Research on Autonomous Vehicle Storage and Retrieval System Cargo Location Optimization in E-commerce Automated Warehouse

Haoxiang Wang¹, Shouwen JI²*, and Gang Su³
¹Xi’an University of Architecture and Technology, Beilin District, Xi’an 710055, Shaanxi, China
²Beijing Jiaotong University, Haidian District, Beijing 100044, China
³Jiangsu golden harbor investment co. LTD, Lianyun District, Jiangsu 222042, China

*Corresponding author

Abstract. Cargo allocation optimization is important to improve the efficiency of e-commerce automated warehouse’s autonomous vehicle storage and retrieval system (AVS/RS) operations. Considering the electrical business logistics characteristic of small batch, batches, variety characteristics, this paper aiming at maximizing the highest efficiency and shelf stability for warehousing efficiency, we established an initial cargo location model, designed an adaptive multi-objective genetic algorithm. MATLAB software programming was used to implement the model solution, and an example verification was performed with an automation warehouse named Jing-dong in China. The comparison between the initial cargo location model and the random storage strategy shows that the model can significantly improve the overall warehousing efficiency and shelf stability of AVS/RS.

Keywords: Autonomous vehicle storage and retrieval system (AVS/RS); Genetic algorithm; Storage location allocation, Storage efficiency; Storage stability.

1. Introduction

In recent years, China's e-commerce logistics has developed rapidly. In order to adapt to the characteristics of small volume, large batches, multiple types, and high order volatility that are unique to e-commerce warehousing and distribution, the autonomous vehicle storage and retrieval system (AVS/RS) in e-commerce logistics applications field is becoming more and more widespread. Cargo allocation directly affects the efficiency of AVS/RS's warehousing, shelving, and picking operations, which is an important part of AVS/RS operation optimization.

Scholars at home and abroad have earlier carried out researches on allocation strategies, adjustment and redistribution of cargo spaces, and automatic storage and retrieval systems for trolleys.

In terms of location allocation strategy, Chen L, Langevin A and Riopel D [1] built a location allocation model based on the AS/RS warehouse, and considered the shared storage principle and duration strategy, with the shortest average picking time as the objective function. C. C. Mu and M. Guo [2] proposed a strategy for allocation of goods into warehouses based on product frequency and a strategy for allocation of goods to warehouse based on product deviation. Y. H. Zhang [3] used the ABC classification principle, combined with the historical order data of the commodity, and considered the frequency of storage, weight and volume and other factors to propose an e-commerce company's location allocation model. Q. Q. Tao [4] set up a dynamic model with operation efficiency as the goal.
and balanced operation as the constraint, and then used flexsim simulation to compare the results with the random storage strategy. From the aspect of cargo space adjustment and redistribution, [5] Moon G and Kim G P [5] studied the impact of different storage strategies on equipment utilization during cargo space redistribution. Monika Kofler et al. [6] improved the redistribution strategy of cargo spaces in the context of large fluctuations in logistics demand. X. Li and Y. M. Zhu [7] aimed at improving the efficiency of storage, readjusting the storage space, and improving the stability of the shelves, and established a storage warehouse model to realize the redistribution of storage space. X. B. Xu and X. Li [8] proposed a dynamic position adjustment method relying on manpower for the online retail industry. The article adjusted the position of the picker without taking a roundabout path during the picking process. Regarding the automatic trolley storage system, Fukunari M and Malmborg C J [9] compared the cycle efficiency of the automatic trolley storage system with traditional stacker storage, and established a queuing model based on a random storage strategy to study the allocation of goods. A simulation experiment was performed. Debjit Roy et al. [10] proposed a protocol for solving vehicle congestion, and established a semi-open queuing network model to analyze system performance and quantify congestion effect to evaluate system performance. S. J. Zhang, Y. J. Fang, Y. He and Y. Xiao [11] also adopted a pre-zoning strategy for storage space allocation of multiple batches of goods in the automatic trolley storage system. For the shelves of existing goods, he carried out space allocation for multiple batches of goods, established a space allocation model with the goal of total storage energy consumption and storage efficiency, and solved it using simulated annealing algorithm. W. Q. Liu, Y. Q. Zhou, J. G. Yang, X. You [12] and J. G. Yang et al. [13] proposed a cargo space allocation model for a new multi-layer checkerboard format three-dimensional rack trolley access system. This system uses RGV son and mother carts for cargo access.

It can be seen from the literature review that at present, there are relatively few AVS / RS cargo space allocations based on the characteristics of e-commerce logistics. This article analyzes characteristics of e-commerce logistics. With the goal of maximizing the efficiency of outbound and inbound storage and the stability of the shelves, it has established a cargo location distributed model, and a multi-objective adaptive genetic algorithm is designed. The model is solved by Matlab software programming, and the example is verified by an e-commerce AVS / RS system.

The rest of the paper is organized as follows: Section II gives introductions to the automated terminal. Section III introduces the research methodology used in this paper; Section IV provides the calculation results; Section V presents the conclusion and future outlook of this paper.

2. Background of E-commerce AVS/RS

The e-commerce AVS / RS is mainly composed of shelves, shuttles, and hoists. The structure is shown in Figure 1.

![Figure 1. Schematic figure of AVS/RS.](image)

There are \( 2r \) rows, \( p \) rows, and \( q \) layers in the shelves, which represent the three directions of the rows, columns, and layers of the shelves. Figure 1 (a) is the left side view of the AVS / RS system. The shelves have a total of \( q \) layers, the height of each layer is \( h \), there are a total of \( p \) columns, and the
width of each cargo compartment is \( l \). Figure 1 (b) is a top view of the AVS / RS system. A hoist is placed at the entrance and exit, located at the midpoint of the bottom edge in the \( k \) direction. The high-level shelves are symmetrical left and right along the I / O axis, the \( k \) coordinate of the left shelf is taken as a negative number, and the right shelf is taken as a positive number. The vertical track is parallel to the rack row. One track serves two rows of racks on the left and right sides of the roadway in this floor, and the distance between two adjacent tracks is \( d \).

3. Research Methods

3.1. Model assumptions

In order to facilitate the research, the following assumptions are made on the optimization of cargo space allocation.

- Ignore system access time and hoist space.
- Ignore rail guided vehicle (RGV) speed changes caused by no-load and heavy-load.
- The acceleration of RGV column and row movements is consistent with the maximum speed, and the hoist and RGV are uniformly variable speed movement.
- The starting position of RGV operation is at the I / O port, and the access operation position is at the center of the cargo space.
- It is assumed that the size of the cargo compartment is suitable for the turnover box.
- The quality and turnover rate of the goods in the daily state of the storage system are known.

3.2. Model establishment

The AVS / RS uses shared storage and classified storage strategies for cargo location allocation. E-commerce products have the characteristics of small volume, multiple batches, and multiple types. The efficiency of storage and retrieval is the most important indicator of AVS / RS. For AVS / RS, shelf stability is very important for the high-speed and reliable operation of the RGV. Therefore, considering the frequency of inbound and outbound storage of the integrated storage system and the stability of the shelf, an optimization model for cargo allocation is established.

1) Objective function \( E_x \) : the most efficient shipment of goods in and out of the \( x \)th batch

\[
\min E_x = \sum_{(k,i,j) \in Z_x} x_{ij} \cdot P_{ij} \cdot t_{ij}
\]

\[
x_{ij} = \begin{cases} 
0 & \text{a cargo in space} \\
1 & \text{no cargo in space} 
\end{cases}
\]

\[
\sum_{(k,i,j) \in Z_x} x_{ij} = n_x \leq N_x
\]

In the formula:
- \((k,i,j)\) : the coordinates of the cargo position, which are rows, columns, and layers.
- \(Z_x\) : the collection of empty positions in the warehouse before the \( x \)-th batch of cargoes enters the warehouse.
- \(P_{ij}\) : turnovers of cargoes at the \((k,i,j)\) cargo space.
- \(t_{ij}\) : time required to move cargo from location \((k,i,j)\) to location I / O.
- \(x_{ij}\) : 01 variable which is used to constrain the one-to-one correspondence between the cargo and the location.
- \(n_x\) : the number of shipments in batch \( x \);
- \(N_x\) : the number of empty positions in the warehouse before the \( x \)th batch of cargoes enters the warehouse.
Among them, Equation 1 is an objective function, which represents the overall efficiency of receiving and storing goods in the $x$-th shipment. Equations 2 and 3 are constraints, which limit the goods to one-to-one correspondence.

When AVS / RS loads and unloads the goods, the hoist moves in the $j$ direction, and the RGV moves in the $k$ and $i$ directions along the horizontal and vertical tracks. The three directions of movements need to be performed one after the other, so the time variable can be expressed as the time sum in the three directions.

When the running speed does not reach $V_m$, the RGV performs uniform acceleration and deceleration with constant acceleration, and the time is $t_i$. When the speed reaches $V_m$, RGV performs uniform acceleration, uniform speed, and uniform deceleration in order, and obtains time such as $t_j$. The specific expressions for the calculation formulas for the two cases are as follows.

$$ t_{ij} = t_k + t_i + t_j $$

$$ t_k = \begin{cases} 2 \sqrt{\left[ \frac{k}{2} \right] d} & \left( \left[ \frac{k}{2} \right] d \leq \frac{v_{\text{m1}}}{2a_1} \right) \\ \frac{k}{2} d + \frac{v_{\text{m1}}}{a_1} & \left( \left[ \frac{k}{2} \right] d > \frac{v_{\text{m1}}}{2a_1} \right) \end{cases} $$

$$ t_i = \begin{cases} 2 \sqrt{\left( \frac{i-1}{2} \right) l} & \left( \frac{i-1}{2} l \leq \frac{v_{\text{m1}}}{2a_1} \right) \\ \frac{i-1}{2} l + \frac{v_{\text{m1}}}{a_1} & \left( \frac{i-1}{2} l > \frac{v_{\text{m1}}}{2a_1} \right) \end{cases} $$

$$ t_j = \begin{cases} 2 \sqrt{\left( \frac{j-1}{2} \right) h} & \left( \frac{j-1}{2} h \leq \frac{v_{\text{m2}}}{2a_2} \right) \\ \frac{j-1}{2} h + \frac{v_{\text{m2}}}{a_2} & \left( \frac{j-1}{2} h > \frac{v_{\text{m2}}}{2a_2} \right) \end{cases} $$

In the formula:

- $t_k, t_i, t_j$: the running time of RGV in $k$ and $i$ directions and hoist in $j$ direction.
- $v_{\text{m1}}, v_{\text{m2}}$: maximum operating speed of RGV and hoist.
- $d$: longitudinal track spacing between adjacent RGVs.
- $h, l$: cargo compartment width and height.
- $\left\lfloor \frac{k}{2} \right\rfloor$: round down $\frac{k}{2}$.

2) **Objective function**: the shelf to be stable after the storage of batch $x$

The product $S$ of the number of layers and the quality of the cargo is used as the stability evaluation index. The higher the quality of the cargo, the lower the number of layers is.

$$ \min S_i = \sum_{x,k,j\in D} x_{ij} \cdot m_{ij} \cdot j $$

In the formula:
\( m_{ij} \): the quality of the goods at location \( x \);
\( j \): the number of layers where the goods are located.

According to the principle of multi-objective function optimization, the weighted sum of the above two objectives can obtain the objective function \( O_x \) of initial cargo location distribution for the \( x \) batch of the cargo, as shown in (9). Where, and is the constraint condition of the weight coefficient of the two targets. Equation (10) shows that and are constraints on the weight coefficients of the two targets.

\[
\min O_x = \omega_1 \cdot E_x + \omega_2 \cdot S_x \\
\text{s.t.} \begin{cases} 
\omega_1 + \omega_2 = 1 \\
0 \leq \omega_1, \omega_2 \leq 1
\end{cases}
\]  

(9)

(10)

3.3. Model solving algorithm design

A genetic algorithm is used to solve the cargo location model.

3) Encoding design

The cargo position and number are used to encode. The search of the cargo location can be realized by changing the cargo location coordinates while keeping the cargo number unchanged. Using decimal coding, four genes on the chromosome form a group, which represents the location of a cargo.

4) Genetic operator design

- Selection operator: Select the first 5\% of the population and save it to the next generation, and select the remaining 95\% of the individuals. The selection method adopts the roulette selection method.
- Crossover operator: The adaptive crossover method is adopted, that is, the crossover probability of an individual changes with the value of its fitness function.
- Mutation operator: The position selection of the \( x \)th shipment of cargo location is affected by the position of the previous (\( x-1 \)) shipment. The gene position after mutation needs to be set in the empty cargo position set when mutation performed.

4. Experimental Result

4.1. E-commerce AVS / RS Basic Data

A company's AVS/RS fast-moving consumer cargos distribution area has a total of 800 shelves in 8 rows, 10 columns, and 10 layers. Each cargo grid has a length of \( l = 2m \), a height of \( h = 1m \), and the distance between adjacent RGV rails is \( d = 5m \). Shelves are symmetrical along the I/O axis, and RGV longitudinal rails are set in each aisle. Each RGV rail serves the left and right two rows of shelves in a certain layer. The maximum speeds of the RGV and the hoist are \( v_{w1} = 3m/s \) and \( v_{w2} = 1m/s \), and the accelerations are \( a_1 = 1m/s^2 \) and \( a_2 = 0.5m/s^2 \).

There are 50 pieces of cargos in a certain batch. The quality and turnover are known before entering the warehouse. The cargos information is shown in Table 1.

4.2. E-commerce AVS / RS cargo location optimization

The weighting of the fitness function for cargo location is 0.6 for warehousing efficiency and 0.4 for shelf stability. The genetic algorithm population size is 200, the number of iterations is 300, and the mutation probability is 0.05. Crossover adopts adaptive crossover method.

| Cargo number | Weight (kg) | Turnover (times) | Cargo number | Weight (kg) | Turnover (times) |
|--------------|-------------|-----------------|--------------|-------------|-----------------|
| 1            | 68          | 39              | 26           | 45          | 54              |
| 2            | 64          | 81              | 27           | 36          | 39              |
| 3            | 60          | 56              | 28           | 42          | 72              |
| 4            | 66          | 80              | 29           | 57          | 75              |
MATLAB is used to solve the GA. The average objective function value and the minimum objective function value of each generation of the population are recorded while iterating. The initial allocation plan is shown in Table 2.

**Table 2.** Initial storage assignment plan of the first batch of cargos.

| Cargo number | R | C | L | Cargo number | R | C | L |
|--------------|---|---|---|--------------|---|---|---|
| 1            | 5 |   | 4 | 26           | 6 | 3 | 1 |
| 2            | 4 | 2 | 3 | 27           | 2 | 1 | 1 |
| 3            | 6 | 1 | 3 | 28           | 5 | 1 | 1 |
| 4            | 5 | 3 | 2 | 29           | 3 | 1 | 2 |
| 5            | 4 | 1 | 3 | 30           | 7 | 1 | 10 |
| 6            | 2 | 2 | 2 | 31           | 5 | 1 | 3 |
| 7            | 3 | 3 | 1 | 32           | 4 | 1 | 1 |
| 8            | 5 | 2 | 2 | 33           | 5 | 2 | 3 |
| 9            | 2 | 2 | 1 | 34           | 4 | 2 | 1 |
| 10           | 3 | 3 | 2 | 35           | 6 | 1 | 1 |
| 11           | 5 | 4 | 1 | 36           | 4 | 2 | 9 |
| 12           | 2 | 1 | 4 | 37           | 4 | 8 | 1 |
| 13           | 6 | 2 | 2 | 38           | 3 | 1 | 1 |
| 14           | 8 | 1 | 1 | 39           | 3 | 5 | 1 |
| 15           | 7 | 1 | 1 | 40           | 6 | 1 | 2 |
| 16           | 4 | 4 | 1 | 41           | 6 | 2 | 1 |
| 17           | 4 | 3 | 1 | 42           | 4 | 2 | 2 |
| 18           | 5 | 1 | 2 | 43           | 8 | 2 | 1 |
| 19           | 4 | 1 | 2 | 44           | 2 | 3 | 1 |
| 20           | 5 | 7 | 4 | 45           | 6 | 2 | 5 |
| 21           | 5 | 2 | 1 | 46           | 4 | 1 | 4 |
| 22           | 5 | 3 | 1 | 47           | 7 | 1 | 2 |
| 23           | 3 | 2 | 1 | 48           | 7 | 2 | 1 |
According to the initial cargo allocation result, the cargo location distribution map is made, as in Figure 2. The blue grid in Figure 2 is the cargo grid occupied by the first batch of cargos. The overall distribution position is more concentrated, and the closer the I/O exit entrance, the denser the cargo are. Such a cargo distribution scheme is more conducive to improving the efficiency of AVS/RS.

4.3. Comparison
To explore the optimization effect of the initial location location model, the model was compared with random storage and 5 experiments are performed. The cargo information of the experiments is shown in Table 3. The total number of cargos is 50. To ensure the accuracy of the experiment, the quality of cargo and turnover remain unchanged during experiments. Record the overall warehousing efficiency and shelf stability of the two kinds of cargo location modes, as shown in Table 4. Plot the results of the 5 experiments, as shown in Figure 3.

As can be seen from the chart, compared with the random storage strategy, the initial cargo location model greatly optimizes the warehousing efficiency of cargos and the unstable effect of cargos on the shelf. On average, the initial cargo location model can improve the warehousing efficiency of goods by about 75% and the shelf stability by 55%, which can be considered to have a significant effect.

5. Conclusion
Based on the current situation of the development of e-commerce logistics, this paper takes the rapid development of e-commerce AVS / RS storage system in the e-commerce industry as the research object, and establishes a cargo location allocation model, then uses genetic algorithms to simulate the model. The calculation results show that the model can improve the efficiency of storage and storage of goods in the storage system and the stability of the shelves, which are of certain significance for the research on the allocation of e-commerce AVS / RS systems.
However, there are still some deficiencies in this study. First, the model does not take into account the speed changes of RGV no-load and heavy load, and only calculates the adjustment time when calculating the adjustment model, and does not calculate the time for RGV to move to the place to be adjusted. Secondly, the model only considers the allocation process of the cargo space, and does not consider the scheduling process of the RGV and the hoist. In fact, the scheduling of the RGV is closely related to the allocation of the cargo space. Future research can be continued based on the results of this article.

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Table 3. Optimization effect of the initial storage assignment model.

| Number of experiments | Random storage | Initial cargo location model | Improvement |
|-----------------------|----------------|-------------------------------|-------------|
|                       | Warehousing efficiency | Shelf stability | Warehousing efficiency | Shelf stability | Warehousing efficiency | Shelf stability |
| 1                     | 39077             | 10222                        | 24817       | 5324        | 73.84%               | 47.92%          |
| 2                     | 43859             | 9616                         | 25095       | 5192        | 78.08%               | 46.01%          |
| 3                     | 46825             | 12997                        | 26371       | 4930        | 72.24%               | 62.07%          |
| 4                     | 47351             | 12499                        | 24928       | 5128        | 73.60%               | 58.97%          |
| 5                     | 47153             | 11681                        | 23927       | 5392        | 75.23%               | 53.84%          |
| Average               | 44853             | 11403                        | 25027.6     | 5193.2      | 74.58%               | 54.46%          |

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