



An ant colony optimization routing algorithm for two order pickers with congestion consideration[☆]



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ABSTRACT

This paper develops a routing method to control the picker congestion that challenges the traditional assumption regarding the narrow-aisle order picking system. We propose a new routing algorithm based on Ant Colony Optimization (ACO) for two order pickers (A-TOP) with congestion consideration. Using two extended dedicated heuristics with congestion consideration as reference group, a comprehensive simulation study is conducted to evaluate the effectiveness of A-TOP. The simulation proves that A-TOP achieves the shortest total picking time in most instances and performs well in dealing with the congestion. The impacts of warehouse layout, order size, and pick:walk-time ratio on A-TOP and system performance are analyzed as well. A-TOP can adapt to different warehouse configurations, meanwhile, it can be easily extended to the situation with more than two order pickers.

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1. Introduction

Order picking is one of the most essential functions in warehouse management due to its significant time consumption as well as its considerable contribution to the overall warehouse operational cost. Improvement in order picking efficiency will lead to the increase in service level as well as the decrease in operational cost directly, and improve the entire supply chain performance indirectly. Generally, the efficiency of order picking is related to multiple factors including layout design (Roodbergen & Vis, 2006), storage assignment (Petersen & Schmenner, 1999), batching (Van Nieuwenhuysse & De Koster, 2009 and Le-Duc & De Koster, 2007), zoning (De Koster, Le-Duc, & Zaerpour, 2012), and order picker routing (Petersen & Aase, 2004 and Kulak, Sahin, & Taner, 2012). Each of them has attracted lots of attention from academic researchers and industrial practitioners (De Koster, Le-Duc, & Roodbergen, 2007). Among these factors, order picker routing, which should be adjusted dynamically according to the real time information in warehouse management, is considered to have the highest flexibility. This paper proposes an ACO-based routing algorithm for the order picking with congestion consideration. The new algorithm might be applied in a real-time environment without dependency on particular warehouse operation strategies.

In most related literature, dedicated heuristics, such as S-Shape, largest gap, and some derivative algorithms of them are commonly applied for order picking primarily because of their simple implementation (De Koster et al., 2007 and Hall, 1993). These dedicated heuristics are more suitable for a traditional warehouse, for the capability of equipment and the limited level of information management. Nowadays, the tremendous developments of automated warehousing equipments as well as warehouse management information systems provide a great opportunity to implement more efficient dynamic order picker routing algorithms in warehouse management practice (Chow, Choy, & Lee, 2007; Chow, Choy, Lee, & Lau, 2006 and Wang, Chen, & Xie, 2010). For instance, the automated picking equipment, such as automated guided forklift, and the indoor positioning technology, such as RFID, are widely deployed in modern warehouses, which enable the online calculation of a route to pick up items.

To date, most of the related research work is limited to the routing methodology for one order picker. However, it is a very common situation in practice that multiple order pickers are working simultaneously in the same picking zone. In this case, the congestion is inevitable. For example, congestion happens when the location one order picker wants to visit is occupied by another order picker, or when two order pickers simultaneously try to traverse the same narrow pick aisle from the opposite directions. Gu, Goe-tschalckx, and McGinnis (2007) stated that congestion should be taken into account for multiple order pickers, when they are working in the same zone with narrow aisles. However, in the existing routing methodologies, congestion is rarely considered, when the picking route is being constructed. Only simple rules are applied

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when congestion happens. For example, when the pick aisle is occupied by order picker B, order picker A will wait at the entrance until the aisle can be accessed. This will considerably deteriorate the order picking efficiency, due to additional non-value waiting time. Therefore, a more efficient routing algorithm is expected to consider the possible congestion when generating the route.

This paper proposes a new routing algorithm based on Ant Colony Optimization (ACO) for two order pickers (A-TOP) with congestion consideration. A comprehensive simulation study is conducted to evaluate the effectiveness of A-TOP in comparison with two extended dedicated heuristics. Meanwhile, the impacts of warehouse layout, order size, and pick:walk-time ratio are analyzed. A-TOP can be flexibly applied to different warehouse operation strategies, and it can be easily extended to the situation of three order pickers or more. The main contributions of this paper are as follow: Firstly, a new ACO-based algorithm is designed to bridge the gap between the omission of congestion issue in routing methodology and the commonly occurrences of congestion in practice. Secondly, benefiting from the developed technologies in both hardware and software fields, the proposed algorithm makes the warehouse operation decision more real-timely.

This paper is organized as follows. Section 2 briefly reviews the related work of order picker routing. Section 3 describes the problem and the related assumptions. In Section 4, the ACO-based routing algorithm is proposed for two order pickers taking congestion into consideration. A comprehensive simulation study is conducted in Section 5 to evaluate the efficiency and to analyze the impact of some factors on the system performance. This paper is concluded in Section 6.

2. Literature review

S-Shape (Traversal) is the most frequently investigated heuristic in the related order picking literature. The basic rule of S-Shape is that all the aisles containing items to be picked are traversed entirely except the last one. In this rule, aisles without picks are ignored, and the order picker returns to the depot, on the completion of the picking task in the last aisle. As a commonly used dedicated heuristic in warehouse management, S-Shape has been recognized as a benchmark in order picker routing literature (Hwang, Oh, & Lee, 2004; Roodbergen & De Koster, 2001b; Theys, Bräysy, Dullaert, & Raaijmakers, 2010). In this paper, two kinds of improved S-Shape heuristics for two order pickers are considered to compare with A-TOP. For different warehouse layouts, there are some other dedicated heuristics, such as for warehouse with decentralized depositing (De Koster & Van der Poort, 1998). Roodbergen and De Koster (2001a, 2001b) and Vaughan and Petersen (1999) established heuristics for warehouse with multiple cross aisles.

Recently, the congestion issue caused by multiple order pickers that work in the same zone arouses concerns among researchers. Pan and Shih (2008) and Pan, Shih, and Wu (2012) proposed throughput rate as the performance criterion to evaluate the order picking efficiency with congestion consideration. Parikh and Meller (2009, 2010) developed the analytical models to estimate worker blocking in both wide-aisle and narrow-aisle order picking systems by changing the pick:walk-time ratio. Pan and Wu (2012) developed a heuristic storage assignment policy that considers both the travel time and the waiting time simultaneously by minimizing the average order fulfillment time. Hong, Johnson, and Peters (2013) proposed an integrated batching and sequencing procedure called the indexed batching model (IBM), with the objective of minimizing the total retrieval time with consideration for picker blocking. However, to date, congestion is rarely considered in order picker routing algorithm.

3. Problem description

This paper considers a typical layout of warehouse with narrow pick aisle as shown in Fig. 1. Similar layout is commonly observed in related literature (Hwang & Cho, 2006; Petersen, 1999; Ratliff & Rosenthal, 1983; Roodbergen, Sharp, & Vis, 2008).

In such a warehouse, order pickers walk or drive along the aisle to pick items from storage. The pick aisle considered in this paper is narrow aisle in order to fully utilize the storage space, which means that the width of pick aisle can only be allowed for one order picker to walk into. A certain number of cross aisles can be located at the front, back, or the middle positions of a warehouse which depend on the warehouse design strategy, with the warehouse divided into a number of blocks by cross aisles. The block closest to the depot is called Block 1 (B_1), and the pick aisle and cross aisle closest to the depot is called Pick Aisle 1 (PA_1) and Cross Aisle 1 (CA_1) correspondingly. For a block, the cross aisle close to the depot is named as the front cross aisle (CA_f), and the cross aisle away from the depot is named as the back cross aisle (CA_b). To clarify the location and route of order pickers, we use the other following notations:

- P_b beginning pick from which the order picker starts the current travel route
- P_t target pick
- B_b the block which contains beginning pick
- B_t the block which contains target pick
- CA_c the current cross aisle that the order picker locates
- PA_c the current pick aisle that the order picker locates
- PA_t the pick aisle which contains target pick
- S_b the subaisle which contains beginning pick
- S_t the subaisle which contains target pick

Following are the additional assumptions considered in the paper:

- (1) Each item is independent of the other items within an order.
- (2) The time of finishing a pick is constant
- (3) The speed of a picker is constant.
- (4) There is no travel direction constraint for pickers in both cross aisles and pick aisles.
- (5) Single depot situation is considered. The route starts from and ends at the depot.
- (6) Pick-by-order policy is chosen, which means the order cannot be spread.
- (7) There is a time interval between each arrival time of orders, which means that order pickers start to pick at different times, which is in line with the actual situation, order pickers often do not set out for picking at the same time.

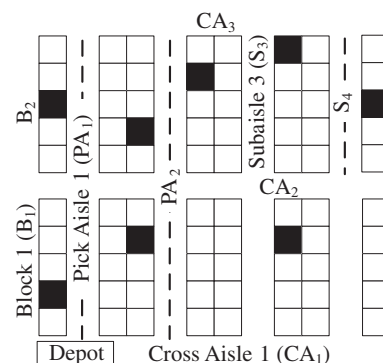


Fig. 1. Warehouse with narrow pick aisle.

4. ACO-based algorithm for two order pickers (A-TOP)

ACO is a meta-heuristic algorithm which simulates the behavior of ant colonies in nature as they forage for food and find the most efficient routes from their nests to food sources. It is commonly used to solve Traveling Salesman Problem (TSP), Vehicle Routing Problem (VRP), and other problems (Gambardella & Dorigo, 1996 and Neto & Filho, 2011). ACO is also feasible for the picker routing problem since this problem is defined as Steiner-TSP (De Koster et al., 2007). When adopting ACO, order pickers have fewer restraints than dedicated heuristics. It means that there exists optimization space between ACO and the heuristics for the flexibility of ACO. The most important reason is that, in ACO, ant travels from one pick to another to construct the picking route. The rules to deal with the congestion can be used in the route constructing process.

A basic structure of ACO, which has already been illustrated in Neto and Filho (2011), is considered here as shown in Fig. 2.

To deal with the congestion problem, there are two main improvements. The routing problem should be represented as a classical TSP which can be dealt with by ACO. In addition, some special rules should be incorporated to make ACO have the capability to tackle the congestion.

4.1. Initialization

4.1.1. Distance initialization

To represent the routing problem as a classical TSP, the distances between every two cities (picks) should be calculated for preparation. Usually, the distance is determined by the length of the shortest path between any two picks (including the depot) with Manhattan distance. Manhattan distance is defined as the rectilinear route measured along parallels to the horizontal and vertical axes of the plane (Theys et al., 2010). Specifically, the Manhattan distance between two points with coordinates (x_1, y_1) and (x_2, y_2) is $|x_1 - x_2| + |y_1 - y_2|$. However, the warehouse layout cannot meet the assumption of city block for Manhattan distance completely. As shown in Fig. 3, there are two feasible travel routes when picks are in the same block but different subaisles, while neither of their travel distance equals to the Manhattan distance. For this situation, we choose the shorter one as the travel distance and default travel route (Kulak et al., 2012).

4.1.2. Pheromone initialization

The value of pheromone referred in ACO is initialized by

$$\tau_{ij}(0) = 1/(\text{NoP} \times \text{NoP} - \text{NoP}), \quad (1)$$

where $\tau_{ij}(0)$ is the pheromone amount in trail between city i and j at time 0, and NoP is the number of picks.

1. Initialize
2. **Execute** /*iteration*/
3. Each ant is positioned on the initial node
4. **Execute** /* step*/
5. Each ant applies a transition state rule to generate the solution
6. Apply a local update rule
7. **Until** all ants have built a complete solution
8. Apply a global pheromone update rule
9. **Until** a stop criterion is satisfied

Fig. 2. Basic structure of ACO (Neto & Filho, 2011).

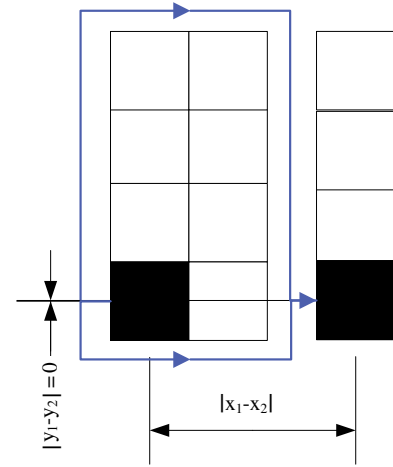


Fig. 3. Multiple travel routes between two picks.

4.2. Construct route and pheromone update

4.2.1. Improvement for ant

To consider the congestion, each ant should make clear whether there are barriers along its route, for example, some picking points or subaisles are occupied by other order pickers. Therefore, a tabu list is required to record the inaccessible time of each location. After constructing a route, the tabu list will be updated by recording the accessed time of each location by the current order picker, which means inaccessible time for other pickers. By exploiting the tabu list, we could construct a route of visiting all the picks without causing congestion in subaisles. To avoid accessing one location at the same time, the latter order picker may have to wait for a while at the entrance of the subaisle. As a result, the actual travel cost will not only be defined by Manhattan distance but also should take the waiting time into account. Therefore, a logic travel distance which means the sum of waiting time and walking time is proposed to measure this travel cost, and this logic travel distance should be determined by some dedicated rules according to the spatial relationship between two picks.

Three kinds of the spatial relationship between the picks are shown in Fig. 4. According to each relationship, detailed travel route and logical travel distance are determined by the following respective steps:

4.2.1.1. Picks in the same subaisle.

- **Step 1:** If order picker can freely reach P_i , walk directly to P_i ; otherwise, go to Step 2.

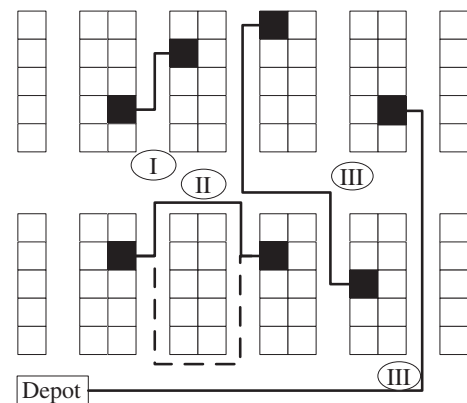


Fig. 4. Spatial relationships between two picks.

- **Step 2:** If order picker is allowed to wait at P_b , as shown in Fig. 5(a), wait until it can get to P_t ; otherwise, as shown in Fig. 5(b), get out the block from an allowed direction, then wait at the entrance until it can get to P_t , then reach P_t .

4.2.1.2. Picks in the same block but in different subaisles.

- **Step 1:** If order picker can freely leave S_b , get out S_b by the default direction and reach the entrance of S_t , go to Step 4; otherwise go to Step 2.
- **Step 2:** If order picker is allowed to wait at P_b , as shown in Fig. 6(a), wait until it can execute the default travel route without congestion, then, get to the entrance of S_t , go to Step 4; otherwise, as shown in Fig. 6(b), go to Step 3.
- **Step 3:** Get out S_b from an allowed direction, walk along the cross aisle and arrive at the entrance of S_t , go to Step 4.
- **Step 4:** Wait at the entrance of S_t until P_t is accessible and get to P_t .

4.2.1.3. Picks (depot) in different blocks.

- **Step 1:** If order picker can freely leave S_b to the cross aisle close to B_t , or P_b is depot, leave P_b to the cross aisle, go to Step 4; otherwise, go to Step 2.
- **Step 2:** If order picker is allowed to wait at P_b , as shown in Fig. 7(a), wait until it can leave, go to Step 4; otherwise, as shown in Fig. 7(b), leave B_b by an allowed direction, go to Step 4.
- **Step 3:** Walk along CA_c to PA_j ($PA_c \leq PA_j \leq PA_t$ or $PA_t \leq PA_j \leq PA_c$), by which picker can traverse the next block between B_t and CA_c with the shortest time including waiting time, then go through the block to the next cross aisle, as shown in Fig. 7(c), go to Step 4.
- **Step 4:** If CA_c is neither CA_f nor CA_b of B_t yet, or CA_c is not CA_1 when P_t is depot, return to Step 3; otherwise, go to Step 5.
- **Step 5:** If P_t is depot, back to depot directly; otherwise, get to the entrance of S_t , and reach P_t when P_t is accessible.

In all of these rules, the precondition for an order picker to access a subaisle is that, there is not another picker occupying any locations which the current order picker will access. If the condition is extended to make sure that order picker can freely leave the subaisle from either entrance, after it finishes the pick, the algorithm can be used in warehouse with more than two order pickers.

It should be mentioned that the travel route and logical distance to all unvisited picks (including depot) should be calculated when ant searching the next pick, because the travel route and logical distance to these unvisited picks change in real time. For example, in Fig. 8, it takes 2 s to move directly from pick *a* to pick *b* now. Five

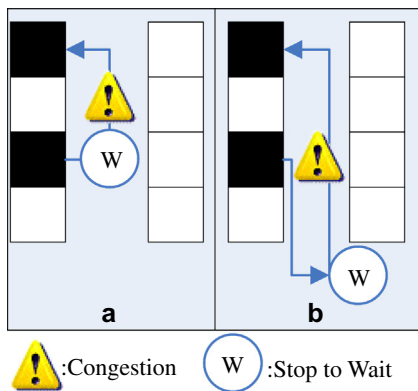


Fig. 5. Picks in the same subaisle.

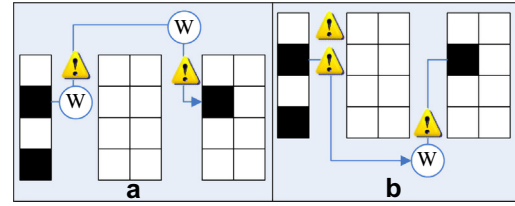


Fig. 6. Picks in the same block but in different subaisles.

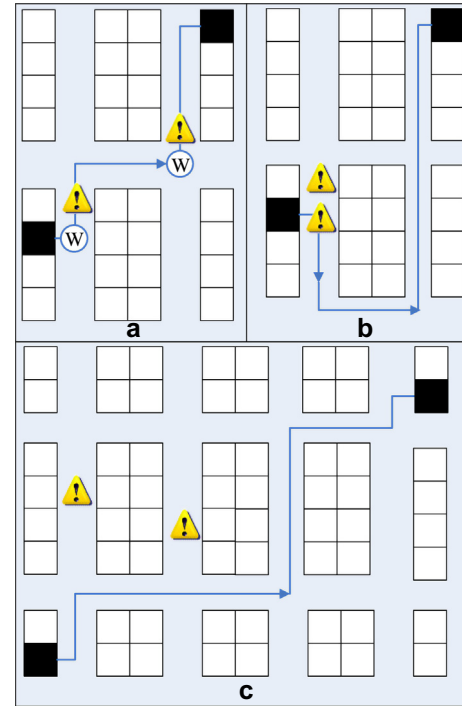


Fig. 7. Picks in different blocks.

seconds later, congestion happens, order picker has to wait until the pick *b* is accessible, which makes the logical distance between these two picks different from the current one. So, the travel route and logical distance should be updated in real time, when constructing the route.

To compare with A-TOP, these rules are also used to improve S-Shape to a new heuristic, named as S-Shape⁺. With these rules, S-Shape⁺ can modify the detailed travel route to avoid causing congestion when order picker executes the default visit sequence. Besides S-Shape⁺, another comparison algorithm is traditional S-Shape. In the traditional S-Shape, order picker waits at entrance if the subaisle is inaccessible.

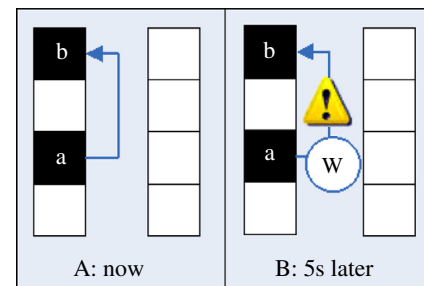


Fig. 8. Travel time changes with time.

As the travel route and logical distance have been determined, the ant chooses a city based on the pheromone and the logic distance between the current pick and other unvisited picks, until the last pick is visited.

4.2.2. Route construction

In ACO, a single ant simulates a picker, whose route is constructed by incrementally visiting picks until all picks have been visited. The ant chooses the next pick to be visited from the set of unvisited picks Ω which is updated before the next pick is selected. The ant returns to the depot when all picks are visited. The total distance L is computed as the evaluation criterion for the route constructed by ant.

Each ant chooses the next pick according to the transition probability of moving to these unvisited picks. The probability $p_{ij}(t)$ that pick j is selected to be visited next after pick i at instant t can be written as

$$p_{ij}(t) = \begin{cases} \frac{[\tau_{ij}(t)]^\alpha \cdot [\eta_{ij}]^\beta}{\sum_{j \in \Omega} [\tau_{ij}(t)]^\alpha \cdot [\eta_{ij}]^\beta}, & \text{if } j \in \Omega, \\ 0, & \text{otherwise,} \end{cases} \quad (2)$$

where $\tau_{ij}(t)$ is the pheromone intensity on trail i to j at instant t , and η_{ij} is the visibility of trail i to j . In this paper, the value of η_{ij} is the reciprocal of logic travel distance between i and j . This choice introduces a bias towards the shortest trail, and $\tau_{ij}(t)$ impels ant choose a familiar trail. Ω is the set of unvisited cities, α and β are the parameters to control the relative importance of the pheromone and the trail visibility ($\alpha \geq 1$, $\beta \geq 1$). It is well known that α and β change the algorithm performance obviously. However, it is really hard to set the efficient values of these two parameters without experiments. The best values of α and β are commonly initialized by knowledge gained from the observation experience.

The process of one ant to construct a visiting sequence in A-TOP is shown in Fig. 9. Each of the ants should construct a feasible route by this process.

4.2.3. Pheromone update

In order to simulate the negative and positive feed-back in ant colony communication, the pheromone on the route must be updated to reflect the ant's performance and improve the quality of

the solutions found. Pheromone update usually includes local (negative) update and global (positive) update. Local update is conducted by reducing the amount of pheromone on all trails in order to simulate the natural evaporation of pheromone. This ensures that no path becomes too dominant, which may lead to get a locally optimal solution. Global update is performed by adding pheromone to all of the trails included in the routes found by these m ants in order to increase the probability that ants select the trails contained in the solutions already found. After all the ants construct their tours, the pheromone intensity on trail i to j at instant $t + 1$ will be updated locally and globally by

$$\tau_{ij}(t + 1) = (1 - \rho)\tau_{ij}(t) + \Delta\tau_{ij}(t, t + 1), \quad (3)$$

in which ρ is the evaporation coefficient of pheromone ($0 < \rho < 1$), and $(1 - \rho)\tau_{ij}(t)$ conducts local update. Global update is implemented by $\Delta\tau_{ij}(t, t + 1)$, which is the variation of pheromone laid on trail i to j between instants t and $t + 1$, which is defined by

$$\Delta\tau_{ij}(t, t + 1) = \sum_{k=1}^m \Delta\tau_{ij}^k(t, t + 1), \quad (4)$$

where $\Delta\tau_{ij}^k(t, t + 1)$ is the variation of pheromone laid on trail i to j due to the action of k th ant between instants t and $t + 1$; it is given by

$$\Delta\tau_{ij}^k(t, t + 1) = \begin{cases} \frac{1}{L_k}, & \text{if the ant } k \text{ passes trail } i \text{ to } j \\ & \text{between instants } t \text{ and } t + 1, \\ 0, & \text{otherwise,} \end{cases} \quad (5)$$

where L_k is the total travel distance for k th ant.

After the ant colony finishes the travel, the shortest route will be saved in the cache. When the algorithm terminates, the route saved in the cache is presented as a good approximation of the optimal route. Additionally, the travel distance of the route in the cache is named as L_r .

4.3. Cataclysm operation

The route construction procedures and pheromone updating processes described above are typical for ACO. To improve the efficiency of ACO and avoid a locally optimal solution, cataclysm operator (C) is included. If the route saved in the cache is not replaced by a shorter one during a certain time (T), the pheromone on the best-so-far route visiting all of the picks will be reset to the initial value. After the cataclysm has happened predetermined times, the algorithm will terminate.

From Section 4.1 to Section 4.3, we can draw the overall chart diagram for A-TOP, as shown in Fig. 10.

5. Experimental study

5.1. Experimental design

In order to evaluate the efficiency of A-TOP, a comprehensive simulation study is conducted. The performance criteria considered in this simulation study are the average picking time (T_p) and the average waiting time (T_w) of the two order pickers.

Considering warehouse layout as well as other operation strategies and parameters have significant impact on the order picker routing algorithm (Hwang et al., 2004; Petersen, 1997; Roodbergen et al., 2008), the following representative environmental factors are investigated in this simulation study. Additionally, two order property factors are included.

- (1) Warehouse layout factors
 - Number of Pick Aisles (NoPA)
 - Pick Aisle Length (AL)

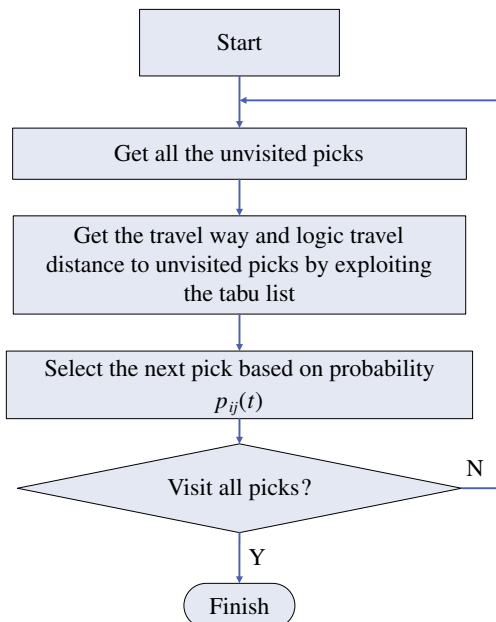


Fig. 9. Flow chart for one ant to construct route.

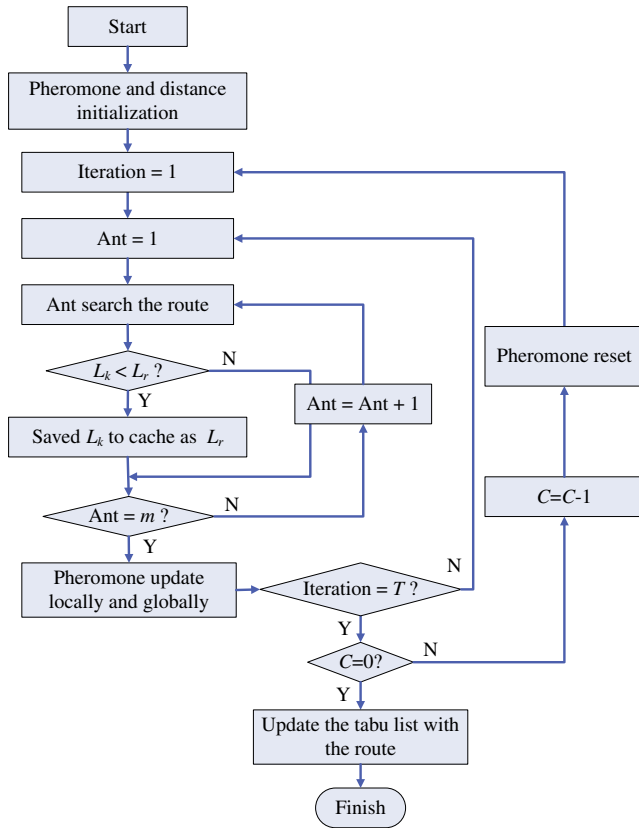


Fig. 10. The flow chart of A-TOP.

Pick Aisle Length is the sum of subaisles length in one pick aisle, whatever how many parts are divided into by cross aisles.

- Number of Cross Aisles (NoCA)
- (2) Order properties factors
- Pick:Walk-time Ratio (PWR)

Pick:Walk-time Ratio (PWR) is proposed by Gue, Meller, and Skufca (2006) and Parikh and Meller (2010) to analyze the operation efficiency of warehouse with congestion consideration. A PWR of 1:1 means that the time spent on picking a single item at a pick is identical to that of walking past a location. The higher the ratio is, the more time will be spent on finishing one picking position.

- Number of Picks (NoP)

Number of Picks (NoP) is chosen for analyzing the effect of picking density to algorithm. Table 1 shows the level of these factors.

Every order picking starts when the First Order Picker begins to work, and it ends when all pickers return to the depot. This is called a Task. The time interval between the start times of two order pickers is 20 s. In each Task, picks are designated from warehouse randomly. The time spent on walking past one location is 1 s. Other actions are assumed to take 0 s.

5.2. Experimental results

All the levels of factors constitute 432 instances, and 100 Tasks are carried out in each instance. The experimental software is programmed by C# .net, and for each of the heuristics the average calculation time for 100 Tasks was less than 10 s on a 2.40 GHz PC.

Table 1
Experimental factors.

| Factors | Level of factors |
|------------------------|----------------------|
| Number of pick aisles | 7, 11, 15 |
| Pick aisle length | 10, 20, 30 |
| Number of cross aisles | 2, 3, 6, 11 |
| Pick:walk-time ratio | 1:1, 5:1, 10:1, 20:1 |
| Number of picks | 10, 20, 30 |

Under the same condition, for A-TOP, the average calculation time is less than 10 s for one Task.

Overall, A-TOP gives the best result of T_p in 376 of the 432 instances. S-Shape⁺ and S-Shape have 28 instances respectively in which performs best. To give a comparison, the percentage difference in T_p between each other is calculated by Eqs. (6) and (7), as shown in Table 2. Data in bold font means unacceptable in 95% confidence interval.

$$A/S = -(T_p(A) - T_p(S))/T_p(S) \times 100, \quad (6)$$

$$S^+/S = -(T_p(S^+) - T_p(S))/T_p(S) \times 100, \quad (7)$$

where A/S is the percentage difference between $T_p(A)$ and $T_p(S)$, S^+/S is the percentage difference between $T_p(S^+)$ and $T_p(S)$, $T_p(A)$ is T_p for A-TOP, $T_p(S^+)$ is T_p for S-Shape⁺, and $T_p(S)$ is T_p for S-Shape.

In the instances in which A-TOP is not the best, the percentage differences between A-TOP and the other algorithms are no more than 6%. However, when A-TOP is the best algorithm, the differences can get up to 41%. It proved that optimization space exists between A-TOP and two improved S-Shapes.

It also appears that there is not too much difference between S-Shape⁺ and S-Shape. The percentage difference between them varies from -3% to 3%, and in 232 instances, S-Shape⁺ is the second-best algorithm.

5.3. Discussion

5.3.1. Effect of warehouse layout on picking time performance

5.3.1.1. Effect of Number of Cross Aisles (NoCA). There are 376 of 432 instances in which A-TOP performs better than S-Shape⁺ and S-Shape on T_p . Among these instances, most warehouse layouts have 6 or 11 cross aisles, following with 2 cross aisles, as shown in Table 3. The more cross aisles a warehouse has, the better A-TOP performs than the other two.

5.3.1.2. Effect of Number of Pick Aisles (NoPA). When a warehouse owns 7 pick aisles, A-TOP got the shortest T_p in just 107 instances. However, when NoPA increases from 7 to 11 and 15, this number increases to 132 and 137 respectively, as shown in Table 4.

5.3.1.3. Effect of Pick Aisle Length (AL). With the same NoPA, A-TOP performs better in longer aisles. This trend can be found in all levels of NoPA, especially in the picking time of the Second Order Picker, as shown in Fig. 11.

These phenomena mainly depend on the aisle-access mode of A-TOP, S-Shape⁺, and S-Shape. S_i is either entirely traversed or entered and left from the same entrance in A-TOP, while for S-Shape⁺ and S-Shape, order pickers have to traverse S_i . When warehouse just has two cross aisles, more aisle-access mode choices make A-TOP have the possibility to optimize the picking route. When the warehouse owns 3 cross aisles, A-TOP performs inferior to S-Shape⁺ and S-Shape. Because the length of traversing a subaisle is the half of the before, this makes S-Shape⁺ and S-Shape get a better performance than they do in the instance of two cross aisles. On the other hand, A-TOP cannot fully exploit the cross aisle in the middle yet. When NoCA increases to 6 and 11, pick aisle is divided

Table 2
Percentage differences in T_p between A-TOP, S-Shape⁺ and S-Shape.

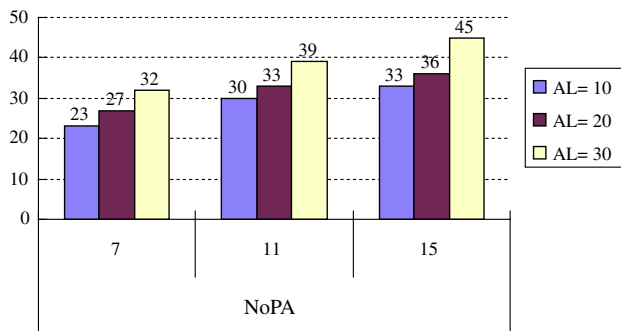
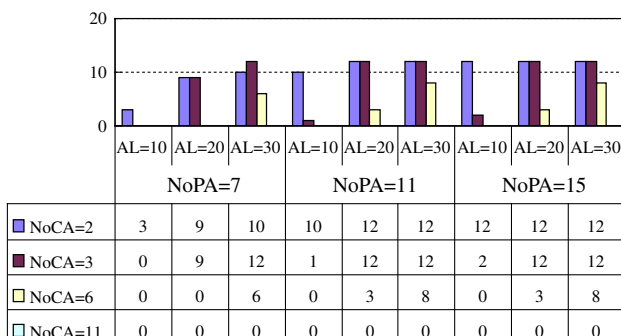
| NoPA | AL | PWR | 1:1 | | | | | | 5:1 | | | | | | 10:1 | | | | | | 20:1 | | | | | | | |
|------|----|-----|-------|-------|-------|-------------------|-------|-------------------|-------|-------------------|-------|-------------------|-------|-------------------|-------|-------------------|-------|-------------------|-------|-------------------|-------|-------------------|-------|-------------------|--------------|-------------------|-----|-------------------|
| | | | NoP | 10 | | 20 | | 30 | | 10 | | 20 | | 30 | | 10 | | 20 | | 30 | | 10 | | 20 | | 30 | | |
| | | | | NoCA | A/S | S ⁺ /S | A/S | S ⁺ /S | A/S | S ⁺ /S | A/S | S ⁺ /S | A/S | S ⁺ /S | A/S | S ⁺ /S | A/S | S ⁺ /S | A/S | S ⁺ /S | A/S | S ⁺ /S | A/S | S ⁺ /S | A/S | S ⁺ /S | A/S | S ⁺ /S |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7 | 10 | 2 | 6.99 | 1.42 | 1.49 | 0.12 | −5.24 | 0.50 | 7.07 | 2.02 | 0.39 | 0.44 | −3.22 | 0.05 | 4.16 | −0.21 | −0.51 | −0.26 | −2.48 | −0.23 | 2.53 | −0.98 | −0.9 | −0.29 | −2.52 | 0.24 | | |
| | | 3 | −0.75 | −1.08 | −0.10 | 0.40 | −2.85 | −0.52 | 0.96 | 0.51 | −1.35 | −0.25 | −2.56 | 0.15 | −1.63 | −0.17 | −1.82 | −0.14 | −2.74 | 0.13 | −1.8 | 0.39 | −2 | −0.14 | −3.24 | −1.18 | | |
| | | 6 | 10.72 | −0.93 | 19.86 | 1.30 | 23.13 | 1.50 | 9.31 | 2.82 | 10.82 | −0.08 | 11.36 | 0.45 | 2.30 | 0.30 | 5.27 | 0.07 | 5.66 | −0.96 | −1.48 | −1.4 | 2.06 | −0.23 | 3.34 | 0.36 | | |
| | 20 | 11 | 11.76 | 0.31 | 20.76 | −1.90 | 27.54 | 0.52 | 6.93 | −1.32 | 11.65 | −0.47 | 17.11 | 1.00 | 1.96 | −1.64 | 7.52 | −1.03 | 8.46 | −0.63 | −1.78 | −0.92 | 2.55 | −0.23 | 4.4 | 0.48 | | |
| | | 2 | 12.72 | 2.04 | 3.76 | −1.97 | −1.42 | 0.62 | 9.85 | −0.59 | 4.09 | 1.56 | −1.16 | 0.15 | 8.53 | −0.53 | 2.36 | 0.14 | −0.87 | 0.94 | 5.28 | −1.5 | 1.26 | −0.52 | −1.73 | −0.16 | | |
| | | 3 | 4.94 | 1.94 | 0.91 | −0.78 | −3.27 | −1 | 1.04 | −0.78 | 0.20 | −0.48 | −2.59 | −1.51 | 0.81 | −0.59 | 1.11 | −0.14 | −1.39 | 0.02 | 1.19 | 0.44 | 1.05 | −0.27 | −1.28 | −0.67 | | |
| | 30 | 6 | 7.03 | −0.08 | 12.87 | 0.30 | 12.99 | −0.56 | 4.20 | −0.64 | 7.75 | −0.37 | 8.32 | −0.52 | 1.57 | −0.32 | 5.09 | 0.58 | 4.89 | −0.48 | −1.22 | −1.16 | 1.58 | −0.43 | 2.55 | 0.09 | | |
| | | 11 | 4.88 | −1.14 | 14.28 | −1.09 | 17.11 | −0.46 | 3.28 | −0.74 | 9.71 | 1.13 | 10.38 | −0.45 | 2.52 | 0.51 | 4.63 | −0.8 | 7 | 0.06 | −1.20 | −0.14 | 2.53 | 0.36 | 2.94 | 0.19 | | |
| | | 2 | 14.32 | 2.44 | 5.78 | 1.08 | −1.6 | −0.30 | 13.71 | 1.35 | 2.76 | −1.25 | −0.14 | 1.03 | 11.97 | 1.03 | 2.53 | −1.24 | −1.97 | 0.19 | 9.31 | 1.42 | 3.26 | 0.71 | −1.08 | 0.4 | | |
| | 11 | 3 | 5.59 | 0.26 | 4.49 | 1.36 | −2.11 | −2.67 | 5.32 | −0.34 | 2.47 | 0.12 | −0.01 | −0.08 | 4.21 | 0.51 | 2.74 | 0.27 | 0.5 | −0.06 | 3.76 | −0.25 | 1.68 | −0.11 | 0.11 | 0.1 | | |
| | | 6 | 5.12 | −0.02 | 10.66 | 0.08 | 12.39 | −0.49 | 3.34 | 0.58 | 8.26 | 0.74 | 7.47 | −0.05 | 2.8 | 0.29 | 5.87 | 1.03 | 6.39 | 0.67 | 0.81 | −0.01 | 3.96 | −0.29 | 3.28 | 0.15 | | |
| | | 11 | 5.72 | 2.89 | 12.52 | 0.05 | 15.19 | 2.11 | 2.19 | −0.44 | 7.78 | 0.12 | 9.54 | 1.12 | 0.21 | −0.51 | 5.68 | 0.69 | 5.64 | 0.37 | −0.03 | 1.45 | 3.24 | 0.03 | 2.5 | −0.16 | | |
| 11 | 10 | 2 | 9.72 | 0.81 | 5.28 | 0.10 | −0.64 | 0.02 | 8.27 | 1.55 | 4.27 | 0.32 | 0.15 | 0.76 | 5.29 | −1.20 | 3.27 | −0.14 | 0.05 | −0.3 | 5.26 | 1.17 | 2.33 | −0.19 | −0.23 | −0.34 | | |
| | | 3 | 3.26 | 2.68 | 1.15 | 0.22 | −0.75 | −0.32 | 0.45 | 0.16 | 0.66 | 0.71 | −2.02 | −0.58 | −1.9 | −0.91 | −0.37 | 0.25 | −0.44 | 0.3 | −2.42 | −0.3 | −1.19 | 0.12 | −1.32 | −0.73 | | |
| | | 6 | 17.28 | 3.89 | 26.84 | 1.96 | 29.28 | −0.28 | 14.32 | 2.62 | 18.36 | −0.70 | 18.44 | 0.84 | 8.51 | 0.32 | 11.44 | 1.08 | 11.29 | 0.23 | 0.96 | −0.32 | 6.65 | 0.46 | 6.11 | −0.73 | | |
| | 20 | 11 | 13.82 | −2.79 | 29.63 | −2.42 | 35.85 | 1.23 | 11.03 | −1.07 | 21.5 | −1.32 | 24.74 | 1.57 | 9.10 | 0.99 | 15.96 | 1.41 | 16.22 | −0.53 | 3.36 | 0.68 | 8.27 | 0.88 | 8.94 | −0.66 | | |
| | | 2 | 14.37 | 0.62 | 10.08 | 0.75 | 4.34 | −0.11 | 10.99 | −0.24 | 8.21 | 1.2 | 1.56 | 0.48 | 11.04 | −0.89 | 4.84 | −1.43 | 1.65 | 0.04 | 7.58 | −1.1 | 5.58 | −0.06 | 1.39 | 0.17 | | |
| | | 3 | 2.23 | −1.84 | 4.24 | 0.06 | 0.77 | −0.09 | 3.63 | 0.72 | 1.41 | −2.48 | 2.14 | 0.34 | 1.35 | −0.42 | 2.1 | −0.43 | 0.1 | −0.32 | 1.90 | 1.04 | 1.77 | −0.38 | 0.95 | 0.89 | | |
| | 30 | 6 | 13.08 | 0.89 | 20.31 | 1.10 | 21.07 | 0.45 | 8.87 | 1.42 | 14.8 | 1.67 | 12.95 | −0.10 | 5.97 | −0.05 | 10.09 | −0.27 | 9.82 | 0.42 | 3.86 | 0.35 | 5.90 | 0.1 | 5.68 | −0.06 | | |
| | | 11 | 10.92 | −2.81 | 24.56 | 1.89 | 27.83 | 1.76 | 10.97 | −0.14 | 14.88 | −1.76 | 18.48 | −0.34 | 5.92 | −1.77 | 11.16 | −0.56 | 13.02 | 0.24 | 3.42 | 1.08 | 7.86 | 0.94 | 8.51 | 1.02 | | |
| | | 2 | 19.55 | 2.83 | 12.30 | 1.98 | 3.67 | 0.19 | 16.15 | 2.52 | 9.54 | −0.67 | 1.531 | 0.03 | 13.38 | 1.69 | 7.51 | −0.89 | 2.3 | −0.11 | 10.8 | −0.8 | 5.99 | −0.41 | 1.97 | −0.62 | | |
| | 15 | 3 | 2.88 | −3.81 | 5.57 | −1.92 | 2.97 | −1.51 | 6.52 | 1.09 | 5.19 | −1.77 | 4.03 | 0.57 | 5.51 | 1.18 | 3.84 | −0.58 | 2.31 | −0.13 | 3.34 | 0.65 | 3.84 | 0.19 | 1.76 | −0.55 | | |
| | | 6 | 11.62 | 2.1 | 16.37 | 1.38 | 18.07 | −1.06 | 7.51 | 0.34 | 12.31 | −0.09 | 13.95 | 1.11 | 5.86 | 1.15 | 9.3 | −0.07 | 9.52 | 0.32 | 2.75 | 0.21 | 6.02 | 0.04 | 5.97 | 0.15 | | |
| | | 11 | 7.86 | 0.41 | 19.03 | 0.29 | 22.16 | −0.63 | 6.86 | −0.36 | 13.21 | −0.21 | 15.66 | −0.66 | 6.33 | 0.43 | 9.95 | 0.81 | 12.28 | 1.02 | 2.44 | 0.19 | 5.66 | −0.09 | 7.51 | −0.16 | | |
| 15 | 10 | 2 | 8.76 | 0.29 | 7.97 | −0.96 | 4.37 | 0.14 | 6.82 | −0.48 | 7.29 | −0.63 | 1.96 | −1.05 | 7.26 | 1.12 | 4.4 | −0.42 | 1.35 | −0.31 | 3.22 | −0.86 | 3.5 | −0.31 | 1.28 | −0.29 | | |
| | | 3 | −0.12 | −0.47 | 0.62 | −0.45 | 1.23 | 0.65 | 1.28 | 0.38 | 0.42 | 0.40 | 0.30 | 0.32 | −0.88 | 0.21 | 0.11 | 0.45 | 0.21 | 0.15 | −0.87 | 0.94 | −0.18 | 0.25 | −0.23 | 0.01 | | |
| | | 6 | 19.8 | 1.14 | 29.90 | −2.55 | 33.16 | −0.36 | 14.64 | 0.87 | 22.71 | 1.41 | 23.02 | 0.03 | 8.62 | −1.04 | 15.82 | 0.22 | 16.11 | 1.3 | 4.55 | −2.57 | 9.43 | 0.75 | 9.5 | −0.1 | | |
| | 20 | 11 | 22.54 | 1.35 | 36.62 | 0.40 | 41.44 | 1.01 | 17.05 | 1.67 | 29.41 | 1.43 | 30.63 | 1.71 | 12.92 | 1.08 | 20.81 | 0.05 | 23.11 | 1.11 | 6.85 | 0.54 | 12.36 | −1.11 | 13.43 | 0.22 | | |
| | | 2 | 14.28 | 0.05 | 13.17 | −0.15 | 8.54 | −0.15 | 13.87 | 1.32 | 11.48 | 0.41 | 6.31 | 0.08 | 11.54 | −0.41 | 9.09 | 0.23 | 6.0 | 1.20 | 10.12 | 0.52 | 7.52 | 0.30 | 3.65 | 0.39 | | |
| | | 3 | 5.05 | 0.74 | 4.10 | −0.64 | 2.62 | −2.05 | 3.27 | 0.06 | 5.13 | 0.76 | 2.45 | −0.10 | 2.17 | −0.56 | 2.40 | −0.81 | 2.12 | −0.36 | 0.83 | −0.76 | 1.67 | 0.00 | 1.9 | 0.44 | | |
| | 30 | 6 | 13.91 | 0.48 | 24.66 | −0.06 | 27.1 | 0.55 | 12.57 | 1.61 | 17.85 | 0.19 | 18.57 | −0.34 | 8.71 | 1.56 | 14.15 | 0.03 | 13.54 | −0.43 | 4.55 | 0.48 | 8.6 | 0.05 | 8.25 | −0.15 | | |
| | | 11 | 16.72 | −0.77 | 29.73 | 0.64 | 34.66 | −0.04 | 16.13 | 2.46 | 24.1 | 1.61 | 24.85 | −0.21 | 13.13 | 4.08 | 16.9 | −1.36 | 19.67 | 0.51 | 6.01 | 0.36 | 11.03 | −0.66 | 11.87 | −0.4 | | |
| | | 2 | 17.9 | 1.66 | 14.70 | −0.08 | 9.07 | 0.26 | 14.58 | −0.94 | 11.32 | −1.80 | 7.36 | 0.18 | 14.26 | −0.37 | 9.86 | −1.05 | 5.95 | 0.10 | 11 | −0.87 | 8.22 | −0.75 | 4.94 | −0.38 | | |
| | 11 | 3 | 6.99 | 0.77 | 6.78 | 0.31 | 4.80 | 0.06 | 4.37 | −1.15 | 6.04 | −0.73 | 5.46 | 0.32 | 6.46 | 1.12 | 5.65 | 0.65 | 4.38 | 0.40 | 2.94 | −0.06 | 4.63 | 0.18 | 2.77 | 0.01 | | |
| | | 6 | 13.65 | 1.02 | 21.49 | 0.90 | 22.9 | 1.26 | 10.45 | −0.39 | 16.97 | 0.80 | 17.29 | 0.66 | 7.92 | 0.89 | 12.15 | −0.66 | 12.44 | −0.88 | 4.93 | 0.59 | 8.25 | −0.32 | 8.35 | 0.13 | | |
| | | 11 | 13.46 | −0.05 | 23 | −3.12 | 27.47 | −0.75 | 10.57 | −2.12 | 20.09 | 0.28 | 21.44 | 0.14 | 8.92 | 0.80 | 15.36 | 0.11 | 17.25 | 0.32 | 4.41 | 0.22 | 10.04 | 0.97 | 11.08 | −0.22 | | |

Table 3The distribution of instances in which A-TOP performs best in T_p .

| NoPA | AL | NoCA | | | |
|------|----|------|----|-----|-----|
| | | 2 | 3 | 6 | 11 |
| 7 | 10 | 5 | 1 | 11 | 11 |
| | 20 | 8 | 8 | 11 | 11 |
| | 30 | 8 | 10 | 12 | 11 |
| 11 | 10 | 9 | 3 | 12 | 12 |
| | 20 | 12 | 12 | 12 | 12 |
| | 30 | 12 | 12 | 12 | 12 |
| 15 | 10 | 12 | 5 | 12 | 12 |
| | 20 | 12 | 12 | 12 | 12 |
| | 30 | 12 | 12 | 12 | 12 |
| Sum | | 90 | 75 | 106 | 105 |

Table 4The distribution of the algorithm that generates the shortest T_p in different NoPA.

| Method | NoPA | | |
|----------------------|------|-----|-----|
| | 7 | 11 | 15 |
| S-Shape ⁺ | 16 | 6 | 6 |
| S-Shape | 21 | 6 | 1 |
| A-TOP | 107 | 132 | 137 |

**Fig. 11.** The distribution of A-TOP performs best in Second Order Picker picking time in different NoPA.**Fig. 12.** The distribution of A-TOP performs best in T_w in different warehouse layout.

A-TOP is better than S-Shape⁺ and S-Shape in a warehouse with a longer aisle length and more pick aisles, because the increase in AL and NoPA means expanding the warehouse scale. Picking density is lower in a larger warehouse with unchanged number of picks. A-TOP can show its flexibility better when picking density is low.

5.3.2. Effect of order properties

5.3.2.1. *Effect of Pick:Walk-time Ratio (PWR).* As Pick:Walk-time Ratio (PWR) increases, the percentage difference in T_p between A-TOP and other two heuristics decreases when other factors remain unchanged, especially when warehouse has more than two cross aisles. The reason is that the increase in PWR means more time spent on picking at a single position rather than walking, but optimization space only exists in walking.

5.3.2.2. *Effect of Number of Picks (NoP).* The most interesting phenomenon is that the impact of NoP on algorithms depends on NoCA. When warehouse sets two or three cross aisles, the more picks to be visited, the less superiority A-TOP has; but when warehouse has 6 or 11 cross aisles, the more picks to be visited, the more superiority A-TOP has. A warehouse having more cross aisles, which can be exploited by A-TOP as mentioned before, more picking time will be saved by a more flexible route.

5.3.3. Effect of warehouse layout on waiting time performance

In 192 of 432 instances, T_w of A-TOP is shorter than that of S-Shape⁺ and S-Shape. With the increase of NoPA and AL, A-TOP performs better in T_w , because the picking density is lower. Additionally, A-TOP makes order picker can choose a feasible route instead of just waiting, as shown in Fig. 12.

On the other hand, routes generated by S-Shape⁺ and S-Shape have an apparently visiting sequence. Both of two order pickers shall service the farthest block which contains picks from the depot at first, and visit all the picks in one block before moving to the next block. The access sequence of subaisles in one block is either from left to right or from an opposite way by traversing the whole subaisle. When there are not too many cross aisles in warehouse, order pickers hardly encounter each other, especially they do not set out to pick at the same time.

Above all, A-TOP generates illogical route for two order pickers, which leads to a high probability of causing congestion. However, A-TOP can deal with the congestion better than S-Shape⁺ and S-Shape.

6. Conclusions

Based on ACO, this paper proposes a routing method for two order pickers working in one area at the same time. The main advantage of the proposed routing method named A-TOP is the consideration of congestion. The application of tabu list which records the inaccessible time and dedicated rules make A-TOP can construct a picking route for pickers, without causing congestion in pick aisles. Furthermore, this algorithm can be also used in warehouse that has more than two order pickers by modifying the dedicated rules of dealing with the congestion.

A simulation is carried out in order to analyze the efficiency of A-TOP. The warehouse layout parameters concerned in this paper, in terms of the number of pick aisles, the length of pick aisles, and the number of cross aisles, are variable. The pick:walk-time ratio and the number of picks are also considered as order property factors. Two kinds of improved dedicated heuristics are proposed for comparison. The average picking time and average waiting time of two order pickers are selected as the performance criteria. The simulation proves that A-TOP gives the shortest average picking time

into smaller pieces. A-TOP's characteristic, allowing order picker to move to another block although picking task in the current block not be finished yet, begins to play an important role in optimization. While using S-Shape⁺ and S-Shape, order picker must visit all the picks in one block before moving to another one, lacking of flexibility. The flexible moving ways of A-TOP provide the possibility of route optimization.

in most of the instances. At the same time, the new algorithm performs well in dealing with the congestion.

In this paper, the time spent on each picking position is deterministic and order picker can obey it. In practice, the speed of order picker and the time spent on a pick are variable. In the environment of this type, how to route for two or more order pickers working in the same zone with congestion consideration is a new problem deserves future research.

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