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An ACO-based online routing method for multiple order pickers with congestion consideration in warehouse

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Abstract One of the challenging problems in order picking is how to deal with the congestion happens in warehouse with multiple pickers. In this paper, we consider an ant colony optimization (ACO)-based online routing method to find picking routes for multiple order pickers under nondeterministic picking time. Here, a default route is formed by ACO for each single picker. Then, we coordinate these routes to alleviate congestion by dedicated rules based on indoor positioning and information sharing technologies, during order pickers serve the picking task. Our results indicate that the proposed method can achieve a reduction in the order service time primarily by coping with the congestion. We conclude that the new method is particularly effective in multiple-block picker-to-parts warehouses.

Keywords Warehouse management · Routing method · Multiple order pickers · Congestion · Ant colony optimization

Introduction

Among many activities carried out in a warehouse, order picking has long been identified as the most labor-intensive and capital-intensive operation. It may consume as much as 60 % of all labor activities in the warehouse (De Koster et al. 2007). For a typical warehouse, the cost of order picking is estimated to be as much as 55 % of the total warehouse operating expense (Tompkins et al. 2003). Improvement in order picking efficiency will directly lead to raising the service level as well as cost cutting, and indirectly improve the entire supply chain performance. For these reasons, order picking has become a major research topic for productivity improvements. Many studies (Gu et al. 2010) have focused mainly on the optimization for picking operating policies of layout design (Roodbergen and Vis 2006; Roodbergen et al. 2008; Melacini et al. 2011), storage assignment (Gagliardi et al. 2012a; Ene and Öztürk 2012; Xiao and Zheng 2012; Yang et al. 2013), zoning (De Koster et al. 2012), batching (Bozer and Kile 2008) and routing method (Hu and Chang 2010; Kulak et al. 2012; Roodbergen and De Koster 2001a,b).

For a picker-to-parts warehouse in which a picker walks along the aisles to pick items, the order service time, which is an increasing function of the travel distance (Petersen 1997), is the main evaluation criterion of warehouse operation efficiency. To shorten order service time, the travel distance should be the first target of optimization. Routing method, which aims at finding out the picking route with the shortest travel distance, is indispensable to order picking. Most of the related studies focused on routing methods for a single order picker (Petersen 1997, 1999; Ratliff and Rosenthal 1983). However, in the real world application, the aisle congestion will occur, when multiple pickers are working together simultaneously within the same region (Gu et al. 2007). In spite of that, the existing routing methods rarely consider congestion for forming the picking route. The picker has to wait at the entrance when the aisle has been occupied by other pickers. The non-value waiting time will inevitably reduce the order picking efficiency. Therefore, taking the congestion into account is necessary for a more efficient routing method.

Additionally, most previous studies ignore the picking time of each item or assume it is constant (Ene and Öztürk 2012; Pan et al. 2012; Xiao and Zheng 2012; De Koster et al. 2012). However, due to the fact that the items of orders

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usually have different sizes and weights, the time taken on picking an item from the storage rack is inconstant. Further, the items need to be picked in a pick location usually vary according to the customer orders. Coupled with the deviation from picking operation, the picking time for a pick location is nondeterministic. This reality makes pickers cannot create picking routes taking congestion into account before starting to pick, because the picker cannot know in advance when and where the congestion will happen. It means the new routing method should deal with the congestion in real time.

This paper aims at proposing an online routing method based on ant colony optimization (ACO) for multiple order pickers (MOP) under nondeterministic picking time (NPT) with congestion consideration, named as A-MOP-NPT for short. In the new method, a default route is generated by ACO before picker set out for picking. Then, the default route is coordinated by some dedicated rules to mitigate the congestion in real time based on indoor positioning and information sharing. The main contributions of this paper are as follow: Firstly, an online ACO-based routing method is designed to bridge the gap between the common assumption of a single picker with deterministic picking time in routing methodology and the reality of multiple pickers with nondeterministic picking time in practice. Secondly, by the simulation, it confirms that the default route resulting from ACO and the ability of coordinating the route in real time are the key points which make the new method can perform better in dealing with the congestion. Finally, benefiting from the developing technology in both hardware and software fields, the proposed algorithm can increase the warehouse throughput by making the order picking operation decision dynamically.

The rest of the paper is organized as follows. "Literature review" section briefly reviews the related work of order picker routing method. "Problem definition" section describes the problem and related assumptions. "Solution methods" section proposes the online routing method for multiple order pickers under nondeterministic picking time with congestion consideration. A comprehensive simulation study is conducted in "Experiment and analysis" section. Finally, in "Conclusion" section, we conclude and propose further research direction.

Literature review

Routing methods

In previous studies, dedicated heuristics, such as S-Shape, Largest Gap and Combine, are widely employed for order picking, because of their simple implementation (De Koster et al. 2007; Hall 1993; Gademann and Van de Velde 2005). The most frequently investigated is S-Shape (Traversal), which has been recognized as a benchmark in the related literature (Roodbergen et al. 2008; Petersen and Aase 2004; Xiao and Zheng 2010). The basic idea of S-Shape is that pickers traverse all the aisles containing items to be picked except the last one. In this rule, aisles without picks are ignored and order picker returns to the depot after finishing the picking task in the last aisle. Largest Gap method essentially divides the aisle into two parts by the largest gap. The gap means the separation between any two adjacent picks, between the first pick and the front entrance, or between the last pick and the back entrance. Picks in the front part are accessed from the front entrance and picks in the back half are accessed from the back entrance. The order picker only traverses the aisle in either the first or the last one to be visited. This method usually performs better than S-Shape when the number of picks per aisle is small (Hall 1993). Combine method traverses the aisles with picks entirely or enter and left at the same entrance. This choice is determined by using dynamic programming (Roodbergen and De Koster 2001b). Besides these methods, there are some other dedicated heuristics for specific warehouse layout, such as decentralized depositing (De Koster and Van der Poort 1998), multiple cross aisles (Roodbergen and De Koster 2001a,b; Vaughan and Petersen 1999). However, these routing methods only focus on a single order picker.

Picker congestion

Recently, the congestion issue caused by multiple order pickers that work in the same zone arouses concerns among researchers (Gu et al. 2007). Particularly, the congestion will slow down the processing, when pick density is high (Gue et al. 2006). Pan and Shih (2008) and Pan and Wu (2012) propose throughput rate as the performance criterion to evaluate the order picking efficiency with congestion consideration. Parikh and Meller (2009, 2010) develop 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 et al. (2012) develop a storage assignment policy that considers both the travel time and the waiting time simultaneously by minimizing the average order fulfillment time. A distance-based batching algorithm using a route-packing based order batching procedure is investigated by Hong et al. (2012a), and they conduct a simulation study to evaluate the proposed method considering picker blocking. Hong et al. (2012b) propose 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. Chen et al. (2013a) develop an ACO-based routing method for two order pickers, which forms picking route for the second order picker with congestion consideration. Recently, Chen et al. (2013b) provide a routing method for multiple order pickers with congestion consideration in off-line warehouse with assumption of deterministic picking time. However, the congestion which happens in online warehouse with multiple order pickers has not been considered yet.

Online warehouse operation

Nowadays, some related studies begin to aim at settling problems in warehouse management dynamically. Ascheuer et al. (1999) modeled the order picking task in automatic storage system as an online Asymmetric Traveling Salesman Problem (ATSP). A polling-based dynamic order picking system for online retailers is developed by Gong and De Koster (2008). Rubrico et al. (2011) present a solution for a dynamic rescheduling problem involving new orders arriving randomly while static orders have been given in advance in warehouse environments. Bukchin et al. (2012) design a Markov decision process (MDP) based approach to set an optimal decision making policy on order batching. Recently, an online order batching algorithm to minimize the maximum completion time of the customer orders arriving within a certain time period is investigated by Henn (2012).

Meanwhile, automation technologies provide great opportunities to implement more efficient dynamic order picker routing methods in warehouse management practice. For instance, automatic navigation, the indoor positioning technology (Zhou and Shi 2009; Kuo and Chang 2013) and information sharing are widely used in modern warehouses (Chow et al. 2006, 2007; Wang et al. 2010; Qu et al. 2012). But, they have not considered dealing with the picker congestion in an online way by using of these technologies.

In summary, the majority of the existing research on routing method is closely related to dedicated heuristics for single order picker without congestion consideration. In this research, we focus on proposing a new routing method to cope with the picker congestion based on indoor positioning and information sharing technology.

Problem definition

Warehouse layout

This paper considers a typical layout of picker-to-part warehouse with narrow pick aisles to increase space utilization with minimal investment costs, as shown in Fig. 1, which is similar with related literature (Caron et al. 1998; Hwang and Cho 2006; Petersen and Schmenner 1999; Gagliardi et al. 2012b; Chen et al. 2013a).

Multiple cross aisles (CA) divide the warehouse into several blocks (B), with pick aisles (PA) divided into subaisles (S). All the cross aisles and blocks are numbered from front to back. Meanwhile, all the pick aisles and subaisles are numbered from left to right. For a block, the cross aisle close to

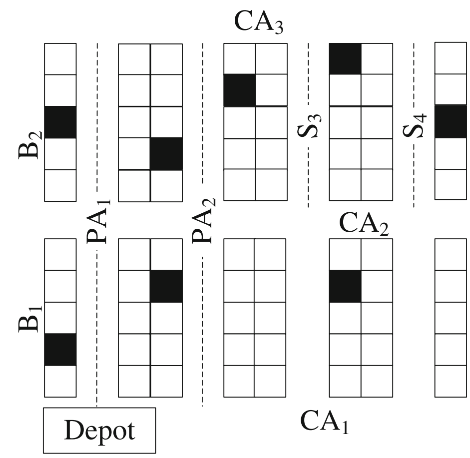

Fig. 1 Warehouse layout with narrow-aisle

the depot is named as the front cross aisle (CA_f), and the cross aisle away from the depot is the back cross aisle (CA_b) (Roodbergen and De Koster 2001b). The CA_f of B_s is the CA_b of B_{s-1}, except for B_1. To locate the order picker and describe the picking route, we use the other following notations:

P_b	start pick from which the picker starts the current travel route
P_t	target pick
B_b	the block which contains start 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 start pick
S_t	the subaisle which contains target pick

Following are the additional assumptions considered in this paper:

(1) Each item is independent of the other items within an order.
(2) The time of finishing a pick location is nondeterministic.
(3) The travel speed of a picker is constant.
(4) There is no travel direction constraint for pickers in cross aisles and pick aisles.
(5) Single depot is considered. The route starts from and ends at the depot.
(6) There is an interval between arrival times of each two orders, which means that order pickers start to pick successively, which is in line with the practice.

Finally, pick-by-order policy is chosen in this picking system. In order picking operation, a customer order may have multiple items to pick. According to pick-by-order policy, these items will be picked by a single order picker. If the

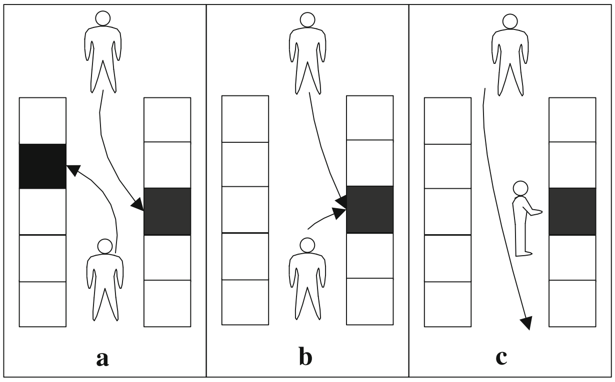

Fig. 2 Picker congestion in narrow-aisle

picking system allows spreading the order, these items will be assigned to multiple order pickers. Spread the order to multiple order pickers can decrease the picking time. However, it will take time to sort (repack) these spread items to an order. Considering pick-by-order policy can focus on investigating the efficiency of routing method and excluding the impact of sort (repack) operation.

Picker congestion in pick aisle

In this kind of warehouse layout, picker congestion is classified into three types as shown in Fig. 2 (Hong et al. 2012b; Chen et al. 2013b). First, pickers want to enter the same aisle and they have to overtake the target picks of each other to access their own target picks (Fig. 2a). Second, pickers try to access the same storage position simultaneously or when the pick is being occupied (Fig. 2b). Third, one picker would like to overtake another picker (Fig. 2c). Usually, to avoid congestion, the picker may have to wait at the aisle entrance, when the succeeding aisle is already occupied by another picker (Pan et al. 2012; Pan and Shih 2008; Pan and Wu 2012). Besides, a strict S-Shape routing policy in a cyclic sequence, which means that any aisle is completely traversed with a dedicated travel direction, is also popular for avoiding congestion (Gue et al. 2006; Gong and De Koster 2008).

Performance criterion considering picker congestion

Our objective is to minimize total order service time, which is the sum of the setup and sort time (S&ST), pick time (PT), travel time (TT), and wait time (WT). As the routing method does not focus on setup and sort, we ignore the effect of S&ST and assume that S&ST is constant for all orders. Additionally, PT is decided by the order, which will not change with different picking routes. Therefore, we focus on the sum of TT and WT, and the following integer linear optimization model can be formulated as performance criterion (Chen et al. 2013b).

Indices and sets

$i, j \in \Omega$ locations including picks and depot, where $i = 0$ means depot

Parameters

d_{ij} travel distance between location i and j
u_i visiting sequence of location i, where $u_0 = 1$
v travel speed of pickers
WT_{ij} wait time generated by moving from i to j
n number of picks and depot

Decision variables

$x_{ij} = 1$ if location i is visited directly after location j

Model formulation

$$\min \sum_{i \neq j \in \Omega} x_{ij} \left(\frac{d_{ij}}{v} + WT_{ij} \right)$$

$$\text{s.t.} \tag{1}$$

$$\sum_{i \in \Omega} x_{ij} = 1, \quad \forall j \in \Omega \tag{2}$$

$$\sum_{j \in \Omega} x_{ij} = 1, \quad \forall i \in \Omega \tag{3}$$

$$u_i - u_j + n x_{ij} \leq n - 1, \quad \forall i, j \in \Omega, i \neq j, i \neq 0, j \neq 0 \tag{4}$$

$$x_{ij} \in \{0, 1\}, \quad \forall i, j \in \Omega \tag{5}$$

The objective function (1) minimizes service time of picking an order in a tour. Constraints (2) and (3) ensure that each location has exact one predecessor and successor, provided the respective location is visited only once in the tour. Constraints (4) enforces there is only a single tour. At last, constraint (5) defines the variable domains.

Solution methods

In this paper, the new routing method is constructed on the basis of ACO. ACO simulates the behavior of ant colonies in nature as foraging and finding the most efficient routes from their nests to food sources. Dorigo and Gambardella (1997) and Bell and McMullen (2004) apply ACO into Traveling Salesman Problem (TSP) and Vehicle Routing Problem (VRP) respectively. To deploy ACO, Ugur and Aydin (2009) and Neto and Filho (2011) develop functional software as a platform. Ghafurian and Javadian (2011) solve the fixed destination multi-depot multiple traveling salesmen problem (MmTSP), and Musa et al. (2010) adopt ACO to cope with the transportation problem in cross-docking network. An ACO-based routing method for an auto-access multilevel conveying device with three-dimensional movement is integrated into the automated storage/retrieval systems by Hu and Chang (2010). Recently, Arnaout (2013) introduces a three-stage ACO for the Euclidean location-allocation problem, and it proves the proposed algorithm outperformed GA and reached better solutions in a faster computational time.

Base on the assumptions above, multiple order pickers leave the depot for picking successively. As mentioned before, the congestion will happen inevitably. Further, the nondeterministic picking time of each pick location makes when and where the congestion will occur is unknown. As a result, the pickers cannot achieve a route taking the congestion into account in advance. Therefore, the new proposed routing method will be developed in two stages. First, for each single picker, the picking task is represented as a model which ACO can deal with. Then, we calculate a default picking route for each single picker without congestion consideration. Second, coordinating these routes in real time by dedicated rules to deal with the congestion in multiple pickers circumstance.

The flowchart of A-MOP-NPT for each single picker is presented in Fig. 3.

The whole procedure of the new method is divided into three main phases:

(1) Achieve the visiting sequence for each single picker

In this phase, the problem is defined as a standard Steiner-TSP (De Koster et al. 2007). First, we adopt Manhattan distances to determine the distance between each pair of two picks (including the depot) as the algorithm's input. Manhattan distance is the rectilinear route measured along parallels to the horizontal and vertical axes of the plane (Theys et al. 2010). However, as shown in Fig. 4, when picks are in the same block but at different subaisles, there are two travel ways with different travel distances, and neither of their lengths equals Manhattan distance. Travel ways have to go through one of the two cross aisles adjacent to the block. In such situation, we choose the shorter one as the travel distance (Theys et al. 2010; Kulak et al. 2012). With the visiting sequence, order picker can determine the next pick to service, after finishing the current one.

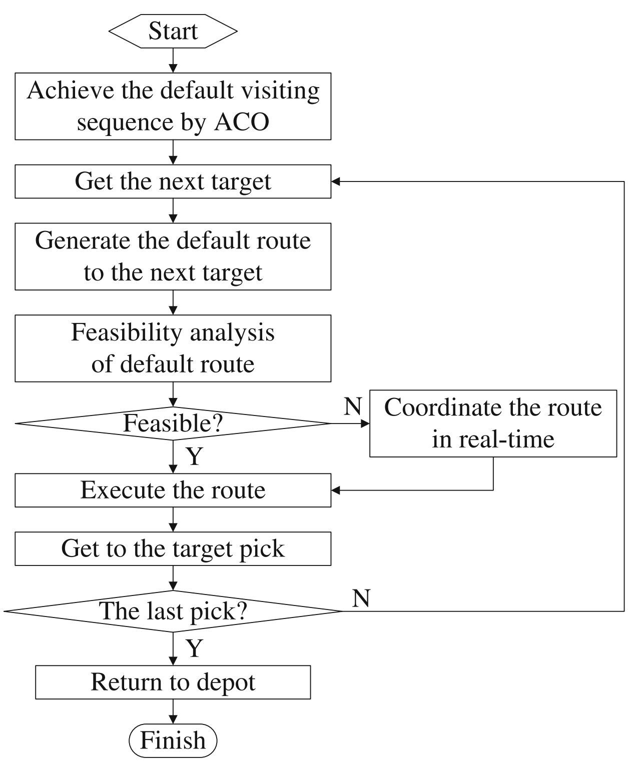

Fig. 3 The flowchart of A-MOP-NPT for each single picker

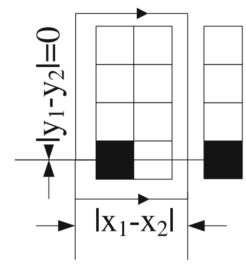

Fig. 4 Multiple travel ways between two picks

(2) Form the default route for each single picker

When the picker confirms the next target pick, a detailed default travel route to this target pick should be generated in advance. Different from the visiting sequence, the default route reflects the spatial relationship between two picks. "Generating the default route" section introduces the rules of forming the default route.

(3) Coordinate the route in real time

In the last phase, to deal with the congestion, the default route for single picker will be coordinated dynamically. When pickers service the order, they share the information such as current location, target pick and next target pick with one another, based on indoor positioning and information sharing technology. By dedicated rules, order picker can adjust the default route based on analyzing the real time information of other pickers. With the coordination, picker can finish the target pick without causing congestion in pick aisle. "Online coordination" section describes the dedicated online coordination rules.

The visiting sequence

In this paper, we assume ant colony consists of $m (m \geq 2)$ ants, and each single ant simulates a picker. The ant chooses the next target pick from the set of unvisited picks and records the Manhattan distance to the target pick. The ant returns to the depot when all picks are visited. The total Manhattan distance L is computed as the evaluation criterion for the solution found by these m ants. Before algorithm starts, the value of pheromone referred in ACO is initialized by (Chen et al. 2013b)

$$\tau_{ij}(0) = \frac{1}{NoP \times (NoP - 1)}, \tag{6}$$

where $\tau_{ij}(0)$ is the pheromone amount in trail between city i and j at instant 0, and NoP is the number of picks to be visited by the order picker which ant colony simulates.

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

$$p_{ij}(t) = \begin{cases} \frac{[\tau_{ij}(t)]^{\alpha}[\eta]^{\beta}}{\sum_{j \in \mathbf{U}}[\tau_{ij}(t)]^{\alpha}[\eta]^{\beta}}, & \text{if } j \in \mathbf{U}, \\ 0, & \text{otherwise}, \end{cases} \tag{7}$$

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 (Dorigo and Gambardella 1997). Here, we define the value of η_{ij} is the reciprocal of travel distance between i and j. This definition leads to giving preference to choose the shortest trail, and $\tau_{ij}(t)$ impels ants choose a familiar trail. **U** is the set of unvisited picks, 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 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.

To simulate the negative (local) and positive (global) feedback in ant colony communication, the pheromone on the route must be updated to reflect the ant's performance and improve the quality of the found solutions (Bell and McMullen 2004). Local update is conducted by reducing the pheromone on all the trails to simulate the natural evaporation of pheromone. This ensures that no path becomes too dominant, which may lead to getting a locally optimal solution. Global update is performed by adding pheromone to trails contained in the found solutions by these ants to increase the probability that ants select the trails selected before (Ghafurian and Javadian 2011). 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

$$\tau_{ij}(t+1) = (1-\rho)\,\tau_{ij}(t) + \Delta\tau_{ij}(t, t+1) \tag{8}$$

in which ρ is the evaporation coefficient of pheromone ($0 < \rho < 1$). $\Delta\tau_{ij}(t, t+1)$ is the variation of pheromone laid on trail i to j between instants t and $t+1$ (Neto and Filho 2011), which is defined by

$$\Delta\tau_{ij}(t, t+1) = \sum_{k=1}^{m} \Delta\tau_{ij}^{k}(t, t+1) \tag{9}$$

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

$$\Delta\tau_{ij}^{k}(t, t+1) = \begin{cases} \frac{1}{L_k}, & \text{if } k\text{th ant passes trail } i \text{ to } j \\ & \text{between instants } t \text{ and } t+1, \\ 0, & \text{otherwise}, \end{cases} \tag{10}$$

where L_k is the total travel distance for the kth ant (Ugur and Aydin 2009).

After the ant colony finishes the travel, the best solution will be saved in the cache. To improve the efficiency of ACO and avoid a locally optimal solution, a cataclysm operator (C) is included. If the route saved in the cache is not replaced by a shorter one during a certain time or iterations (T), the pheromone on the best-so-far route visiting all of the picks will be reset to half of the current value. After the cataclysm has happened predetermined times, the algorithm will terminate. When the algorithm terminates, the solution saved in the cache is presented as a good approximation of the optimal visiting sequence. The flowchart of ACO is presented in Fig. 5.

Generating the default route

As mentioned above, the default route should be determined by specific rules, depending on the spatial relationship between each pair of picks or picks and depot. All the spatial relationships are classified into three categories, as shown in Fig. 6 (Chen et al. 2013a). They are: (1) picks in the same subaisle, (2) picks in the same block but in different subaisles and (3) picks (depot) in different blocks.

Therefore, the travel route is determined by the following steps for each category:

(1) Picks in the same subaisle:

Step 1: Walk to P_t directly.

(2) Picks in the same block but in different subaisles:
There are two ways between the two picks, as mentioned above. The default travel way is the shorter one.

Step 1: Leave S_b from the chosen direction
Step 2: Walk along CA_c to the entrance of S_t
Step 3: Enter S_t and get to P_t.

(3) Picks (depot) in different blocks:

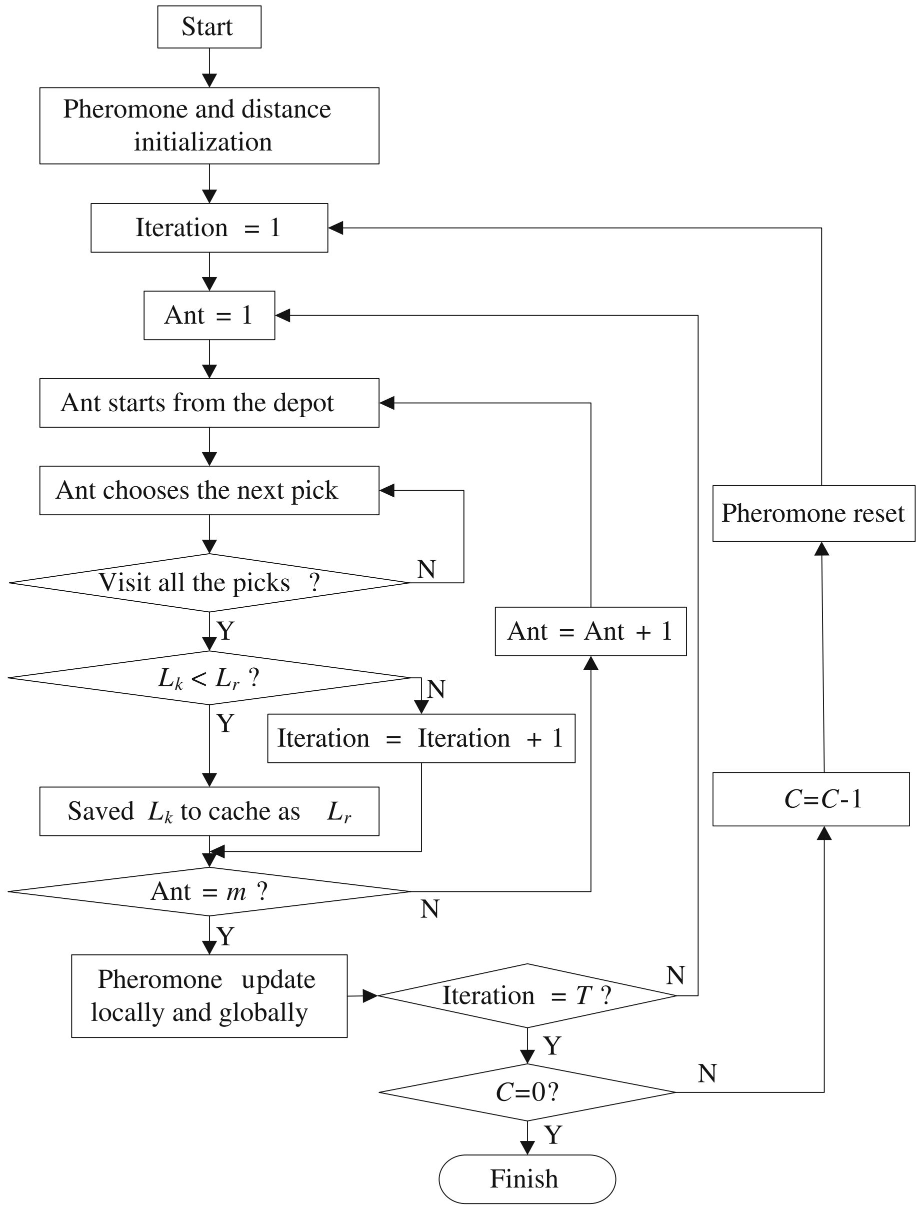

Fig. 5 The flowchart of forming visiting sequence by ACO

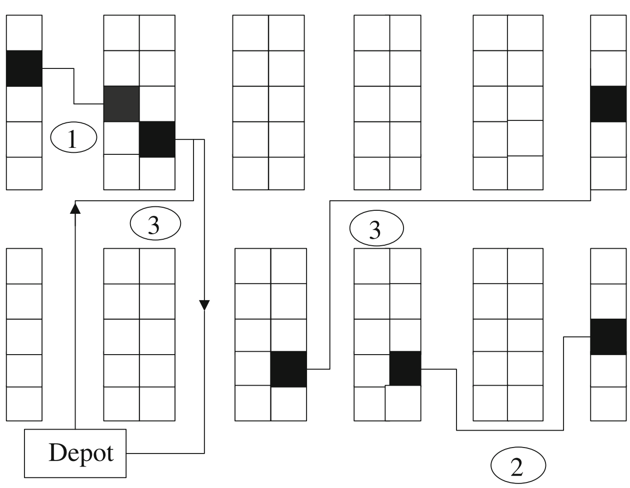

Fig. 6 Spatial relationship between two picks

Step 1: Leave S_b from the entrance close to B_t
Step 2: Walk along PA_c to either CA_f or CA_b of B_t
Step 3: Go along CA_c to the entrance of S_t
Step 4: Enter S_t and get to P_t.

Online coordination

When order picker carries out the default route, congestion may happen, for the default route only concerns the spatial relationship. To avoid congestion in the aisle, the order picker will coordinate the default route by analyzing the current environmental information. Before entering a pick aisle, an order picker should inspect whether other order pickers are staying in the aisle. If there is no order picker, the aisle is accessible. Otherwise, the order picker should take action to avoid congestion, by analyzing the moving trends of the

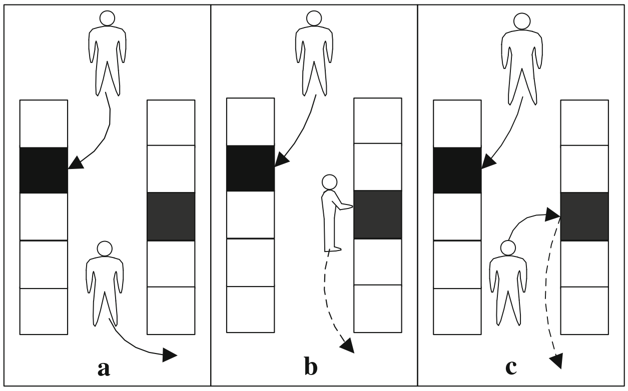

Fig. 7 Three situations allow the current picker to walk into a pick aisle

order pickers in the aisle. Different from exclusive access control for pick aisle, if all the order pickers in the aisle do not obstruct the operation of current order picker, the aisle is also accessible to the current order picker. The following situations mean that the aisle is accessible:

Situation 1: The order picker in the aisle is leaving from the other entrance, as shown in Fig. 7a.
Situation 2: The order picker in the aisle is picking the last pick in this aisle, and the default route to the next target requires leaving the aisle from the other entrance, as shown in Fig. 7b.
Situation 3: The order picker in the aisle is moving to its last target pick in this aisle, and this target is closer to the entrance away from the current picker than the current picker's target. Further, the picker in the aisle will leave the aisle from this entrance once it finishes its target pick, shown in Fig. 7c.

All these three situations mean that the order picker in the aisle will not disturb the picking operation of current order picker. In other situations, the current order picker should wait some time until all the order pickers in the aisle satisfy one of these three situations. This wait time will be record as WT_{ij} of moving from former pick location to this target pick. If more than two order pickers want to pick the same aisle at the same time, the start times of these two or more order pickers will be compared to decide the priority. The earliest order picker will first enter the aisle when the aisle is accessible, other order pickers will wait at the entrance.

Moreover, if the current order picker just wants to traverse through the block, and $PA_c \neq PA_t$, the picker can choose another accessible aisle, which between PA_c and PA_t, to traverse through without congestion, as shown in Fig. 8. If all the aisles between PA_c and PA_t may cause congestion, the current order picker will have to wait until one of these aisles is accessible.

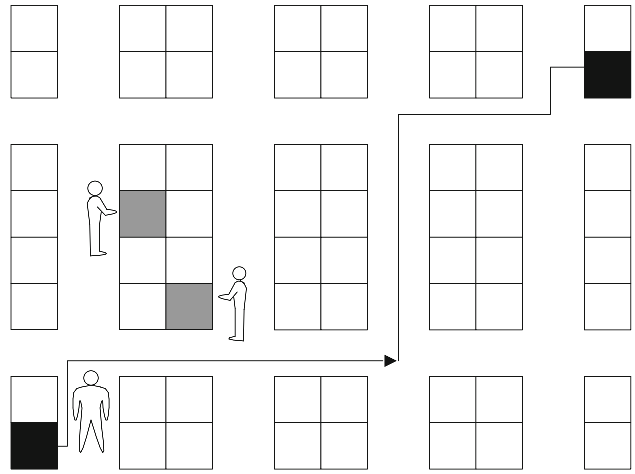

Fig. 8 Choose the suitable aisle to avoid congestion

Experiment and analysis

Experimental design

The experiment, which is conducted over various order picking environments, is designed to observe the improvement in order throughput and the computational performance of the proposed method. The experimental software is programmed with C# language at the .Net platform on a 2.40 GHz PC. In all ACO solutions, the following search parameters are set to values that are found to be robust in previous research and ANOVA test: $\alpha = 1, \beta = 5, \rho = 0.15$, and $m = 30$. Each run of the model consisted of 20,000 iterations of the trail construction and trail updating processes. Four routing methods are implemented for comparison in this study. The first three methods are S-Shape (SS), Largest Gap (L) and Combine (C) for a single order picker, as mentioned before. The fourth one is only adopting the Default Route (D) formed by ACO. All the methods form picking route just depending on the spatial relationship between picks, and adopt exclusive access control for pick aisle.

To validate the effectiveness of the proposed method, this paper considers multiple warehouse instances. These parameters are given in Table 1.

These parameters have significant impacts on the order picker routing method (Pan et al. 2012; Roodbergen and De Koster 2001b; Hwang et al. 2004), and they can be classified to following two kinds.

(1) Warehouse layout factors

- Number of Pick Aisles (NoPA)
- Pick Aisle Length (AL)
- Number of Cross Aisles (NoCA)
- Number of Order Pickers (NoOP)

Table 1 Related factors of the warehouse configuration

Parameter	Specification
Number of Pick Aisles (NoPA)	7, 15
Distance between two consecutive aisles in seconds	3
Pick Aisle Length (AL) in seconds	10, 30
The time of walking past one location in seconds	1
Number of Cross Aisles (NoCA)	2, 3, 6, 11
Width of cross aisle in seconds	1
Number of Order Pickers (NoOP)	2, 10
Number of Picks (NoP) per order	10, 30
Pick: Walk-time Ratio (PWR)	5:1, 20:1

All the specifications of NoPA and AL compose four kinds of storage capacity (140, 300, 420 and 900), and these specifications are referred to Roodbergen and De Koster (2001b). Note that Pick Aisle Length is the whole length of one pick aisle, no matter how many subaisles the pick aisle is divided into by cross aisles. The four number (2, 3, 6, 11) of NoCA can divide the pick aisles into 1, 2, 5 and 10 blocks respectively.

(2) Order property factors

- Number of Picks (NoP)
- Pick: Walk-time Ratio (PWR)

NoP is chosen to analyze the effect of picking density on the algorithm. PWR is first proposed by (Gue et al. 2006; Parikh and Meller 2009, 2010) to analyze the congestion in order picking. A PWR of 1:1 means the time spent on picking a single item at a location is identical with that of walking past the location. The higher value means that more time will be spent on finishing one picking position. In the nondeterministic picking time circumstances, the value of PWR is an expected value of the real picking time of one picking position.

Every picking operation starts once the first order picker begins to work and ends until all pickers return to the depot. This is called a Task, and the whole picking operation time of a Task is named as Task execution time (T_e). The interval between the start times of two successive order pickers is assumed as 20 s. Except walking, waiting and picking, other actions are assumed to take 0 s. To generate a Task, we fix NoP and NoOP at first. Next, for each pick in order, storage locations are randomly drawn independently from uniform distribution. The picking time for each pick location is drawn according to normal distribution, where standard deviation $\sigma = 1$ and expectation $\mu = PWR$. Then, these orders are assigned to respective order picker. During the Task, besides T_e, the congestion frequency and the waiting time are also recorded. Both of them are considered as the performance criteria considered in this simulation study as well as T_e.

Experimental results

Combining all the factors, we have 128 instances in total, and 100 Tasks are carried out in each instance, and results are processed by ANOVA tests with SPSS. Overall, A-MOP-NPT gives the best result of T_e in 122 of the 128 instances, and A-MOP-NPT is the second best in the rest 5 instances. T_e is given in Table 2. Data in bold font means unacceptable in 95 % confidence interval. To make a comparison, the percentage difference in T_e between S-Shape and the other algorithms are calculated by Eqs. (11), (12), (13) and (14), as shown in Table 3. A-MOP-NPT shows an obvious optimizing performance. The largest percentage difference can get up to 33 %. Even in the instances where A-MOP-NPT does not perform the best, the percentage differences are no less than −1 %. All these prove that A-MOP-NPT can improve the throughput effectively, and it is operable in practice.

$$L/SS = -(T_e(L) - T_e(SS))/T_e(SS) \times 100, \quad (11)$$

$$C/SS = -(T_e(C) - T_e(SS))/T_e(SS) \times 100, \quad (12)$$

$$D/SS = -(T_e(D) - T_e(SS))/T_e(SS) \times 100, \quad (13)$$

$$M/SS = -(T_e(M) - T_e(SS))/T_e(SS) \times 100, \quad (14)$$

where L/SS is short for the percentage difference between $T_e(L)$ and $T_e(SS)$, C/SS is short for the percentage difference between $T_e(C)$ and $T_e(SS)$, D/SS is short for the percentage difference between $T_e(D)$ and $T_e(SS)$, M/SS is short for the percentage difference between $T_e(M)$ and $T_e(SS)$, $T_e(SS)$ is T_e for S-Shape, $T_e(L)$ is T_e for Largest Gap, $T_e(C)$ is T_e for Combine, $T_e(D)$ is T_e for Default Route, and $T_e(M)$ is T_e for A-MOP-NPT.

Tables 4 and 5 show the average congestion frequency and waiting time of each order picker for one Task respectively. Similarly, data in bold font means unacceptable in 95 % confidence interval. In Tables 4 and 5, we can find out the main reason for optimization of T_e when apply A-MOP-NPT. In 80 instances, A-MOP-NPT causes the lowest congestion frequency. Meanwhile, in 91 instances, pickers spend the shortest time on waiting when adopt A-MOP-NPT.

Discussion

From the result, it proves that A-MOP-NPT performs best, especially in a larger scale warehouse. The largest difference between A-MOP-NPT and S-Shape results in the warehouse with NoPA = 15 and AL = 10. Because congestion will happen less frequently in a larger warehouse. Order pickers should have to traverse more and longer aisles when adopting S-Shape. However, A-MOP-NPT and Default route, whose routes are formed on the basis of ACO, do not require pickers

Table 2 T_e of S-Shape, Largest Gap, Combine, Default Route and A-MOP-NPT

NoPA	AL	NoOP	2																			
		NoP	10										30									
		PWR	5:1					20:1					5:1					20:1				
		NoCA	SS	L	C	D	M	SS	L	C	D	M	SS	L	C	D	M	SS	L	C	D	M
		2	168	155	158	156	154	354	336	336	332	321	279	293	274	287	277	826	845	819	825	813
		3	148	155	142	143	140	316	328	307	303	301	269	297	258	277	263	787	818	759	775	757
		6	149	157	155	141	136	308	318	320	295	293	309	343	321	273	262	803	832	835	748	733
	10	11	162	167	155	153	148	318	321	302	305	301	340	394	353	287	278	816	867	836	746	738
		2	301	260	281	244	238	497	443	456	417	421	455	470	447	449	425	1,010	1,033	994	984	969
		3	237	224	221	211	203	410	397	391	377	362	411	422	391	406	382	939	947	900	904	874
		6	205	201	198	194	181	365	365	360	346	333	400	406	401	359	343	895	904	903	832	809
7	30	11	199	208	199	197	185	358	362	347	349	335	393	422	397	355	338	874	899	885	820	803
		2	233	206	213	209	205	404	369	371	372	367	390	370	375	371	363	912	871	881	889	860
		3	199	227	193	193	189	358	383	345	350	344	357	400	334	346	333	848	880	820	834	818
		6	229	247	231	197	187	381	405	386	347	341	443	519	449	344	328	906	988	932	808	789
	10	11	247	258	242	206	196	405	410	374	356	349	521	619	526	361	344	975	1091	997	817	803
		2	417	325	358	324	318	584	483	520	480	478	694	630	643	604	584	1,206	1,113	1,142	1,107	1,075
		3	299	294	271	274	258	458	456	429	426	413	569	551	519	513	489	1,056	1,032	989	980	952
		6	279	292	276	247	233	436	446	436	400	386	563	600	539	460	433	1,031	1,060	1,011	919	896
15	30	11	282	299	279	254	241	437	447	426	403	389	575	653	583	451	424	1,048	1,116	1,027	907	880

Table 2 continued

NoPA	AL	NoOP	10																				
		NoP	10										30										
		PWR	5:1					20:1					5:1					20:1					
		NoCA	SS	L	C	D	M	SS	L	C	D	M	SS	L	C	D	M	SS	L	C	D	M	
		2	366	365	363	346	329	767	799	748	710	680	557	677	546	598	560	1,750	2,009	1,766	1,786	1,756	
		3	315	329	309	315	300	572	613	557	555	534	452	573	440	484	452	1,382	1,630	1,369	1369	**1,293**	
		6	322	321	324	307	297	509	522	506	487	479	482	540	509	446	428	1,156	1,284	1,211	1,056	1,024	
	10	11	329	328	324	315	309	489	498	474	481	471	509	566	525	457	442	1,080	1,151	1,104	968	964	
		2	635	612	597	520	504	1,074	1,069	1,020	891	832	957	1,080	916	931	868	2,175	2,461	2,158	2,082	2,008	
		3	426	432	409	397	378	750	751	707	658	597	685	805	663	660	618	1,672	1,895	1,626	1,497	1,411	
		6	369	369	366	361	342	571	583	565	544	518	588	628	600	549	517	1,319	1,399	1,343	1,165	1,091	
7	30	11	366	367	364	357	340	539	544	528	529	514	562	588	568	529	506	1,178	1,222	1,170	1,047	1,022	
		2	490	418	480	437	372	681	624	641	629	618	610	604	591	608	590	1,562	1,493	1,521	1,487	1,466	
		3	385	414	381	401	354	555	592	541	546	535	535	670	512	533	509	1,263	1,353	1,204	1,220	1,179	
		6	415	418	419	376	347	561	581	564	523	512	637	749	686	507	488	1,188	1,304	1,213	1,037	1,010	
	10	11	424	419	417	376	359	571	578	554	525	516	703	814	721	530	510	1,202	1,323	1,221	1,023	1,002	
		2	673	566	611	544	524	992	853	901	795	771	1,071	1,032	1,054	984	937	2,047	1,913	1,987	1,793	1,739	
		3	480	493	451	453	428	687	714	669	639	620	818	828	751	733	703	1,593	1,572	1,494	1,390	1,339	
		6	454	462	457	425	396	618	633	618	577	558	747	838	769	634	597	1,322	1,396	1,310	1,139	1,107	
15	30	11	459	465	450	420	403	611	616	601	579	563	770	847	775	626	590	1,282	1,374	1,268	1,104	1,072	

Table 3 Percentage differences in T_e between S-Shape, Largest Gap, Combine, Default Route and A-MOP-NPT

NoPA	AL	NoOP	2															
		NoP	10								30							
		PWR	5:1				20:1				5:1				20:1			
		NoCA	L/SS	C/SS	D/SS	M/SS	L/SS	C/SS	D/SS	M/SS	L/SS	C/SS	D/SS	M/SS	L/SS	C/SS	D/SS	M/SS
		2	7.58	6.01	6.96	8.59	4.91	4.97	5.98	9.34	−5.24	1.66	−3.17	0.55	−2.33	0.84	0.17	1.56
		3	−4.68	4.04	3.70	5.28	−3.83	2.92	4.18	4.95	−10.3	4.09	−3.06	2.39	−3.93	3.54	1.55	3.83
		6	−5.14	−4.08	5.56	8.53	−3.23	−3.97	4.08	4.90	−11.1	−3.81	11.64	15.39	−3.55	−3.99	6.83	8.67
	10	11	−3.47	4.25	5.42	8.55	−1.07	5.05	4.23	5.50	−15.9	−3.76	15.50	18.20	−6.27	−2.43	8.57	9.58
		2	13.60	6.57	18.87	20.83	10.92	8.29	16.04	15.42	−3.39	1.77	1.23	6.64	−2.27	1.63	2.63	4.09
		3	5.59	6.83	10.97	14.27	3.18	4.56	7.95	11.57	−2.68	4.94	1.24	7.18	−0.79	4.20	3.77	7.02
		6	2.27	3.57	5.69	11.95	−0.14	1.28	5.15	8.57	−1.67	−0.34	10.08	14.23	−0.92	−0.86	7.07	9.61
7	30	11	−4.12	0.18	1.06	7.42	−1.08	3.04	2.39	6.30	−7.19	−0.95	9.71	14.03	−2.81	−1.25	6.21	8.16
		2	11.92	8.74	10.59	12.02	8.50	8.10	7.89	8.99	5.20	3.93	4.91	6.98	4.45	3.41	2.50	5.68
		3	−14.0	3.04	2.87	5.05	−6.95	3.66	2.24	4.07	−12.1	6.35	2.87	6.54	−3.76	3.36	1.71	3.59
		6	−7.75	−0.95	14.04	18.39	−6.18	−1.26	8.99	10.65	−17.3	−1.41	22.27	25.82	−9.02	−2.83	10.84	12.92
	10	11	−4.45	1.94	16.58	20.55	−1.39	7.59	11.92	13.78	−18.8	−0.95	30.66	33.90	−11.9	−2.23	16.21	17.69
		2	22.06	14.05	22.29	23.74	17.30	10.93	17.76	18.14	9.22	7.38	13.03	15.90	7.65	5.27	8.18	10.86
		3	1.54	9.38	8.54	13.57	0.52	6.41	7.02	9.93	3.19	8.75	9.75	14.08	2.34	6.38	7.23	9.89
		6	−4.53	1.05	11.46	16.58	−2.35	−0.01	8.22	11.53	−6.63	4.22	18.31	23.10	−2.84	1.95	10.86	13.13
15	30	11	−6.09	0.92	9.77	14.44	−2.22	2.62	7.99	11.19	−13.6	−1.45	21.44	26.27	−6.51	1.99	13.42	16.06

Table 3 continued

NoPA	AL	NoOP	10															
		NoP	10								30							
		PWR	5:1				20:1				5:1				20:1			
		NoCA	L/SS	C/SS	D/SS	M/SS	L/SS	C/SS	D/SS	M/SS	L/SS	C/SS	D/SS	M/SS	L/SS	C/SS	D/SS	M/SS
		2	0.08	0.75	5.49	9.99	−4.22	2.42	7.37	11.36	−21.6	1.91	−7.36	−0.68	−14.8	−0.94	−2.06	−0.36
		3	−4.56	1.89	−0.04	4.75	−7.19	2.67	2.96	6.61	−26.8	2.63	−7.17	0.08	−17.9	0.92	0.92	6.43
		6	0.26	−0.76	4.47	7.55	−2.53	0.56	4.31	5.93	−12.1	−5.64	7.34	11.19	−11.1	−4.75	8.67	11.42
	10	11	0.11	1.45	4.13	6.13	−1.92	3.01	1.65	3.62	−11.3	−3.20	10.12	13.13	−6.61	−2.24	10.35	10.74
		2	3.71	5.99	18.05	20.56	0.47	5.05	17.07	22.57	−12.9	4.27	2.73	9.31	−13.1	0.79	4.29	7.69
		3	−1.33	4.04	6.76	11.30	−0.05	5.76	12.35	20.38	−17.5	3.24	3.64	9.82	−13.5	2.73	10.44	15.61
		6	−0.07	0.84	2.12	7.23	−2.03	1.07	4.80	9.36	−6.74	−2.04	6.68	12.02	−6.12	−1.83	11.68	17.31
7	30	11	−0.31	0.48	2.29	6.96	−1.02	1.98	1.83	4.56	−4.64	−1.04	5.90	9.93	−3.75	0.67	11.10	13.20
		2	14.60	1.95	10.83	24.12	8.40	5.86	7.64	9.19	0.99	3.05	0.23	3.25	4.42	2.65	4.81	6.18
		3	−7.76	0.94	−4.24	8.05	−6.68	2.49	1.68	3.65	−25.2	4.37	0.49	4.99	−7.15	4.68	3.43	6.66
		6	−0.82	−0.95	9.43	16.29	−3.47	−0.48	6.88	8.79	−17.7	−7.75	20.30	23.39	−9.70	−2.09	12.76	14.97
	10	11	1.12	1.57	11.15	15.25	−1.26	3.00	8.04	9.62	−15.8	−2.54	24.60	27.42	−10.1	−1.62	14.83	16.59
		2	15.87	9.24	19.25	22.23	14.04	9.18	19.86	22.26	3.59	1.57	8.11	12.47	6.56	2.95	12.41	15.06
		3	−2.83	5.98	5.49	10.84	−4.03	2.57	6.88	9.75	−1.22	8.16	10.33	14.01	1.30	6.19	12.69	15.93
		6	−1.86	−0.70	6.35	12.70	−2.49	0.00	6.60	9.71	−12.2	−2.98	15.09	20.06	−5.62	0.91	13.85	16.28
15	30	11	−1.22	2.06	8.59	12.38	−0.83	1.67	5.27	7.92	−10.1	−0.70	18.71	23.40	−7.22	1.07	13.85	16.37

Table 4 Average congestion frequency of each order picker for one task

NoPA	AL	NoOP	2																			
		NoP	10										30									
		PWR	5:1					20:1					5:1					20:1				
		NoCA	SS	L	C	D	M	SS	L	C	D	M	SS	L	C	D	M	SS	L	C	D	M
		2	0.52	0.73	0.56	0.59	0.56	1.19	1.01	0.94	0.84	0.79	1.19	1.73	1.29	1.19	1.11	1.26	1.54	1.33	1.31	1.23
		3	0.39	0.47	0.31	0.22	0.24	0.86	1.08	0.89	0.65	0.69	1.27	1.80	1.00	1.48	1.12	1.60	2.21	1.67	1.32	1.52
		6	0.18	0.35	0.19	0.23	0.20	0.59	0.78	0.65	0.45	0.40	0.90	1.39	1.02	0.84	0.59	2.13	2.80	2.15	1.33	1.29
	10	11	0.17	0.27	0.12	0.13	0.05	0.50	0.69	0.36	0.47	0.38	0.61	0.99	0.53	0.43	0.46	1.63	2.20	1.46	0.90	0.93
		2	0.97	0.99	0.92	0.60	0.65	1.18	1.04	1.04	0.64	0.71	1.56	1.66	1.49	1.19	0.93	1.37	1.64	1.33	1.29	1.34
		3	0.69	0.89	0.72	0.52	0.47	0.98	1.03	1.01	0.57	0.52	1.44	2.22	1.63	1.15	1.14	1.84	2.34	1.74	1.25	1.42
		6	0.20	0.39	0.26	0.25	0.17	0.61	0.83	0.65	0.57	0.44	1.20	1.55	1.36	0.72	0.85	2.12	2.71	2.25	0.99	0.97
7	30	11	0.16	0.19	0.18	0.23	0.16	0.64	0.74	0.54	0.33	0.26	0.85	1.08	0.83	0.35	0.46	1.75	2.23	1.65	0.82	0.91
		2	0.53	0.54	0.41	0.49	0.34	0.84	0.76	0.79	0.63	0.63	1.22	1.62	1.42	1.16	1.20	1.87	1.76	1.82	1.69	1.31
		3	0.28	0.24	0.21	0.30	0.19	0.62	0.52	0.54	0.64	0.44	1.25	1.63	0.90	0.93	0.85	2.01	1.99	1.90	1.44	1.27
		6	0.10	0.18	0.13	0.19	0.14	0.34	0.37	0.27	0.30	0.31	0.58	1.00	0.67	0.53	0.45	1.49	1.65	1.49	1.01	0.93
	10	11	0.04	0.16	0.09	0.14	0.04	0.22	0.19	0.25	0.27	0.23	0.41	0.64	0.32	0.34	0.31	0.71	1.30	0.89	0.56	0.55
		2	0.95	0.74	0.74	0.54	0.60	0.80	0.69	0.75	0.52	0.61	1.71	1.90	1.82	1.22	1.23	1.87	1.70	1.78	1.34	1.30
		3	0.38	0.45	0.40	0.35	0.22	0.60	0.58	0.62	0.39	0.36	1.79	1.78	1.52	1.07	0.97	1.67	1.81	1.88	1.06	0.96
		6	0.09	0.17	0.14	0.13	0.10	0.31	0.37	0.33	0.29	0.22	0.81	1.04	0.91	0.49	0.47	1.49	1.55	1.36	0.68	0.69
15	30	11	0.03	0.16	0.11	0.11	0.09	0.25	0.25	0.19	0.24	0.21	0.37	0.54	0.43	0.37	0.24	1.16	1.22	0.94	0.36	0.51

Table 4 continued

NoPA	AL	NoOP	10																			
		NoP	10										30									
		PWR	5:1					20:1					5:1					20:1				
		NoCA	SS	L	C	D	M	SS	L	C	D	M	SS	L	C	D	M	SS	L	C	D	M
		2	1.67	3.44	1.72	2.06	1.84	3.19	4.23	3.01	3.20	3.19	3.50	6.31	3.46	4.07	3.96	3.57	6.41	3.58	**4.26**	4.10
		3	1.27	2.30	1.15	1.46	0.96	3.06	5.00	3.07	2.96	2.85	3.29	9.25	3.26	**4.38**	3.92	5.68	10.9	5.59	6.08	6.48
		6	0.85	1.26	0.86	1.05	0.54	2.35	3.81	2.19	2.33	2.13	3.01	6.90	3.59	3.54	2.74	8.13	12.6	8.69	6.86	6.93
	10	11	0.53	1.01	0.49	0.75	0.44	1.61	2.75	1.42	1.86	1.46	2.07	4.28	2.20	2.57	2.18	7.29	11.7	6.49	5.40	5.11
		2	3.16	3.88	3.02	3.00	2.86	3.30	4.16	3.16	3.39	3.30	3.97	6.65	3.78	4.77	4.54	3.85	6.50	3.73	4.77	4.61
		3	2.40	3.87	2.19	2.07	1.74	3.23	4.91	3.29	2.91	2.74	5.53	10.5	5.38	5.30	4.92	5.66	10.8	5.55	5.81	6.21
		6	0.97	1.55	1.04	1.25	0.90	2.58	3.95	2.42	2.27	1.93	3.95	8.04	4.57	3.58	3.23	7.92	11.9	8.05	5.68	5.66
7	30	11	0.62	1.19	0.58	0.91	0.62	1.90	2.94	1.86	1.85	1.58	2.46	4.60	2.53	2.45	2.08	7.03	11.6	6.83	4.58	**4.40**
		2	1.60	2.76	1.36	1.36	1.21	3.02	4.61	3.00	2.71	2.61	4.86	9.79	4.81	4.81	**4.34**	5.58	10.8	5.72	5.85	5.97
		3	0.85	1.90	0.80	0.83	0.55	2.03	3.63	1.88	1.99	1.77	3.20	10.1	3.01	3.44	3.11	7.20	13.5	7.12	6.58	6.54
		6	0.57	1.04	0.57	0.72	0.30	1.18	2.05	1.14	1.41	1.19	2.21	6.43	2.36	2.23	1.61	5.92	11.3	6.08	5.05	4.84
	10	11	0.39	0.88	0.35	0.56	0.19	0.85	1.34	0.65	1.12	0.87	1.45	3.65	1.44	1.71	1.23	**4.20**	7.46	3.44	3.58	3.36
		2	3.05	4.21	2.80	2.27	2.06	3.37	4.84	3.36	2.79	2.77	5.90	10.3	6.05	5.53	5.40	5.94	10.8	5.98	6.24	6.09
		3	1.46	2.61	1.33	1.29	1.07	2.25	4.15	2.34	1.96	1.81	6.09	11.7	5.72	**4.47**	**4.46**	7.07	13.3	6.88	5.73	5.94
		6	0.55	1.24	0.63	0.68	0.41	1.23	2.30	1.24	1.27	1.03	2.89	6.86	2.82	2.29	1.96	5.73	10.9	5.85	3.98	3.90
15	30	11	0.39	0.88	0.36	0.58	0.28	0.99	1.62	0.96	1.12	0.94	1.76	3.70	1.69	1.55	1.13	4.32	7.49	3.95	2.81	2.76

Table 5 Average waiting time of each order picker for one Task

NoPA	AL	NoOP	2																			
		NoP	10										30									
		PWR	5:1					20:1					5:1					20:1				
		NoCA	SS	L	C	D	M	SS	L	C	D	M	SS	L	C	D	M	SS	L	C	D	M
		2	4.15	4.79	4.16	4.97	3.97	25.9	21.7	21.3	20.6	17.4	9.13	17.0	9.4	13.4	12.6	58.3	74.6	58.5	60.3	61.1
		3	1.58	1.89	1.71	0.89	1.53	14.0	15.4	13.6	9.6	11.4	6.64	9.04	4.93	9.77	7.09	39.6	52.2	40.2	35.4	32.7
		6	0.73	0.88	0.93	0.95	0.64	5.59	5.69	7.13	4.03	4.96	4.45	4.41	4.15	3.14	2.42	28.1	32.2	28.3	20.0	17.6
	10	11	0.61	0.55	0.55	0.41	0.11	3.77	4.99	3.68	3.94	3.32	1.93	2.32	1.86	1.34	1.26	17.3	17.6	16.8	7.33	9.39
		2	17.0	14.2	15.6	8.8	10.9	39.9	32.2	34.7	22.8	23.9	24.1	35.0	24.8	29.9	23.8	76.2	99.6	77.5	82.9	82.0
		3	6.52	6.55	6.63	4.47	4.07	21.1	19.9	19.5	11.2	9.3	11.4	18.3	13.7	14.0	10.7	55.8	67.8	55.5	43.1	39.2
		6	1.22	1.36	1.47	0.82	0.79	8.11	8.58	7.63	5.81	4.62	7.36	5.81	8.52	3.62	4.36	33.7	40.3	37.5	17.1	14.6
7	30	11	0.61	0.45	0.80	0.86	0.45	5.77	5.75	5.44	3.69	2.10	3.46	3.26	3.37	1.43	1.75	21.5	22.6	21.5	10.4	12.1
		2	4.58	2.44	2.49	3.48	2.19	16.4	11.9	13.8	12.0	9.55	7.67	10.4	10.9	9.4	10.6	49.1	40.0	48.5	51.1	39.4
		3	1.67	0.52	0.94	1.46	1.02	8.38	4.83	6.99	6.99	5.27	6.60	5.37	4.84	5.49	4.46	31.8	27.2	34.0	27.2	22.5
		6	0.90	0.30	1.01	0.99	0.50	3.32	2.64	2.65	2.98	3.13	2.46	1.81	3.80	2.09	1.61	16.5	14.5	18.6	11.7	11.0
	10	11	0.19	0.24	0.81	0.90	0.07	1.94	1.20	2.27	2.45	2.02	2.17	1.08	2.27	1.42	0.82	7.79	9.32	10.5	5.29	6.44
		2	16.1	10.5	11.2	8.3	9.0	26.2	15.7	21.2	13.5	15.4	25.9	28.2	28.3	21.7	20.5	61.0	55.1	60.5	55.1	47.9
		3	4.49	2.41	3.20	2.58	1.64	11.6	8.61	10.7	5.33	5.81	15.7	11.4	14.1	10.4	8.76	37.1	34.5	43.3	23.4	18.3
		6	0.50	0.46	1.17	0.85	0.47	3.35	2.70	3.28	3.28	2.40	5.25	3.33	5.41	2.99	2.08	21.2	17.0	18.8	10.9	9.92
15	30	11	0.39	0.31	0.99	0.42	0.29	1.62	1.10	1.28	1.49	1.76	2.13	1.15	2.77	1.56	1.09	11.5	10.1	9.96	3.55	5.17

Table 5 continued

NoPA	AL	NoOP	10																			
		NoP	10										30									
		PWR	5:1					20:1					5:1					20:1				
		NoCA	SS	L	C	D	M	SS	L	C	D	M	SS	L	C	D	M	SS	L	C	D	M
		2	20.1	31.1	22.7	26.8	20.7	166	180	164	163	150	71.6	130	69.5	109	97.2	461	612	472	544	532
		3	7.92	10.6	7.38	11.7	5.44	75.1	93.3	71.0	72.0	**61.6**	21.4	86.8	22.1	47.5	36.7	280	472	287	315	284
		6	5.45	3.05	5.47	5.14	1.85	29.9	33.7	28.5	29.6	27.1	16.0	31.4	23.1	16.7	12.5	155	207	166	129	117
	10	11	3.03	1.83	3.06	2.96	1.12	17.7	18.9	15.5	19.1	16.7	9.71	12.0	11.5	8.22	6.75	90.3	100	79.9	**60.5**	**58.9**
		2	110	113	104	89	80	269	272	255	236	204	200	281	186	249	222	598	793	603	691	656
		3	29.4	33.2	26.2	25.1	18.3	119	131	115	94.0	**66.4**	80.9	168	82.3	95.2	76.7	375	573	368	340	298
		6	6.06	5.02	6.94	7.52	4.65	43.8	44.3	38.2	35.8	26.6	30.4	46.3	37.7	26.0	19.4	204	242	212	133	109
7	30	11	3.21	2.70	2.94	3.75	2.16	22.8	21.6	21.1	20.7	17.5	13.7	14.6	14.2	10.6	8.84	114	130	114	**67.8**	**59.1**
		2	26.1	18.5	27.2	23.9	10.1	88.5	72.5	81.7	73.2	**68.5**	46.5	64.8	48.6	**67.0**	**57.9**	321	331	325	333	326
		3	8.86	9.17	10.1	13.9	2.82	34.2	34.2	31.6	33.5	27.1	21.2	59.8	20.1	25.1	19.0	188	221	191	183	156
		6	8.37	2.90	9.13	7.48	1.02	16.0	13.7	14.8	15.3	13.5	23.7	34.9	36.0	9.69	6.14	93.9	106	95.4	70.3	**64.6**
	10	11	3.58	1.65	4.76	4.33	0.52	9.30	7.39	7.84	10.6	8.65	18.5	13.2	20.9	6.79	3.60	53.7	58.6	46.6	39.1	37.6
		2	79.2	56.4	66.6	48.2	41.7	167	135	151	108	103	157	193	173	162	150	439	461	450	398	384
		3	18.0	18.1	15.5	15.9	9.6	55.3	56.4	55.1	45.4	36.0	75.1	82.4	67.9	54.3	50.9	268	274	255	191	165
		6	5.83	3.85	7.95	5.13	1.98	17.1	18.0	18.1	16.6	13.0	27.8	41.7	38.5	15.2	10.8	106	120	111	**62.7**	**57.3**
15	30	11	3.30	2.40	3.50	3.91	1.04	11.3	10.1	10.9	10.9	9.49	19.7	14.5	22.3	7.81	4.31	62.1	60.4	57.9	33.8	31.6

traverse the whole aisle. It means A-MOP-NPT and Default Route can cut down the total travel distance. Combine has two choices to visit an aisle, which makes it can also outperform S-Shape. Besides, when pick density is high, Largest Gap becomes the worst one, this is inline with Hall (1993). Moreover, A-MOP-NPT performs better than Default Route in almost all the scenarios. Because online coordination makes A-MOP-NPT alleviate the congestion in real time. Order pickers spend less time on waiting with the help of A-MOP-NPT. Coupling with the default travel route formed by ACO, which is usually shorter than that of S-Shape, it is not surprising that A-MOP-NPT can heighten the throughput effectively. Further, the simulation confirms that the A-MOP-NPT can adapt to different kinds of picker-to-parts warehouse layouts.

Further, the effect of these warehouse parameters on picking efficiency can be analyzed as well.

Effect of warehouse layout

(1) NoPA

For a warehouse with 15 pick aisles, the T_e is much longer, because order pickers has to visit more pick aisles. Meanwhile, the waiting time and congestion frequency are decreased. Because the picking density will be lower in a warehouse with more pick aisles, order pickers are harder to meet one another. The same reason explains the result that A-MOP-NPT can perform better in a warehouse with more pick aisles.

(2) AL

When pick aisle becomes longer, order pickers will spend more time in one pick aisle, which results in increase in T_e. On the other hand, although the picking density decreases with increased pick aisle length, the probability of pick aisle being accessed remains unchanged. The longer staying time in one aisle increases the congestion frequency and the waiting time.

(3) NoCA

Cross aisles divide the pick aisle into subaisles, and order pickers will not have to traverse through the whole pick aisle to reach the picking target pick. Benefiting from these cross aisles, order pickers can also avoid meeting one another in the same pick aisle. More cross aisles can decrease the congestion frequency and the waiting time. However, T_e does not decrease linearly with the increase of NoCA, because order picker has to spend time on walking along the cross aisle to the target aisle. Too many cross aisles extend the travel distance between two picks belonging to different blocks, resulting in increase in T_e.

(4) NoOP

When more order pickers work in a warehouse simultaneously, the congestion will happen more often, and directly causing increased waiting time. However, when warehouse owns 10 order pickers, the change of some parameters will not always lead to the same effect. When NoCA $= 2$, NoP $=$ 30 and NoOP $= 10$, the congestion frequency increases with NoPA increases from 7 to 15. In other instances, the congestion frequency usually decreases, when NoPA increases. When picking density reaches a certain high level, increasing NoPA can not effectually reduce congestion frequency in a single pick aisle. On the contrary, the increase in NoPA causes the total congestion frequency increasing.

Effect of order properties

(1) NoP

As the order size increases, the waiting time and T_e also increase. This outcome is predictable since the residence time of pickers in the aisle rises with the increases of the picking density in each aisle.

(2) PWR

Increasing PWR spontaneously increases T_e and the waiting time. This phenomenon is reasonable because the residence time of pickers in the aisle increases as the expected time for finishing one pick increases.

In summary, if the picking density is too high or the warehouse owns long pick aisles, it is practicable to set more cross aisles to achieve a higher throughput. An appropriate NoCA can also make A-MOP-NPT show its advantages in application. From the result, we can find that the largest percentage differences are achieved in the instances with two cross aisles, when picking density is low. While in high picking density instances, the largest percentage differences can appear in the instances with 11 cross aisles. It is worth noting that when the picking density exceeds an appropriate level, the waiting time has more impacts on the order picking efficiency, comparing to the travel distance. On the other hand, a proper warehouse layout considering the workload of each aisle can cut down the congestion frequency and optimize the travel distance effectively. In the suitable configuration, A-MOP-NPT can achieve the largest percentage difference as well.

Conclusion

This paper proposes an online ACO-based routing method for a picker-to-parts warehouse with multiple pickers, named A-MOP-NPT. A-MOP-NPT aims at forming picking routes for multiple order pickers under nondeterministic picking time with congestion consideration in real time, based on information sharing and indoor positioning technology. The new method first forms a default route for each single picker by ACO, and then coordinates these routes to deal with the congestion during the picking service in real time. With this method, order pickers can alleviate the congestion during picking operation and shorten the whole order service time. A simulation is carried out for analyzing the efficiency of A-MOP-NPT. The warehouse layout and order property are concerned as parameters. In the simulation A-MOP-NPT shows the highest throughput in most of the instances. At the same time, the new method performs well in dealing with the congestion. All of these are owing to the default route formed by ACO and the coordination in real time to avoid congestion in the pick aisle.

In this paper, the order picker adopts pick-by-order policy, and there is no capacity limit for the order picker. In practice, the order may have to be spread or batched to match the order picker's capacity. Moreover, to avoid congestion, order pickers may try to reassign the target pick to the pickers in the aisle. Besides, orders may arrive when all the order pickers have left the depot to pick. How to spread or batch orders to the working order pickers and form picking route in real time is a new problem which deserves future research.

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