Effect of picker congestion on travel time in an order picking operation

Erika TAJIMA*, Masaaki SUZUKI*, Aya ISHIKAKI*, Masato HAMADA** and Wataru KAWAI**

* Tokyo University of Science
2641, Yamazaki, Noda, Chiba 278-8510, Japan
E-mail: 7419522@ed.tus.ac.jp
** Data-Chef. Co., Ltd.
2-10-1 Yasakadai, Suma, Kobe, Hyogo, 654-0161, Japan

Received: 23 November 2019; Revised: 25 May 2020; Accepted: 23 June 2020

1. Introduction

In recent years, customer needs have diversified and companies have been forced to deliver products quickly to their customers. Distribution warehouses play an important role in improving the efficiency of the entire supply chain, and improving the efficiency of the order preparation operation, otherwise known as order picking, is therefore essential. This research models an order picking operation in which two or more pickers are operating simultaneously, and the optimal design for operation efficiency is analyzed. Here, the picker targets multi-picking, which entails the collection of multiple products in one tour, and the picker always selects the shortest route for collecting the products. In this research, the behavior of the pickers is modeled using a multi-agent system, such that multiple pickers pass one another in the warehouse and a conflict due to excessive congestion is reproduced. The effect prompted by changes to both the layout and the storage assignment using the aforementioned model was clarified. The simulation results show that an optimal warehouse design based on warehouse characteristics (picking area size and differences in the demand frequency of each product) and the number of pickers operating simultaneously significantly affects the efficiency of the order picking operation. Furthermore, it is possible to reduce picker travel time by using the class storage method. The greater the difference in the demand frequency of each product, the greater the effect.

Keywords: Warehouse, Layout design, Storage assignment, Multi agent system, Multi picking
and the effects of design changes for all warehouse characteristics. The ultimate goal is to use this to create a system that supports companies in their decision to change their warehouse design. Therefore, it is necessary to analyze the impact of each element of the layout and storage assignment on the efficiency of the order picking operation.

The warehouse layout constitutes the number and length of the shelves, the widths of the aisles and cross aisles, and the position of the pickup and deposit (P&D) point. Pohl et al. (2009) conducted analysis to determine the layout that most effectively minimizes the distance traveled by a single picker, who is moving steadily. They clarified that introducing a cross aisle improves operation efficiency. Storage assignment aims to improve operation efficiency by placing high demand products in the vicinity of the P&D point. Hausman et al. (1976) analyzed storage assignment of an automatic storage and retrieval system (AS/RS), in which multiple products are combined into one congestion load. They then proposed the optimum demand based storage assignment of three classes of products. However, these researches analyze the layout and storage assignment that minimize the travel distance of the picker, assuming the steady movement of a single picker. Therefore, the competition caused by multiple pickers operating simultaneously is not considered. Furthermore, in an actual warehouse, the picker collects multiple products in one tour, but in these researches, the pickers collect only two products. Based on our current knowledge, little research has been constructed on optimal layout and storage assignment under the assumption that multiple pickers are performing multi-picking.

Multiple pickers operating simultaneously interfered with the behavior of the pickers, resulting in a delay in travel time. Restrictions on behavior, such as not being able to take out products because other pickers are operating, or not being able to proceed even though they want to, can lead to stress for pickers. In addition, frequent encounters of pickers in small warehouses also increase the risk of injury. Constructing a model in which multiple pickers operate simultaneously and analyzing a warehouse design that reduces travel time is very important because it not only contributes to operation efficiency but also reduces picker stress and prevents accidents. This paper focuses its analysis on warehouses with very narrow widths between storage shelves and frequent competition between pickers.

This research attempts to clarify the layout and storage-assignment combination that optimizes the picking frequency of the products. In addition, the effects of changing storage assignment for each condition are analyzed simultaneously. The optimal layout design is analyzed while also considering routing with multi-picking. This will provide a qualitative assessment of designs that will increase operation efficiency for several warehouse features.

The paper is divided into six main sections. Section 2 shows a literature survey on the layout design and the storage assignment analyzed in this research. Section 3 shows how to evaluate the travel distance of a picker. Section 4 explains the model settings and scenarios analyzed in this research, and Section 5 shows the simulation results using them. Finally, Section 6 presents conclusions and opportunities for future research.

2. Literature review

2.1 Layout design

As mentioned above, the layout comprises four elements: the number and length of the shelves, the width of the aisles, the width of the cross aisles, and the position of the P&D point. Petersen (2002) clarified the influence of the
length and number of the aisle on travel time using a simulation. Caron et al. (2000) analyzed the impact of the cross aisle and the position of the P&D point in the storage assignment based on the cube-per-order index. Pohl et al. (2009) calculated the expected dual-command travel distance of a fishbone layout, and clarified that the fishbone layout is more efficient than that resulting from a placement in which the cross aisles are orthogonal or parallel to the P&D point.

However, in many researches, the objective function is the moving distance (De Koster et al., 2007). Therefore, the spatial interactions among multiple pickers operating simultaneously are not considered. Such interactions cause wait times for operations and delays in travel time. This research aims to minimize the travel time in warehouses with multiple pickers by modeling the order picking of those in a multi-agent system.

2.2 Storage assignment

In storage assignment, the storage location of products is determined based on the turnover rate. Generally, random, dedicated and class storage methods are used. Random storage determines the storage location of each product at random. This method is aimed at maximizing the storage rate, but tends to increase the travel time of the picker (Tompkins et al., 2010). In dedicated storage, products are located in a fixed storage location based on product characteristics such as demand frequency, weight, and size (Heskett, 1963). This method has a tendency to lower the storage rate while reducing the picker travel time, compared to random storage (Caron et al., 1998). Class storage groups products into multiple classes and then assigns the classes to a dedicated area of the warehouse (Zulj et al., 2018). Storage assignment within the area is random. This method has the advantages of both a high storage rate and reduced travel time (Chan and Chan, 2011). Therefore, in recent years, class storage has been adopted in many warehouses.

Hausman et al. (1976) analyzed the effect of class based storage in AS/RS to determine the optimum class region. Le-Dec and De Koster (2005) focused on class based storage assignment in a manual order picking operation and determined the optimal storage area for each class. However, this research does not take into account the competition that occurs when multiple pickers operate simultaneously. Roodbergen et al. (2015) used simulation to analyze the optimal warehouse layout and storage assignment for pickers who perform multi-picking. Pohl et al. (2011) analyzed the relationship between full turnover storage and layout in dual-command operations. However, in actual order picking, the pickers collect multiple items simultaneously. Furthermore, all of these researches adopt the travel distance as the objective function.

In this research, it is assumed that multiple pickers are performing the order picking operation simultaneously, and the effects of warehouse layout and storage assignment on picker travel time are clarified. Herein, we use a multi-agent system, and model multi-picking in which the picker collects multiple products in one tour, and analyze the effects of differences in the demand frequency of each product.

3. Calculation method of travel distance

3.1 Theoretical value based on expected travel distance

In many researches on order picking, travel time is calculated based on expected travel distance. In this research, theoretical values are defined as follows, based on the research by Pohl et al. (2011).

In this research, it is assumed that all pickers depart from the P&D point, collect arbitrary \( n \) products in the warehouse, and return to the P&D point. At this time, the expected travel distance for one tour \( E[DC] \) is expressed as follows, using the expected round-trip distance from the P&D point to a certain point \( E[SC] \) and the expected travel distance between collecting \( n \) products from \( N \) storage shelves in the warehouse \( E[TB] \).

\[
E[DC] = E[SC] + E[TB]
\] (1)

\( E[SC] \) is calculated as follows, using the travel distance \( d_i \) from the P&D point to any product \( i \) and the probability \( p_i \) that any product \( i \) is collected.

\[
E[SC] = 2 \sum_{i=1}^{N} d_i p_i
\] (2)
If the number of products collected by the picker in one tour is \( n \), there are \( \binom{N}{n} \) combinations of products collected. \( E[TB] \) is calculated as follows, where \( \delta_j \) is the shortest distance between each product in the combination \( j \) of products collected by the picker and \( q_j \) is the probability of selecting the combination \( j \).

\[
E[TB] = \sum_{j=1}^{C_n} \delta_j q_j
\]

Furthermore, the picker travel time \( E[WT] \) is calculated using the expected travel distance \( E[DC] \) as follows.

\[
E[WT] = \frac{E[DC]}{v_t^0}
\]

where \( v_t^0 \) is the picker’s speed of movement.

3.2 Multi agent system

This research has to model an order picking operation that can be adapted to the characteristics of any warehouse. Therefore, it is necessary to be able to reproduce the behavior of the picker in both wide and narrow passages. This paper analyzes a warehouse with very narrow widths between storage shelves and frequent picker-to-picker competition. When the passage is wide, pickers are likely to be largely unaffected by other pickers and obstacles, so they are capable of steady behavior. On the other hand, when multiple pickers operate simultaneously in a warehouse with a narrow aisle width, the pickers act in interaction with each other. Specifically, when a picker passes through a narrow passage, the encounter with other pickers increases, which frequently results in the following phenomena. If there is another picker ahead of the path of the picker, it becomes an obstacle and the picker slows down or changes course (avoids the obstacle). In some cases, backing off or stopping due to collision may occur. In other words, this model has to reproduce the phenomenon in which other people and obstacles restrict the behavior of pickers in warehouses where operations are performed under conditions where pickers frequently meet each other.

Therefore, this research uses a multi-agent system to model the behavior of pickers. A multi-agent system is a simulation model containing a large number of autonomous agents with different internal states and behavioral rules governing different characteristics. Such a model creates group behavior through interactions among agents with various individualities; thus, it is suitable for reproducing and predicting bottom-up phenomena.

The agent-based model in this research is a social force model, which dynamically expresses the force received from other agents and obstacles. This was developed by Helbing and Molnar (1995) for crowd analysis and exit research and is known as a simulation suitable for reproducing crowd behavior. The social force model is different from the cellular automaton model used in conventional multi-agent systems in that it can reproduce the walking path (e.g., oblique movement) in which the pedestrian moves smoothly.

Mehran et al. (2009) used a social force model to analyze crowd behavior in dense situations and contributed to the detection of abnormal behavior for pedestrian safety considerations. Kusuma and Azhari (2013) modeled the behavior of customers in the market and examined how people can move efficiently in crowded situations. Arteaga and Park (2020) modeled evacuation behavior in buildings during emergencies, replicating pedestrians interacting with others and obstacles in dense situations. This was used to analyze the optimal layout of the facility with regard to emergencies. Furthermore, Tajima et al. (2020) used a social force model in a research aimed at alleviating congestion in convenience stores to build a model. This research compares the social force model with theoretical values using expected travel distance for actual customer behavior. It is concluded that the social force model is more suitable to represent pedestrian behavior in crowded situations than the theoretical value using expected travel distance.

These results indicate that it is possible to replicate the behavior of a picker in a real warehouse by constructing a model in which the picker is influenced by others and obstacles using a social force model.

Güller and Hegmanns (2014) modeled order picking operations in an automated warehouse using a multi-agent system and analyzed routing methods to reduce encounters between pickers. However, this research assumes a picking robot moving on a three-dimensional grid of rails, which is different from the human picking task we would like to
represent. As far as we know, there are no researches that analyze the optimal warehouse design while taking into account that pickers are influenced by the surrounding environment, let alone the social force model. Therefore, this research uses the social force model to construct the model.

In the social force model, each agent $i$ is represented as a material point with mass $m_i$. Actual force is expressed as an Eq. (5) because the agents change their velocity based on individual goals or environmental constraints (Fig. 2).

$$ m_i \frac{d\vec{v}_i}{dt} = \vec{F}_a = \vec{F}_p + \vec{F}_{int} $$

- **Personal desire force**: $\vec{F}_p$

  In general, people in crowds seek a certain goal, and each agent has a desired direction and velocity $\vec{v}_i^p$. However, because the crowd limits individual movements, the actual velocity of the agent $\vec{v}_i$ is different from the desired velocity, and the agent tends to approach the desired velocity based on the personal desire to do so. \( \tau \) is the relaxation parameter. Therefore, the personal desire force is defined as:

$$ \vec{F}_p = \frac{1}{\tau} \left( \vec{v}_i^p - \vec{v}_i \right) $$

In this model, the picker moves to the storage location of the next product to collect or the P&D point.

- **Interaction force**: $\vec{F}_{int}$

  Interaction force $\vec{F}_{int}$ comprises repulsion force $\vec{F}_{ped}$, based on the psychological tendency to maintain the social distance between agents, and the environmental force $\vec{F}_w$, which aims to avoid obstacles, such as walls. Interaction force is defined as:

$$ \vec{F}_{int} = \vec{F}_{ped} + \vec{F}_w $$

$\vec{F}_{ped}$ is a force that keeps agents in the crowd at a distance to avoid causing discomfort for other agents (Fig. 3). This research wants to express the phenomenon that multiple pickers operate simultaneously and the pickers become obstacles to each other. Therefore, $\vec{F}_{ped}$ is the interaction force received from other pickers, and $\vec{F}_w$ is the repulsive force received from the product shelf or wall.

In this research, the order picking operation is modeled using a social force model, and the travel time of the picker is calculated.

Fig. 2 Schematic of the social force model
4. The model

In this research, the design of the warehouse and picker is based on the data actually observed in the warehouse of a company that is distributing apparel products. This warehouse of this company is characterized by the narrow width between the storage shelves. Therefore, if the behavior of the picker in this warehouse can be reproduced, it is possible to construct a model that can be used not only for warehouses with ample aisle widths, but also for any features such as narrow aisle widths.

4.1 Warehouse models

The model assumptions are listed below.

- The number of products in the warehouse is \( N = 400, 500, 600 \). In each pattern, the number of aisles is 11, and the aisle width \( w \) is 0.8m. The width of each storage area is 0.4 m.
- The width of the aisle between the shelves is sufficient to allow two pickers to pass each other.
- The position of the P&D point is fixed. The closest distance from the P&D point to the storage shelf \( w_{PD} \) is 1m.
- The layout in Fig. 4 is a basic design. The effect resulting from the introduction of the cross aisles into the basic design was analyzed.
- Storage shelves are arranged vertically to the P&D point.

![Fig. 3 An example of \( F_{ped} \)](image)

![Fig. 4 Basic Design.](image)
4.2 Picker

When picking is performed, it is assumed that:
- The picker collects five products in one tour.
- The number of pickers operating simultaneously is 1, 5, 10, 15, or 20.
- \( m_i = 55 \text{kg}, \ v_i^0 = 1.3 \text{m/s}, \ v_i^P = 1.3 \text{m/s} \).

This research optimizes the picker travel time while ignoring the product collection time. The picker was assumed to operate for one hour. In addition, the order of collection in the five products that the picker collects in one tour is determined using a local search as follows (Fig. 5).

i. 5 products to be collected are randomly selected.
ii. Sort the 5 products into any order, which is the initial routing order.
iii. Calculates the travel distance of the initial routing order, and set it to \( E^*[DC] \).
iv. Any 2 of the 5 products are selected and the travel distance when these routing orders are sorted is calculated. If the sorted travel distance is shorter than \( E^*[DC] \), the travel distance \( E^*[DC] \) and routing order are updated.

This procedure is repeated 1000 times.

The product collection order was calculated using Visual Basic for Applications (VBA), and the optimal collection order was calculated for all collection patterns. The collection order is determined so that the travel distance is minimized. The picker selects one of the generated routing patterns and moves in the warehouse. Here, the routing pattern is the order in which the picker collects products.

![Fig. 5 Procedure for determining product collection order.](image)

4.3 Analysis scenario

4.3.1 Layout

In this research, the effect of changing the number of cross aisles in each basic design was analyzed. The introductory conditions of the cross aisle used in this model are shown below.
The number of cross aisles introduced \( C \) is analyzed in five ways: 0, 1, 2, 3, and 4.

- In each layout, the cross aisles are introduced at the position that is equally divided by \((C + 1)\).
- The cross aisle width is 0.8m, which is the same as that of the picking aisle.

### 4.3.2 Storage assignment

In this research, the effect was analyzed by comparing class-based storage with random storage. In this research, the products are divided into three classes as shown in Fig. 6. The product groups requested most frequently are assigned to positions closer to the P&D point. Here, assuming the case in which the access ratio to each area was changed as follows, the effect of the change in layout was analyzed for each.

**Pattern I:** A:90%, B:8%, C:2%

**Pattern II:** A:70%, B:20%, C:10%

**Pattern III:** A:50%, B:30%, C:20%

**Pattern IV:** Same turn ratio for each class (Random Storage)

![Diagram of class storage](image)

**Fig. 6** Example of class storage in this model \((N = 400, C = 1)\).

### 5. Simulation result

Simulations were conducted for each scenario. Here, the travel time is the time it takes for one tour (from a picker leaving the P&D point to returning to the P&D point again). An experiment is conducted assuming that the order picking operation is performed for one hour. Indicators to evaluate the simulation results are determined. This research considers the conflicts caused by multiple pickers operating simultaneously and want to evaluate each design.

In addition, an evaluation measure should be used to determine whether the overall operation efficiency of the warehouse has been improved. Figure 7 shows the total travel time and productivity for different numbers of pickers \((N=400, \text{Pattern I})\). Here, total travel time = average travel time \(\times\) the number of pickers, and productivity = number of operations completed in time / the number of pickers. If the competition between pickers is not taken into account, total travel time will always increase linearly and productivity will always be constant because pickers behave in a stationary manner. However, in practice, the increase in the number of pickers has resulted in a significant increase in total travel time (the solid pink line in Fig. 7) above the straight line of ideal total travel time (the dotted gray line in Fig. 7). Productivity (the solid blue line in Fig. 9) is declining. From this, it can be said that travel time and productivity are appropriate to evaluate designs that consider multiple picker conflicts. Of these, this research uses the average travel time.
to evaluate the design. The maximum values of productivity and travel time were also compared, but only the average travel time is described in this paper because similar results were obtained.

In this chapter, the following experimental results are shown.
(1) Comparison of theoretical values and simulation values of this model
(2) Changes in average travel time due to differences in the number of cross aisles (When the number of pickers is 20)
(3) Optimum number of cross aisles (Difference in number of pickers and demand frequency of each product)

5.1 Comparison of theoretical and simulation values

For the sake of simplicity, it was assumed herein that the picker collects 5 products in one tour. The performance of this model is compared to that of the conventional evaluation method using theoretical values. Here, the theoretical value of the travel distance is calculated using the procedure shown in 3.1. The number of products in the warehouse is \( N = 400, 500 \) and \( 600 \), and the number of products the picker collects in 1 tour is \( n = 5 \). The distance from the P&D point to any product \( d_i \) and the shortest travel distance for the collection of \( n \) products \( \delta_j \) are calculated using the values given in Sections 4.1 and 4.3 for each combination. The probability \( p_i \) (\( i = 1, \ldots, N \)) of selecting commodity \( i \) and the probability \( q_j \) of selecting collection pattern \( j \) are calculated based on the percentage of access to each storage shelf presented in Section 4.3.2. For random storage in pattern 4, all access probabilities are equal.

Theoretical values assume that a single picker will perform a steady-state action. In other words, the picker does not alter the behavior of detouring the path or walking speed because the other pickers are not an obstacle. Therefore, it is assumed that the results are similar to the case where the number of pickers is one in this model. Therefore, it is assumed that the theoretical values are the same conditions as in this model with a single picker and similar results are calculated.

Tables 1-3 show the comparison that was drawn between the theoretical values and the simulation results when the number of products in the warehouse is 400, 500, or 600. This result shows that when the number of pickers is one, the performance of the layout with one cross aisle is high under any condition. Similar results were obtained when the theoretical values were used. As the number of cross aisles increases, the expected travel distance \( E[TB] \) between any product can be expected to decrease, while the expected reciprocal travel distance \( E[SC] \) from the P&D point to a certain product increases. Therefore, the introduction of excessive cross aisles may increase the picker travel time. For a single picker, it is considered that this result was obtained because the increase in \( E[SC] \) exceeded the decrease in \( E[TB] \) as the number of cross aisles increased. The reason for the subtle errors between the theoretical value and simulation values is the slight change in speed that occurs when the picker is going straight or turning. From the above, the validity of this model was proved because similar results (optimal warehouse design) could be calculated under the same conditions.

Conversely, when the number of pickers is 20, the optimal number of cross aisles increases under each condition. If
the number of pickers operating simultaneously increases, frequent competition between the pickers in the warehouse may occur. Therefore, the frequency of pickers passing each other or colliding can be reduced by increasing the number of cross aisles. Therefore, it can be said that the optimal number of cross aisles increases with an increase in the number of pickers.

Furthermore, the basic design is based on the case where layout and storage assignment is not considered (Pattern IV, no cross aisle). It can be seen that the average travel time of the picker is significantly reduced by changing from the basic design to the optimal design according to each pattern (difference in demand frequency). For example, if there are 20 pickers and \( N = 400 \), the average travel time per picker is reduced by 24.1~40.2%. Similarly, the average travel time was reduced by 22.5~35.6% for \( N = 500 \) and 20.6~32.7% for \( N = 600 \). These indicate that changing the layout and storage assignment can reduce the travel time of the pickers.

Figure 8 shows a part of the simulation execution screen in the case of 1 picker and 20 pickers. The following can be observed from the execution screen. When there is only one picker, the picker is unaffected by the other pickers and therefore always moves straight through the warehouse at a constant speed. In the case of 20 pickers, it was confirmed that pickers often slowed down or detoured when they passed each other in the narrow aisle between storage shelves. From this, it was confirmed that the cause of the travel time delay when multiple pickers operate simultaneously was generated, and it was considered that the phenomenon occurring in an actual warehouse could be reproduced.

### Table 1 Comparison of theoretical and simulation values (\( N = 400 \)) : Average travel time [sec/picker]

| Number of cross aisles C | Pattern I Theoretical value | Pattern I Simulation value | Pattern II Theoretical value | Pattern II Simulation value | Pattern III Theoretical value | Pattern III Simulation value | Pattern IV Theoretical value | Pattern IV Simulation value |
|-------------------------|-----------------------------|---------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                         | 1 picker 20 pickers         | 1 picker 20 pickers       | 1 picker 20 pickers         | 1 picker 20 pickers         | 1 picker 20 pickers         | 1 picker 20 pickers         | 1 picker 20 pickers         | 1 picker 20 pickers         |
| 0                       | 62.13 69.11 91.51           | 66.65 65.40 108.00        | 77.65 80.71 117.31         | 98.06 99.68 131.28         |                             |                             |                             |                             |
| 1                       | 57.21 59.33 82.40           | 66.09 51.20 106.80        | 74.95 74.25 112.63         | 95.51 97.87 124.39         |                             |                             |                             |                             |
| 2                       | 59.39 59.48 80.88           | 67.66 55.30 95.10         | 76.13 76.91 99.66          | 96.86 98.53 118.33         |                             |                             |                             |                             |
| 3                       | 59.96 57.54 78.50           | 70.23 62.80 97.32         | 78.78 77.18 110.83         | 99.25 106.43 122.92        |                             |                             |                             |                             |
| 4                       | 61.75 62.23 84.07           | 71.99 66.04 101.50        | 80.80 80.36 116.94         | 101.40 107.11 128.35       |                             |                             |                             |                             |

### Table 2 Comparison of theoretical and simulation values (\( N = 500 \)) : Average travel time [sec/picker]

| Number of cross aisles C | Pattern I Theoretical value | Pattern I Simulation value | Pattern II Theoretical value | Pattern II Simulation value | Pattern III Theoretical value | Pattern III Simulation value | Pattern IV Theoretical value | Pattern IV Simulation value |
|-------------------------|-----------------------------|---------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                         | 1 picker 20 pickers         | 1 picker 20 pickers       | 1 picker 20 pickers         | 1 picker 20 pickers         | 1 picker 20 pickers         | 1 picker 20 pickers         | 1 picker 20 pickers         | 1 picker 20 pickers         |
| 0                       | 60.71 71.13 101.50          | 68.09 67.80 110.10        | 75.32 78.57 121.26         | 111.94 123.74 134.57       |                             |                             |                             |                             |
| 1                       | 57.12 56.88 96.25           | 65.32 52.10 101.90        | 70.96 68.99 115.06         | 104.28 104.05 123.32       |                             |                             |                             |                             |
| 2                       | 58.17 63.64 93.93           | 66.91 56.90 98.90         | 71.97 77.33 104.23         | 105.27 107.57 116.92       |                             |                             |                             |                             |
| 3                       | 60.21 71.73 86.72           | 68.34 63.10 96.40         | 74.07 78.08 120.02         | 105.99 110.69 121.81       |                             |                             |                             |                             |
| 4                       | 64.74 72.21 92.10           | 70.37 66.25 103.81        | 75.16 79.22 121.99         | 107.81 115.18 127.71       |                             |                             |                             |                             |

### Table 3 Comparison of theoretical and simulation values (\( N = 600 \)) : Average travel time [sec/picker]

| Number of cross aisles C | Pattern I Theoretical value | Pattern I Simulation value | Pattern II Theoretical value | Pattern II Simulation value | Pattern III Theoretical value | Pattern III Simulation value | Pattern IV Theoretical value | Pattern IV Simulation value |
|-------------------------|-----------------------------|---------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                         | 1 picker 20 pickers         | 1 picker 20 pickers       | 1 picker 20 pickers         | 1 picker 20 pickers         | 1 picker 20 pickers         | 1 picker 20 pickers         | 1 picker 20 pickers         | 1 picker 20 pickers         |
| 0                       | 54.28 53.46 104.19          | 63.85 69.94 113.32        | 72.67 72.57 117.30         | 101.77 128.14 135.84       |                             |                             |                             |                             |
| 1                       | 46.78 47.31 96.81           | 55.81 53.11 105.18        | 65.54 68.94 115.79         | 96.37 92.54 127.21         |                             |                             |                             |                             |
| 2                       | 48.34 52.54 92.03           | 56.97 57.33 101.91        | 66.83 70.18 107.92         | 96.72 104.01 121.94        |                             |                             |                             |                             |
| 3                       | 49.26 66.22 91.36           | 59.05 64.29 97.97         | 66.15 74.78 127.03         | 97.93 104.53 131.93        |                             |                             |                             |                             |
| 4                       | 52.22 67.32 88.58           | 60.62 67.17 101.34        | 67.15 75.13 129.65         | 100.55 105.62 140.37       |                             |                             |                             |                             |
5.2 Transition of average travel time

Figures 9(a), (b) and (c) show the transition in the average travel time when the number of pickers operating simultaneously is 20 and the number of cross aisles is increased. It can be seen that the optimal number of cross aisles is two for patterns II, III, and IV, when the number of products in the warehouse is $N = 400$. Meanwhile, in pattern I, the optimum number of cross aisles is three. When the difference in the demand frequency of each product is significant (as in Pattern I), the pickers are concentrated in the Class A area. For this reason, increasing the number of cross aisles may increase the effect by which competition is reduced between pickers.

Next, we consider the results when the number of products in the warehouse is 500 or 600. Based on Fig. 9(b) and (c), patterns III and IV are the same as when the optimal number of cross aisles is $N = 400$. On the other hand, the optimum number of cross aisles for pattern II is three when $N = 500$ and $N = 600$. The optimum number of cross aisles in Pattern I is three when $N = 500$ and four or more when $N = 600$. This shows that the optimal number of cross aisles increases in the presence of a difference in the demand frequency of each product. As the number of products in the warehouse increases, that is, the picking area increases, the length of the path along which the pickers compete with each other also increases (Fig. 10). For example, consider the case of introducing a single cross aisle. Since the width of one storage shelf is 0.4 m, in the case of $N = 400$, the length of one picking aisle is $0.4 \times 10 = 4$ m because there are 10 storage shelves in one aisle. Similarly, for $N = 600$, the length of one picking aisle is 6 m. That is, if there is a situation in which behavior is restricted by the presence of one picker and several other pickers on the same picking aisle, it can be said that the number of competing pickers and the time restricted may increase because the area is longer at $N = 600$ than at $N = 400$. If the size of the warehouse is small, pickers are often operating on the same shelves and aisles. As a result, there is a lot of passing and congestion in the aisles. On the other hand, if the size of the warehouse is large, the pickers will pass each other and congestion will be reduced, but the pickers will be less able to move laterally. These considerations were taken into account in the experiments, and it was found that the number of optimal cross aisles increased with the size of the warehouse. This can be said to be a result of the social force model. However, when the number of pickers is equal, the smaller the size of the warehouse, the more effective the reduction in transfer time will be by introducing a cross aisle.

Therefore, the optimal number of cross aisles increases in accordance with increases in the picking area size and a difference in the demand frequency of each product.

In addition, Fig. 9(a), (b), and (c) show that the picker travel time can be reduced by changing the storage assignment to the class storage method as the difference in product demand frequency increases.
Competition between pickers. One section of the layout when the number of products in the warehouse is $N = 400, 600$ and there is one cross aisle. When $N = 400$, the length of the picking aisle is shorter than when $N = 600$. When $N = 600$, the picking aisle becomes longer, and if a picker is in the same aisle, there is no way for him or her to exit.

Fig. 10  Competition between pickers. One section of the layout when the number of products in the warehouse is $N = 400, 600$ and there is one cross aisle. When $N = 400$, the length of the picking aisle is shorter than when $N = 600$. When $N = 600$, the picking aisle becomes longer, and if a picker is in the same aisle, there is no way for him or her to exit.
5.3 Optimum number of cross aisles

Figure 11 shows the optimal number of cross aisles for the difference between the number of pickers operating simultaneously (1, 5, 10, 15, or 20 people) and the difference in the demand frequency of each product (patterns I to IV). This result shows that the optimal number of cross aisles increases as the number of pickers operating simultaneously and the difference in the demand frequency of products increase. This factor represents the increase in the frequency of competition between pickers in accordance with an increase in the number of pickers and a difference in the demand frequency of each product.

From the above, it can be said that determining the optimal number of cross aisles according to the characteristics of the warehouse (the size of the warehouse, the difference in the demand frequency of each product and the number of pickers operating simultaneously) affects the efficiency of the order picking operation.

5.4 Consideration

The simulation results are discussed. In this research, the model was firstly confirmed to be working correctly by comparing the theoretical values with this model. Comparison of the constructed model with the theoretical values proved...
the validity of the model, and furthermore, we were able to reproduce the phenomenon that occurs when multiple pickers operate simultaneously. In the presence of more than one picker, it was also observed that travel time delays were clearly occurring. From this, it can be said that in order to analyze the optimal design, it is important to take into account the phenomena that occur when multiple pickers operate simultaneously. The experimental results show that class storage is superior to random storage under all conditions. It also shows that travel time can be significantly reduced by changing the layout and storage assignment to the appropriate design according to the characteristics of the warehouse. Using the experimental parameters of this research, the travel time was reduced by up to 40.2%. The experimental results show that the optimal number of cross aisles increases as the difference in the number of pickers and the frequency of demand for each product increases. This is shown in Fig. 12. Furthermore, the optimal number of cross aisle was found to be proportional to the size of the warehouse. The degree of improvement in operation efficiency due to the change from basic design to optimal design is higher in the upper right corner of Fig. 12. The reason for this is that for the same number of pickers, the smaller the warehouse, the more likely it is that pickers will compete with each other.

The results also show that increasing the number of pickers operating simultaneously is an effective means of increasing operating capacity, while decreasing performance per picker. In addition, an excessive number of pickers is associated with increased stress and an increased risk of injury. Therefore, the number of pickers needs to be judged carefully. From the above, it is possible to efficiently perform an order picking operation by determining the number of cross aisles based on the characteristics of the warehouse (the size of the warehouse, differences in the demand frequency of each product, and the number of pickers operating simultaneously).

However, this simulation analysis is performed only under limited conditions. Different results may be calculated for experiments in large warehouses (with wide aisles) where picker conflicts are not frequent. In addition, the location of the P&D points and the shape of the warehouse are elements that make up the layout. The analysis was conducted under the assumption that these are invariant. Different results may be calculated by taking these into account. Furthermore, this research calculated the results that storage assignment is superior to random storage under all conditions. However, in actual practice, random storage is sometimes used more often than class storage because the use of random storage leads to an increase in the storage rate. Therefore, an analysis that takes into account the advantages of using random storage is necessary.

![Fig. 12 Qualitative evaluation of optimal design in warehouse features.](image)

As the number of pickers and the difference in the frequency of demand for each product in the warehouse increases, the optimal number of cross aisles increases. The number of cross aisle is proportionate to the size of the warehouse. The higher the right side of the figure, the more efficient the operation is by changing from the basic design to the optimal design.
6. Conclusion

The ultimate goal of this research is to construct a model in which multiple pickers perform order picking operations simultaneously, and to calculate the optimal warehouse design for the characteristics of the warehouse and its effects, and to construct a system to support the decision-making process for companies to change the warehouse design using this model. Therefore, this paper analyzes the impact of changes in layout and storage assignment elements on the operation efficiency of order picking.

Here, assuming that a picker performs multi-picking, his or her behavior is modeled by a multi-agent system. Comparison of the constructed model with the theoretical values proves the validity of the model and reproduces the phenomenon that occurs when multiple pickers operate simultaneously. Using the experimental parameters of this research, the travel time was reduced by up to 40.2%. The experimental results show that an increase in the number of pickers and the difference in the frequency of demand for each commodity leads to an increase in the optimal number of cross aisles. Furthermore, the optimal number of cross aisles was found to be proportional to the size of the warehouse.

All of these results are due to conflicts caused by multiple pickers operating simultaneously. Therefore, in order to consider the optimal warehouse design to improve operation efficiency, it is necessary to consider the situation where multiple pickers are operating simultaneously. From the above, it is possible to efficiently perform an order picking operation by determining the number of cross aisles based on the characteristics of the warehouse.

Although this research conducted simulation experiments using data from a company with which we have collaborated, the quantitative evaluation and validation by comparison with the figures in the field are insufficient. Therefore, it is necessary to improve the accuracy of the model by conducting field experiments in the future. In order to calculate the optimal design and its effect on the characteristics of any warehouse, not only qualitative results but also quantitative indicators are needed. In the future, it is important to analyze the thresholds for determining the optimal design. Further, the challenge is to conduct an analysis that incorporates other elements of layout and storage assignment.

Acknowledgments

This research was partially supported by the Japan Society for the Promotion of Science (JSPS), KAKENHI, Grant-in-Aid for Scientific Research (C), 16K01262 from 2015.

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