Storage assignment in a narrow-aisle warehouse with multi-picker situation

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Abstract

A picker locates the indicated products in different aisles of a warehouse according to a sequence in the actual picking model. The picking model can be considered as an open restricted queuing network, and each aisle can be considered a workstation in the multi-picker situation. The problem of storage assignment in a narrow-aisle warehouse with a multi-picker system is addressed herein to minimize the pick time of all orders. First, we construct an initial solution by cube-per-order index (COI) rule. A novel heuristic algorithm is also presented to improve the initial solution by employing open restricted queuing networks. The results show that the algorithms developed perform substantially better than COI rule. Comparisons of the performance of the proposed algorithms are presented.

Keywords: storage assignment, cube-per-order index, waiting time, queuing networks

1. Introduction

Products must be picked from specified storage locations in warehouses and distribution centers. This process, known as the orderpicking process, is driven by customer orders, that consist of a number of orderlines. Each orderline represents one product or article code that has to be shipped to the customer in a certain quantity, the orderline quantity (de Koster 1999). The picking process is, generally the most laborious of all warehouse processes as it may consume as much as 60% of all labor activities in the warehouse (Drury 1988). Therefore, it is worthwhile to improve the efficiency of the picking process via the following three strategies. First, analyze the average time and average distance of the picking process. Second, discuss the picking process from the perspective of the warehouse or storage layout. Finally, investigate the picking process from the order batching perspective. This paper focuses on the warehouse layout, i.e., storage assignment.

The warehouse layout problem has been extensively studied. Barrett (1977) evaluated the effectiveness of various rules for order-picking systems that allow multiple stops for each crane trip into the aisle of a high-rise warehouse. Using a simulation study, he compared different ‘ABC’ characteristics and customer ordering patterns based on realistic data concluding that efficient operation is obtainable with relatively small batch sizes, a simple heuristic for assigning orders to picking lots, and turnover-based storage assignments. Frazelle and Sharp (1989) verified that the correlated assignment policy offers tremendous potential for reductions in pick times. The reductions are significant to warrant a comprehensive analysis of the order data and creation of a formal parts assignment strategy based on order data and stock keeping unit (SKU) popularity. Such a strategy is notably less expensive (possibly resulting in fewer headaches) than employing more labor and purchasing additional hardware to achieve the same improvements.

Jarvis and Mcdowell (1991) developed the necessary conditions for optimal product location in a class of symmetric warehouses. Simply assigning the most frequently picked items to the nearest aisles will not necessarily minimize the average travel distance if the aisles are not symmetrical. In addition, the necessary conditions for optimal product location were presented and a heuristic based upon these conditions was developed. However, this study failed to consider the effects of congestion. Ruben and Jacobs (1999) developed the batch construction heuristics and tested under three strategies for assigning storage space to individual items. Their results indicate that the methods used can significantly impact order retrieval efforts in walk/ride and pick systems. In this research they model the congestion effect by partitioning each aisle into 20 sections of equal area and restricting access to each area to a single picker. Thus, in theory, 20 order pickers could occupy a single aisle and experience no congestion.
The cube-per-order Index (COI) put forward by Heskett (1963) is the mostly widely applied assignment methods. The COI takes the sale frequency of products and space requirements into consideration to calculate a COI value. The items with smaller COI values will be allocated to the storage rack that is easy to pick, while the products requiring small space and the best selling products are placed nearest to the depot. The COI method attempts to balance these two objectives. Jarvis and Mcdowell (1991) stated that possible congestion should be considered in a system with multi-pickers and limited aisles. Delays will occur under the current condition since only one person is permitted to enter the narrow aisle to pick products. Thus, there should be a trade-off between the picking distance and the blocking-caused delay for the assignment.

The literature on waiting is still deficient. Developing a suitable storage location arrangement can reduce both the picking distance and the picking time. If consideration is given to shortening the picking distance while neglecting the picking process, then the potential path-blocking problem may emerge. Thus, the only feasible way to solve this phenomenon is to employ an analytical approach to the queuing networks. The following three solution types can be divided according to the configurations and features of the queuing networks: tandem configuration, split and merge configuration, and arbitrary configuration. The approximation approach is typically applied to solve the queuing networks because of the difficulties involved in acquiring accurate solutions from general networks. Hillier and Boling’s (1966) proximity analytical approach presumed the arrival time interval or service time as exponential or an Erlang distribution but it could only solve the tandem configuration of the queuing networks. Kerbache and Smith’s (1987) approximation approach claimed that if the coefficient of variation is more than 1, then the hyper-exponential distribution will be utilized in the proximity service time distribution. If the coefficient of variation is below 1, then Erlang distribution will be employed to derive the proximity, except that it is more applicable for the system using a rate smaller than 0.7. Perros and Altik (1986) presumed that time follows the Coxion distribution, which is an exponential distribution by irregular time intervals, and the arrival process is presumed to be a Poisson process. Takahashi et al. (1980) presented an approximation method to analyze open restricted queuing networks with exponential inter-arrival and service times. A node-by-node decomposition performed by introducing pseudo-arrival rates and effective service rates so easily computed approximations of various characteristic quantities such as blocking probabilities, output rate, etc., can obtained for the network. Pseudo-arrival rates and effective service rates were developed to achieve an approximated node-by-node decomposition. The idea is based on the consideration that the parameter representing inter-dependency among the nodes is the blocking probability. The amount of calculation in this method increases only linearly according to the number of nodes.

In summary, very little research exists into operating strategies for multiple aisle walk and pick systems. The aisle congestion aspect of the problem and the effect on retrieval time has not been treated in the literature. Only one study has proposed and tested a number of batch construction heuristics under the three types of storage assignment strategies. In addition, they model the effect of these policies on warehouse congestion levels.

Waiting issues in storage assignment are considered herein by first constructing an initial solution via the COI rule and second, presenting a new heuristic algorithm to enhance the initial solution by solving the open restricted queuing networks.

### 2. Problem descriptions

Each picker is responsible for one picking lot in most of the narrow-aisle warehouse picking models. Generally, each picker should pick by order and he/she should not exceed the one in front of him/her. Therefore, a picking model can be treated as an open restricted queuing network, and each aisle as a workstation. The time a picker spends in one aisle is treated as the service time, which depends on the contents of the picking list. The layout of a parallel aisle warehouse is shown in Fig. 1, and the following assumptions are made.

- There are two fixed depots, i.e. input depot and output depot.
- Sufficient stock is usually available to meet the daily demand.
- Customers place their orders in terms of full product boxes only, i.e. orders for split boxes are not permitted.
- The picking time is proportional to the number of boxes.
- The aisle width is small and a vehicle is driven down the center of aisles. If the vehicle stops at a point, the boxes are picked from both sides without traveling additional distance.

Figure 1 can be regard as \( n \) finite queues in tandem (see Fig. 2). The queuing network analysis method can analyze on the waiting problems in storage assignment after a picking module is transferred into a queuing network module. The picker who already finished the service in a previous station can not enter another aisle if one station is full (and the previous aisle is therefore occupied by this picker). Consequently, the blocking decreases the efficiency of the system. In other words, the blocking phenomenon refers to the probability the aisle is occupied by pickers. Therefore, the blocking probability will be applied herein to measure the service level of the waiting phenomenon in the picking process.
Two factors related to the products space necessity and sales frequency are considered in the COI assignment method. The optimal assignment can be derived through the COI method if some conditions are assumed. For example, space necessity factors do not need to be considered as each item will be equally distributed into each aisle according to picking frequency if Gray et al. (1992) assignment method is applied. Moreover, the items that are closer to the aisles have higher picking frequency.

The shortest average walking distance, similar picking time in each aisle, and shortest waiting time in the aisles are also assumed. The blocking probability of each aisle will be calculated according to the result of this assignment method. The minimum will be considered as the reference blocking probability $\varepsilon$ and this value will be applied to measure the waiting level of the picking process while the COI assignment method is applied.

The heuristic assignment method developed to enhance the waiting phenomenon that would happen in picking process is designed as follows:

1. Calculate the COI value for each item. Assign each item to the storage location according to the COI value.
2. Evaluate the blocking probability of each aisle, i.e., analyze the influence for the COI assignment to the picking process.
3. Decide which item can be assigned to the storage rack first after comparing the blocking probability with the reference value.
3. Problem formulation

The structure of the considered narrow-aisle and multi-picker warehouse is limited to a two-dimensional storage allocation. One face of the rack has \( m \) rows and \( 2n \) columns, making \( 2mn \) storage locations. The locations are numbered sequentially by 1 through \( 2mn \). The warehouse operates a traversal policy with \( n \) aisles and single cross-aisle. An order consists of one or more types of items to be located from several locations in the warehouse.

3.1 Nomenclature

\( \lambda_i \)  
The order arrival rate is determined according to the Poisson process from out of the warehouse to aisle \( i \).

\( d_i \)  
The actual order arrival rate from the inner warehouse to aisle \( i \). The picker can arrive in aisle \( i \) only in the none-blocked time intervals.

\( \lambda'_i \)  
The pseudo-arrival rate of aisle \( i \). The order arrival rate does not consider the blocked time intervals from inside the warehouse to aisle \( i \).

\( \varepsilon_i \)  
The blocking probability of aisle \( i \). The ratio of non-blocked time intervals to the whole time is 1\( - \varepsilon_i \).

\( \mu_i \)  
The service rate of aisle \( i \) is determined according to the exponential distribution. It does not consider the block situations.

\( \mu'_i \)  
The effective service rate of aisle \( i \), according to the exponential distribution. It includes the holding time in block situation.

\( \alpha_{ij} \)  
The probability of succeeding to pick items of aisle \( j \) while finishing the aisle \( i \) picking process.

\( \rho_i \)  
The utilization rate of aisle \( i \).

\( P_i(n) \)  
The probability of aisle \( i \) just has \( n \) pickers.

\( P_i(0) \)  
The probability of aisle \( i \) just has none picker.

\( \epsilon_i \)  
The maximum queue capacity of aisle \( i \).

\( ED_i \)  
The expected picking distance in aisle \( i \). (meter)

\( T_i \)  
The expected picking time in aisle \( i \). (minute)

\( v \)  
The walking velocity of pickers. (meter/minute)

\( t \)  
The picking time for each item. (minute)

\( l \)  
The storage rack width. (meter)

3.2 An approximation method for an open restricted queuing network

The picking process (with \( n \) aisles, and traversal policy applied) can be considered a tandem network with \( n \) aisles as previously described. The approximation method presented by Takahashi et al. (1980) can solve arbitrary open restricted queuing networks which include the tandem type. This method can also ease the calculations and solve problems in the larger queuing networks. This method focuses on the blocking probability, which is the index that represents the relationship among the aisles. Pseudo-arrival rates \( \lambda'_i \) and effective service rates \( \mu'_i \) are also presented to deal with the interdependent relationship of each aisle in the network, and to achieve an approximate aisle-by-aisle analysis. The following formula (1) to (7) enables each aisle in the network to be individually analyzed (with M/M/1/s/1), then various effectiveness measurement values in the queuing network can be obtained to solve the simultaneous equations of all the aisles. The solving formulas are as follows:

\[
\lambda'_i = \frac{d_i}{1 - \varepsilon_i}  \tag{1}
\]

\[
\varepsilon_i = P_i(s_i + 1)  \tag{2}
\]

\[
\frac{1}{\mu'_i} = \frac{1}{\mu_i} + \sum_{j} \frac{\alpha_{ij} \varepsilon_j}{\mu'_j} \left[ 1 + \sum_{k} \frac{P_k \alpha_{kj} \mu'_k}{\mu'_k + \mu'_i} \right]  \tag{3}
\]

\[
d_i = \mu'_i (1 - P_i(0))  \tag{4}
\]

\[
\rho_i = \frac{\lambda'_i + \lambda_i}{\mu'_i}  \tag{5}
\]

\[
P_i(n) = \rho_i^n P_i(0)  \tag{6}
\]
The following assumptions must be made when an approximation method is utilized in the picking process system.

1. The picking time in each aisle follows an exponential distribution.
2. Order arrivals from outside of the warehouse obey the Poisson process.
3. Arrivals from outside of the warehouse only happen in the first aisle.
4. The maximum queue capacity of each aisle is 1.

Using formula (1)-(7) in each aisle of the narrow-aisle warehouse, we can establish the simultaneous equations as follows:

Aisle 1 (\(\lambda = 0\))

\[
\frac{1}{\mu_i} = \frac{1}{\mu_i} + \frac{\epsilon_i}{\mu_i} \\
\rho_i = \frac{\lambda_i}{\mu_i} \\
\omega_i = \frac{\rho_i^* (1 - \rho_i)}{1 - \rho_i^*}
\]

Intermediate aisle (\(\lambda_i = 0\) \(i = 2, 3, \ldots, n - 1\))

\[
\frac{1}{\mu_i} = \frac{1}{\mu_i} + \frac{\epsilon_i}{\mu_i} \\
\bar{\lambda_i} = \frac{d_i}{1 - \epsilon_i} \\
d_i = \mu_i^* (1 - P_{i-1}(0)) \\
P_{i-1}(0) = \frac{1 - \rho_{i-1}^*}{1 - \rho_i^*} \\
\rho_i = \frac{\bar{\lambda_i}}{\mu_i} \\
\omega_i = \frac{\rho_i^* (1 - \rho_i)}{1 - \rho_i^*}
\]

Aisle n (\(\lambda_n = 0\), \(\mu_n^* = \mu_n\)):

\[
\bar{\lambda_n} = \frac{d_n}{1 - \epsilon_n} \\
d_n = \mu_n^* (1 - P_{n-1}(0)) \\
P_{n-1}(0) = \frac{1 - \rho_{n-1}^*}{1 - \rho_n^*} \\
\rho_n = \frac{\bar{\lambda_n}}{\mu_n} \\
\omega_n = \frac{\rho_n^* (1 - \rho_n)}{1 - \rho_n^*}
\]

The probability that a picker must travel \(j\) locations to pick an item in aisle \(i\) is

\[
PL_{ij} = P_0 \prod_{q=j+1}^{n} (1 - P_q)
\]

The expected distance of picking an item in aisle \(i\) is
The expected time of picking an item in aisle $i$ is

$$T_i = \frac{2ED_i}{v} + \sum_{j=1}^{n} P_j$$  \hspace{1cm} (24)$$

The service rate of workstation $i$ is

$$\mu_i = \frac{1}{T_i}$$  \hspace{1cm} (25)$$

### 3.3 The heuristic assignment method

The following steps are applied in the COI assignment process to enhance the possible waiting problems in the picking process. First, the waiting problems caused by assigned items are observed. The storage assignment of the next items are adjusted to decrease blocking. The heuristic assignment method proceed as follows.

**Step 1.** Establish the simultaneous equations using an approximation method in an open restricted queuing network.

**Step 2.** Calculate the COI value, which is the average picking probability and reference blocking probability.

**Step 3.** Assign in ascending order according to COI values.

**Step 4.** Choose the allocated storage rack for the next item according to its blocking probability.

**Step 5.** Proceed with Step 4 if not all items have been allocated. Otherwise, finish.

### 4. Simulation model and results

The simulation software employed in this paper is PROduction MODELer (ProModel). It is popular PC-based software and can be applied to manufacture and distribution systems. ProModel can provides animation and reports for detail simulation results. It is useful for realizing the process of simulation and for analyzing simulation results (ProModel PC User’s Manual).

#### 4.1 Set-up of the simulation experiments

In the simulation experiments, the following assumptions were made:

- All information about orders to be picked is known in advance.
- All items of all orders have an equal weight as compared with the picker’s capacity.
- There is a fixed depot.
- The depot is located at the front end of the most right aisle.
- Vertical movement of order pickers may be disregarded.
- Within an aisle, two-sided picking is performed: that is, simultaneous picking from the right and left side within an aisle.
- Every order must be completed (or picked) in one tour, i.e., an order cannot be divided into two or more tours.
- Using only return picking policy within the narrow aisle.
- All picking aisles are of equal length and width.
- All aisles are also assumed to have an equal number of product locations.
- Only one product type may be stored per storage location.

The picking layout illustrated in this paper is shown in Fig. 3. This picking system includes 4 aisles and 16 product storage locations. All products in this system are packed in small cartons that can be handled manually. The picking time of each carton is 0.4 min.

#### 4.2 Simulation 1

Considering orders arrive at the depot as a static process. Therefore, all the orders have been processed at the beginning. This simulation compares the time required to complete 300, 90, and 30 orders with different
numbers of pickers between the COI assignment and the heuristic assignment methods. The results are illustrated in Table 1.

The results of simulation 1 lead to the following conclusions:

1. The order completion time is the same when the number of pickers is increased from five to six due to the improper arrangement of storage in the COI method because aisle blocking restricts the maximum order completion rate.

2. The need for manpower can be reduced since the heuristic assignment only needs three pickers to complete all the orders in the same period as four pickers in the COI as displayed in Table 1.

3. The heuristic assignment can reduce the order completion time by 22.2% during most of this simulation.

Table 1. The results of simulation 1: the order completion time

<table>
<thead>
<tr>
<th>No. of orders</th>
<th>No. of pickers</th>
<th>Order completion time</th>
<th>Improvement(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Heuristic</td>
<td>COI</td>
</tr>
<tr>
<td>300</td>
<td>3</td>
<td>33hrs, 55min</td>
<td>37hrs, 9min</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>29hrs, 11min</td>
<td>33hrs, 32min</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>27hrs, 20min</td>
<td>33hrs, 11min</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>26hrs, 40min</td>
<td>33hrs, 11min</td>
</tr>
<tr>
<td>90</td>
<td>3</td>
<td>10hrs, 18min</td>
<td>11hrs, 32min</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>9hrs, 4min</td>
<td>10hrs, 19min</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>8hrs, 27min</td>
<td>10hrs, 7min</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>8hrs, 11min</td>
<td>10hrs, 7min</td>
</tr>
<tr>
<td>30</td>
<td>3</td>
<td>3hrs, 39min</td>
<td>3hrs, 59min</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3hrs, 5min</td>
<td>3hrs, 38min</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2hrs, 49min</td>
<td>3hrs, 36min</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2hrs, 48min</td>
<td>3hrs, 36min</td>
</tr>
</tbody>
</table>
### 4.3 Simulation 2

Considering orders arrive at the depot as a dynamic process. This simulation compares the number of orders completed in 8 hours under different order arrival rates and the different number of pickers between the COI and the heuristic assignments. The results are illustrated in Table 2.

It is possible to achieve at the following points from the simulated data from the Table 2:

1. The workload is lower under the order arrival rate of 0.15 (orders per minute) so that there is not much difference in the number of orders completed between these two assignments. However, those pickers using the heuristic assignment storage use considerably less time than that of the COI.

2. The order arrival rate is greater than the order completion rate under the order arrival rate of 0.2 and 0.25 (orders per minute) so that these two assignments cannot complete the majority of the orders. The heuristic assignment can complete 88 orders while the COI is restricted by aisle blocking and can only complete 70 orders at most. Zone picking should be taken into consideration to shorten the completion time of individual orders since this system may accumulate an unlimited number of orders.

3. The heuristic assignment can increase the orders by 25.7% in this simulation.

<table>
<thead>
<tr>
<th>Order arrival rate (orders/min)</th>
<th>No. of orders</th>
<th>No. of pickers</th>
<th>Operation time</th>
<th>No. of orders completion</th>
<th>Improv. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Heuristic</td>
<td>COI</td>
<td>Heuristic</td>
</tr>
<tr>
<td>0.15</td>
<td>72</td>
<td></td>
<td>3</td>
<td>90.6</td>
<td>96.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>74.8</td>
<td>91.0</td>
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<td>5</td>
<td>62.5</td>
<td>79.4</td>
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<td></td>
<td>6</td>
<td>52.9</td>
<td>69.0</td>
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<tr>
<td>0.2</td>
<td>94</td>
<td></td>
<td>3</td>
<td>97.6</td>
<td>97.6</td>
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<tr>
<td></td>
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<td>4</td>
<td>96.6</td>
<td>97.0</td>
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<td></td>
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<tr>
<td>0.25</td>
<td>119</td>
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<td>5</td>
<td>96.3</td>
<td>97.1</td>
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<td></td>
<td></td>
<td>6</td>
<td>94.4</td>
<td>96.6</td>
</tr>
</tbody>
</table>

### 5. Conclusions

The picking process is an operation with the greatest amount of resources expended in the distribution center whereas increasing the efficiency of the picking process achieves the two goals of resource reduction and high-frequency rapid distribution. The suitability of storage layout to storage assignment and the waiting concept was introduced herein before forwarding the heuristic assignment method to remedy the aisle blocking possibly caused by the COI assignment.

The following can be concluded from this investigation:

1. Most previous studies on how to improve storage layout focused only on shortening the picking distance. However, the waiting time caused by aisle blocking also significantly affects the picking process efficiency. Other factors include the number of pickers and the state of order arrival. Therefore, minimizing the picking distance may not necessarily give rise to the maximum picking efficiency. The storage layout should be taken into consideration.

2. A smaller blocking probability $\varepsilon$ makes the average picking probability for different aisle consistent and increases the order completion rate. Therefore, the COI method will not consider the space requirement.

3. The heuristic assignment developed in this paper cannot guarantee that an item will not be assigned to the storage rack closer to the depot when the COI value is very large with highly frequent items ordered. This may reduce the waiting time improvements but it can eliminate a disadvantage of COI method – frequently ordered items with large volume being placed at farther ends of the depot.
Acknowledgments

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具多揀貨員之窄通道倉庫的儲位指派之研究

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摘要

實際的揀貨模式中，大都是由一位揀貨員負責一張揀貨單，依序在揀貨區各通道內揀取所需的品項，這樣的揀貨模式可以將其視為一等候網路，每個通道可視為一個工作站，揀貨員在通道內揀貨可視為接受服務，其服務時間长短則視揀貨單內容而定，利用此一等候網路的概念，本研究提出一啟發式儲位指派演算法，用以改善揀貨作業可能發生的等候問題，首先，我們計算品項的每類體積指標值（cube-per-order index）來排定品項被指派的優先順序，此優先順序即所謂的初始解，其次，利用所提出的啟發式儲位指派演算法對初始解加以改善，最後，本研究亦針對所提出的啟發式儲位指派演算法的績效加以測試及報導。

關鍵字：儲位指派、每類體積指標、等待時間、等候網路