has to wait on the conveyor, thus blocking all bins behind it until the buffer has space. In Figure 4, Case#1, a bin is waiting to enter zone #1, but the lift is busy servicing other bins and its buffer is also full. Thus this bin blocked following bins, even though some of those bin are trying to go to zone #2, whose lift is idle. Another blocking case is illustrated in Figure 4, Case#2. Each section of the conveyor could only carry a limited number of bins. Once this section is full, the bins directly behind it could not be conveyed forward anymore.

## 5 COORDINATED CONTROL OF STORAGE INFLOW

As discussed in the previous section, controlling the bin inflows on conveyor and balancing inventory levels both have significant impact to the order fulfillment performance: the former determines the efficiency of inflows (balance in-store elevation workload and avoid conveyor blocking), and the later affects the outflows (balance out-store taking-down workload). Planning the storage assignment wisely is thus important here. Meanwhile, conveyor blocking should be avoided as much as possible to reduce unnecessary satisfaction of the system performance.

On the other hand, the complexity of the control method is often constrained by conveyor-side hardware components, e.g. PLCs and scanners. Simple control methods which are "good enough" are often preferred over ones that search for optimal solutions but are complicated in implementation. Three different control policies are proposed (Table 2). These policies control the go and no-go of each bin when the bin arrives the enter point of each zone (as highlighted in Figure 2), and periodical controlling of lift buffers is applied for inventory balancing. A random assignment policy is also introduced as a baseline for comparison.

Table 2: Inflow Control Policies.

| **Policy Name** | **Check Position(s) on In-store Conveyor** | **Lift Buffer Control** |
|---|---|---|
| Enter When Possible (EWP) | Zone Enter Points | Yes |
| Forward As Much As Possible (FWD) | Zone Enter Points | Yes |
| Balanced Assignment (BLC) | Conveyor Entrance | Yes |
| Random Assignment (RND) | Conveyor Entrance | No |

### 5.1 Dynamic Control of Lift Buffer

Although the physical capacity of each lift buffer is normally fixed during the design phase, by dynamically controlling the maximum allowed bins in each lift buffer, the in-store flows to the rack storage zones would be balanced.

This lift buffer control policy is supposed to work together with the entering control policies. The following control is taken periodically with interval $D_T$:

```
CB_m: capacity of lift buffer m. CB_m = 3 in this study
CB'_m: number of bins allowed in lift buffer m
D_N: buffer adjust factor
Ī: average inventory level of M zones
For each zone m:
    If(I_m > Ī + 4D_N): CB'_m = 0 (close buffer)
    Else If(I_m > Ī + 2D_N): CB'_m = 1
    Else If(I_m > Ī + D_N): CB'_m = 2
    Else: CB'_m = CB_m
```

Where values of $D_T$ and $D_N$ should be decided based on the expected throughput of each AVS/RS. When a lift buffer's current size reaches its current allowed limit $CB'_m$, it is considered as **full** and bins are not allowed to enter it.

### 5.2 Enter When Possible (EWP)

Bins are conveyed forward on the in-store conveyor and thus visiting the enter points one after another. This policy focuses on maximizing the bin inflow. With this policy, a bin will try to get off and enter the storage whenever it is possible. When a bin arrives the enter point of any zone $m$:

```
If(m==M)
    Bin try to enter lift buffer m;
Else
    If(lift buffer m is full)
        Bin continue conveying until reaches entering point of zone m+1;
    Else
        Bin enter lift buffer of zone m;
```

### 5.3 Forward As Much As Possible (FWD)

This policy focuses on minimizing the blocking effects. With this policy, a bin will be conveyed forward as much as possible, until it could no longer enter the next conveyor section. Whenever a bin arrives the enter point of any zone $m$:

```
Find last zone M' whose lift buffer is not closed (CB'_{M'} > 0). M' ≤ M
If(m==M')
    Bin try to enter lift buffer m;
Else
    If(lift buffer m+1 is full AND conveyor section m+1 is full)
        Bin try to enter lift buffer m;
    Else
        Bin continue conveying until reaches entering point zone m+1;
```

### 5.4 Balanced Assignment (BLC)

This policy focuses on balancing the bin inflows and also minimizing the blocking effects. With this policy, a bin is assigned a target storage zone in advance when it enters the conveyor. When a bin passes the conveyor merge point and enters the in-store conveyor:

```
NT_m: number of bins currently targeting to zone m
Find zone m* ϵ [1,M] with smallest NT_m. For ties, pick the larger (further) one.
NT_{m*} = NT_{m*} +1
```

The bin will be conveyed until it reaches the entering point of target zone $m^*$. Then, the bin will try to enter lift buffer $m^*$: when the bin successfully entered lift buffer $m^*$, set $NT_{m^*} = NT_{m^*}$ - 1. If the lift buffer $m^*$ is currently full, the bin has to wait on conveyor until availability in lift buffer $m^*$.

### 5.5 Random Assignment (RND)

This police works similar to the Balanced Assignment, the only difference is that when entering the conveyor, bin is randomly assigned any of the zones with equal probabilities. The purpose of introducing this police is just to study the "not-controlled" state of the inflow.

## 6 SIMULATION MODELLING

A Discrete Event Simulation model is developed using the AnyLogic 8.4 (Figure 4). AnyLogic is a multimethod simulation modeling tool (Grigoryev 2015). An eight-zone AVS/RS based warehouse system is modelled.

### 6.1 Model Parameters

The main parameters of the model are presented in Table 3. Section lengths between zones enter points on in-store conveyor and section lengths between zone exit points on out-store conveyor are both 10 meters. Based on the bin size and minimum gap between bins, the maximum capacity of each conveyor section ($CC_m$) is decided to be 15. The arrival of out-store requests is modeled as Markovian Arrival Process. The arrival of new bins batch is modeled as Markovian Arrival Process, in which each batch contains $B = 20$ bins.

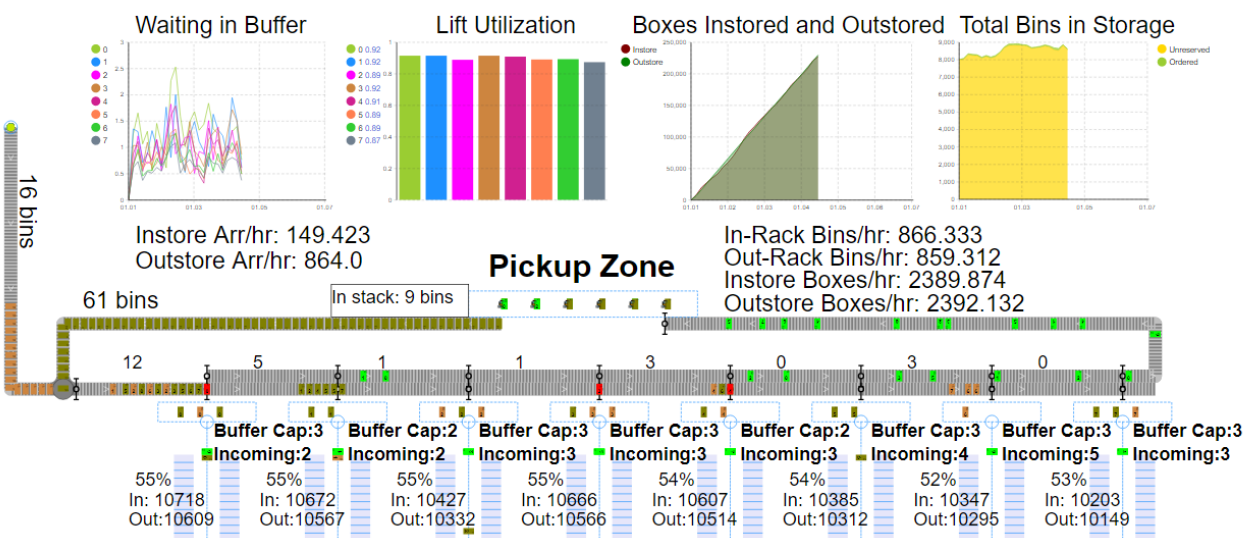


Figure 4: Simulation Model built with AnyLogic.

Table 3: Simulation Model Parameters.

| **AVS/RS Parameters** | | **Conveyor System Parameters** | |
|---|---|---|---|
| Number of zones: $M$ | 8 | Conveyor type | Roller |
| Number of tiers $S_T$ | 10 | Conveyor speed | 1m/s |
| Number of rack cells per tier $S_R$ | 200 | In-store conveyor length | 80m |
| Lift mode | Single lift | Out-store conveyor length | 70+45=115m |
| Lift buffer capacity | 3 | Returning conveyor length | 35m |
| Vehicle mode | Tier-captive | Capacity per section $CC_m$ | 15 |

Finally, 6 pick-up stations are modeled in the simulation – each with 30 seconds processing time per bin. Because the returning conveyor has limited capacity due to its length, when the returning conveyor is full, returning bins will be stacked in the pick-up zone.

### 6.2 Result Indicators

Various indicators are recorded from simulation and presented either as statistics or as charts tracking the simulation (Figure 4). Three indicator sets are recorded at the end of simulation:

1) Request fulfillment time, including average, standard deviation, min, max, $75^{th}$ and $90^{th}$ percentile.
2) Lifts overall utilization, including average, standard deviation, min and max.
3) Average bin throughput and SKU throughput per hour.

## 7 EXPERIMENT

A Monte-Carlo experiment was conducted to compare performance of the 4 policies discussed in section 5 using scenarios over 5 expected throughput levels (Table 3) and 2 pick-up patterns (Table 4). 8 replications are conducted for each scenario, resulting in 320 total simulation runs. Each replication is run for 10 days, with 3 days warm up period.

Table 4: Throughput level configurations.

| Throughput Level Config# | Expected Lifts Service Time $\tau_L$ (seconds) | Expected Lifts Utilization $\rho_L$ | Expected Bin Throughput $T_{Bin}$ (per hour) |
|---|---|---|---|
| T1 | Uniform (5, 25) | 0.75 | 720 |
| T2 | | 0.80 | 768 |
| T3 | | 0.85 | 816 |
| T4 | | 0.90 | 864 |
| T5 | | 0.95 | 912 |

Table 5: Pick-up pattern configurations.

| Pick-up Config# | Bin SKUs Capacity $Q$ | Pick-up Quantity Distribution | Average Pick-up Quantity $P$ | Return Rate $k$ |
|---|---|---|---|---|
| P1 | 16 | Discrete Uniform (1, 5) | 2.7671 | 0.8271 |
| P2 | | Discrete Uniform (1, 9) | 4.2914 | 0.7318 |

(**$P$** and **$k$** are computed based on **$Q$** and the pick-up quantity distributions)

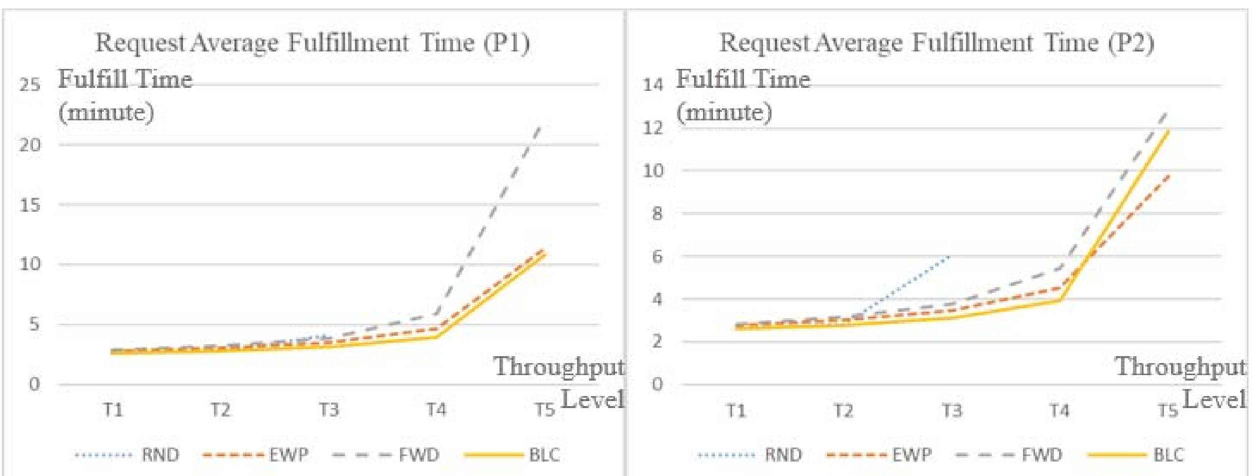


Figure 5: Experiment results of request fulfillment time (average).

The experiment results (Figure 5) show that with both pick-up patterns, when the throughput level is relatively low (where $\rho_L \leq 80\%$), the control policies show no advantage over the baseline (Random Assignment): the Balanced Assignment performs barely as good as the baseline, while the other two policies even slightly worse. However, when the throughput level is higher ($\rho_L$ = 85%), the control polices start outperforming the baseline. As the throughput gets even higher ($\rho_L \geq 90\%$), the system becomes unstable with the baseline policy. It is later observed that in baseline case $\rho_L$ could not exceed 87.5% due to blocking effects, and thus limiting the actual throughput. In most scenarios the Balanced Assignment policy works the best among the three control policies in improving the request fulfillment performance.

## 8 CONCLUSIONS

In this research, coordination between subsystems in AVS/RS based warehouse system is investigated. Results from a simulation experiment indicate the necessity of coordinated controlling under high throughput and thus high machine utilization. Future study may investigate coordinated controlling of warehouse based on various AS/RS configurations, including CBS/RS, SBS/RS with two-lift configurations, AVS/RS with tier-to-tier configuration and so on. More options of conveying system control policies and picking-up policies are promising to be explored as well.

## ACKNOWLEDGMENTS

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