Design and Operational Insights for Autonomous Vehicle-based Storage and Retrieval Systems

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Outline

1 Scope and System Description

2 Design Parameters and Trade-offs

3 Analytical Model to Evaluate Design Trade-offs

4 Design Insights and Effect on System Performance

5 Conclusions
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Typical Warehouse Functions and Flows

- Reserve storage & pallet picking
- Case picking
- Broken case picking
- Accumulation, sortation, and packing
- Shipping
- Replenishment
- Receiving
- Cross-docking
- Direct put away to reserve
- Direct put away to primary
- From suppliers
- From customers (returned, resused)

Scope of this research

- Reserve picking area handles unit-load operations
- Operations require high flexibility and responsiveness
AVS/R System: Overview

- AVS/RS: Uses autonomous vehicles
- System configuration
  - Rectilinear movement
  - Horizontal movement (x and y axes) by autonomous vehicles
  - Vertical movement (z axis) by lifts
  - Vehicles move between tiers using lifts
- Modular and adaptive design
## Comparison: AS/RS and AVS/RS

<table>
<thead>
<tr>
<th>Category</th>
<th>AS/RS</th>
<th>AVS/RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Configuration</td>
<td>Conveyors and Aisle-captive cranes as S/R devices</td>
<td>Vehicles and Lifts as S/R devices</td>
</tr>
<tr>
<td>Load Movement</td>
<td>Simultaneous</td>
<td>Sequential</td>
</tr>
<tr>
<td>Load/Unload Point</td>
<td>One per aisle</td>
<td>One per zone</td>
</tr>
<tr>
<td>System Throughput</td>
<td>Determined by capacity of crane per aisle and number of aisles</td>
<td>Determined by number of vehicles and lifts</td>
</tr>
</tbody>
</table>

**AVS/RS has potential to improve system efficiency, reliability, and throughput flexibility**
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Design Parameters in AVS/RS

System Sizing Decisions
- Number of vehicles and lifts, Depth/Width ratio
- Location of cross-aisle, number of zones

Operational Decisions
- Vehicle assignment rule, dwell point policy, command cycle
- Storage policy, transaction scheduling policy (FCFS, Random)

Need for Analytical Models
- Estimate transaction cycle time, queue lengths, throughput, vehicle utilization
- Quickly identify efficient operating range of design parameters
Research Questions

- **Influence of Depth/Width Ratio**
  - How does the Depth/Width ($\frac{D}{W}$) ratio (deep aisles and shallow cross-aisle or shallow aisles and deep cross-aisle or somewhere in between) affect the system performance?

- **Influence of dwell point policies**
  - How does the dwell point policy (Point of Service Completion (POSC), End of Aisle (EOA), and Load/Unload point (LU)) affect the system performance?

- **Influence of zones**
  - How does the number of zones affect the system performance?
What are the tradeoffs involved in single tier system with autonomous vehicles?

Efficient single tier systems form effective building blocks for multi-tier systems
Effect of Dwell Point Policy: Retrieval

How does the dwell point policy influence storage and retrieval cycle times?
Effect of Number of Zones: Retrieval

Case 1 - One Zone

Case 2 - Two Zones

vs.

Tradeoffs between: reduced horizontal travel and loss of vehicle pooling
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Assumptions

- **System Design Assumptions**
  - One Load/Unload point (relaxed later)
  - Single command cycle
  - Random vehicle assignment
  - POSC dwell point policy (relaxed later)
  - Random storage policy
  - FCFS transaction scheduling

- **Model Assumptions**
  - Poisson arrivals
  - No blocking during vehicle movement
Queuing Model to Analyze Design Trade-offs

Model solved using a decomposition-based approach
Performance Measures

1. Vehicle utilization
2. Average number of transactions waiting for service
3. Expected storage cycle time and retrieval cycle time
4. Distribution of vehicles in the tier
Model Validation against Simulation

1. Depth/Width Ratio = 0.5, 1, 1.5, 3
   \[ \frac{D}{W} = 0.5 \quad \frac{D}{W} = 1.0 \quad \frac{D}{W} = 1.5 \quad \frac{D}{W} = 3.0 \]

2. Number of storage locations = 2000, 4000, 7300

3. Number of vehicles = 1, 3, 5, 10

4. Transaction arrival rate (pallets/hr) = 20-430 in increments of 10 pallets/hr

- 240 cases analyzed using AutoMod© simulation package
- Maximum absolute percentage errors in vehicle utilization and cycle times are 2% and 10% respectively
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Effect of $\frac{D}{W}$ Ratio: Insight 1

What is the optimal Depth/Width Ratio=0.5, 1, 2 or 3?

- $\frac{D}{W} = 0.5$
- $\frac{D}{W} = 1.0$
- $\frac{D}{W} = 2.0$
- $\frac{D}{W} = 3.0$
Effect of $\frac{D}{W}$ Ratio: Insight 1

Depth/Width Ratio = 2 is the best choice
Effect of Number of Zones: Insight 2

One zone

Two zones

Five zones
Effect of Number of Zones: Insight 2

One zone
Increases vehicle travel times

Five zones
Increases transaction waiting times

Two zones
Typically 2-3 zones improves system performance
Effect of Dwell Point Policy: Insight 3

LU and EOA dwell point policies are better than POSC
Overall Impact of Design Parameters Setting

Example: 7300 Locations, 6 Vehicles, $\lambda_s, \lambda_r=(75,75)$ pallets/hr

<table>
<thead>
<tr>
<th>Comparison of Scenarios</th>
<th>$E[CT_s]$ (sec)</th>
<th>$E[CT_r]$ (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One Zone, POSC Dwell, $\frac{D}{W}=1.5$</td>
<td>147</td>
<td>187</td>
</tr>
<tr>
<td>Two Zones, LU Dwell, $\frac{D}{W}$ for each zone $=2$</td>
<td>97</td>
<td>128</td>
</tr>
</tbody>
</table>

$\sim$34% reduction in $E[CT_s]$ and $\sim$32% reduction in $E[CT_r]$ with Two Zones, LU Dwell, and $\frac{D}{W}=2$ for each zone
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Conclusions

- Developed analytical model of a single tier
- Model validates well against simulation
- Computationally inexpensive – quick results
- Provided design insights for a single tier
- The number of zones and the Depth/Width ratio have a significant impact on system performance.