OR Spectrum (2009) 31:759–774
DOI 10.1007/s00291-008-0131-x

REGULAR ARTICLE

The use of bucket brigades in zone order picking systems

Pyung-Hoi Koo

Published online: 7 March 2008

Abstract As the transactions through electronic commerce and TV home shopping increase, the warehouses often receive a large amount of small orders to be picked within tight time windows. One of the important warehousing activities is order picking, the process of retrieving a number of items from warehouse storage to meet a number of independent customer orders. This paper examines a new order picking method, bucket brigade order picking (BB picking). Bucket brigade is a way of coordinating workers who progressively perform a set of operations on a flow line. In the BB picking system, a worker performs operations on an order until the next worker downstream takes it over; then goes back to the previous worker upstream to take over a new order. We discuss distinct characteristics in order picking systems when bucket brigades are applied. We identify some efficiency losses under the BB picking and present a new BB picking protocol to improve the performance of order picking systems. The new BB picking is compared with the existing BB picking and zone picking through simulation experiments.

Keywords Warehouse order picking · Bucket brigades · Zone picking · Self-balancing · Dynamic assignment

1 Introduction

Warehouses form an important link in a firm's supply chain network. A variety of logistics activities are carried out in a warehouse, which include receiving, storing,

P.-H. Koo (✉)
Department of Systems Management and Engineering, Pukyong National University,
San 100 Yongdang Namgu, Busan 608-739, South Korea
e-mail: phkoo@pknu.ac.kr

order picking, sorting, packing, and shipping. Among these, order picking—the process of retrieving a number of individual items from warehouse storage for the purpose of fulfilling an order for a customer—is one of the most critical warehouse tasks. Order picking accounts for as much as 55% of the total warehouse operating expense (Tomkins et al. 2003). Today, as the transactions through electronic commerce and TV home shopping increase, warehouses often receive a large amount of small orders to be picked within tight time windows. Hence, fast and efficient order picking is critical in today's logistics systems.

There are many different order picking types found in the warehouses. The efficiency of order picking depends on various factors, such as warehouse layout, storage strategy, picking strategy, picking routing, order batching, and so on. Among these, picking strategy is related to how the orders are picked. Orders may be either released in a batch or individually. Order picking systems can be classified into picker-to-parts and parts-to-picker. In the picker-to-parts system, which is commonly applied in industries, order pickers travel along the aisles to pick items, while in the parts-to-picker system, aisle-bound cranes retrieve one or more unit loads and bring them to a depot where a picker takes the required number of items.

One of the picker-to-parts systems that are widely used in industries is zone picking. For zone picking, the warehouse is divided into several picking zones so that each picker is dedicated to a single zone. Depending on a process sequence, zoning is further classified into progressive zoning and synchronized zoning. Under progressive zoning, each order is completed only after it has sequentially visited all the zones containing its items while under synchronized zoning, all the zones are processing the same order at the same time. One of the important issues in zone picking is to equalize the workload of the zones so that the pickers have balanced workloads. A few research works have been done to balance the workload among zones (Jane 2000; Jane and Laih 2005). Here, historical customer orders are examined and the items are assigned to storage zones in order for each zone to have workload as equal as possible. This approach is expected to provide balanced workload among zones in the long run. However, since the items to be picked are mostly different from order to order in today's logistics systems, the zones are hardly balanced in real picking environment.

To solve the balancing problems in zone picking, bucket brigades may be applied in order picking systems. Bucket brigade is a way of coordinating workers who progressively assemble a product along a flow line. Each worker in the flow line follows a simple rule: perform operations on a product until the next worker downstream takes over the product; then go back to the previous worker upstream to take over a new product. In this way, the line balances itself and no work-in-process is allowed unattended in the system. This paper describes bucket brigades applied in order picking systems. We discuss distinct characteristics in bucket brigade order picking (BB picking). Some efficiency losses under the BB picking are identified. We propose an alternative method to improve existing BB picking systems and investigate the performance of bucket brigades. A simulation model for bucket brigade operations is constructed with which the performance of BB picking systems is compared with that of zone picking systems.

2 Zone picking

A typical zone picking system is shown in Fig. 1 (adapted from Bartholdi et al. 2001). Flow rack with rollers to slide cases forward is arranged in aisles through which a unidirectional conveyor runs. Each cardboard box is assigned to collect products for a specific order. An order is a list of items for a single customer or a group of customers, together with quantities to be picked. The picking system is divided into several serial zones to each of which one picker is assigned. After picking up an ordered item from the rack, the picker puts it into a cardboard box on the conveyor behind him and slides the box along the passive conveyor as he moves down the aisle. On reaching the end of his zone, the picker leaves the order on the passive conveyor for the next picker and returns to the beginning of his zone for a new picking order. Each worker remains in his zone, moving boxes forward while picking, and is idle if there are no orders waiting when he returns to the beginning of his zone. The last picker pushes the boxes of a completed order onto a take-away conveyor. The powered take-away conveyor transports the completed orders to a shipping area.

The idea in zone picking is that the products are allocated into proper storage zones to equalize workloads among all pickers so that each picker has almost the same workload and the pick lane runs smoothly. If the workload is not balanced, a picker keeps busy with too much workload while the other pickers remain idle without the order to be filled. The unbalanced workload results in long lead time and less throughput rate. Literature on zone picking is very limited. Gray et al. (1992) present a multistage hierarchical model to design warehouses with zone picking where the number of zones and pickers, zone sizes, storage assignment, and order batching are determined through economic tradeoffs. De Koster (1994) models a zone picking system as a Jackson queueing network, which allows fast estimation of order lead time

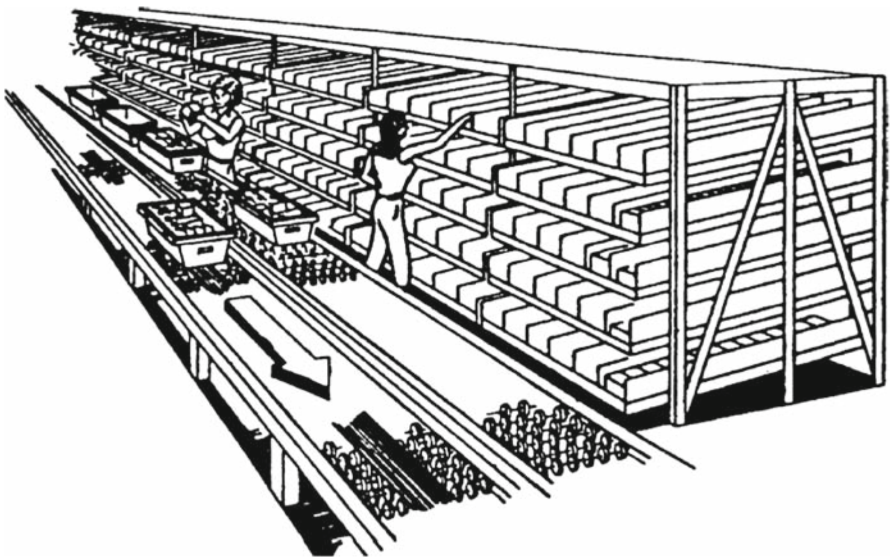


Fig. 1 An order picking system (adapted from Bartholdi et al. 2001)

and work-in-process. The model can be used to evaluate the effects of changing the system layout, the number of zones, the number of pickers, and the conveyor speed. Using simulation studies, Peterson (2002) shows that the zone shape, the number of items on the pick-list, and the storage policy have a substantial impact on the average travel distance within the zone. Jane (2000) presents a heuristic algorithm for balanced assignment in a zone picking system. Considering fluctuation in an order volume over time, the algorithm adjusts the number of zones. Later, Jane and Laih 2005 propose an assignment algorithm in a synchronized zone picking system in which all the zone pickers are working on the same order simultaneously. A similarity coefficient of any two items is presented for measuring the coappearance of both items in the same order. To minimize the idle time of the synchronized zone picking system, the items frequently asked together (i.e., with high similarity coefficient) are located into different zones. Jewkes et al. (2004) consider a specific zone picking system, where pickers work at home bases within their zones and are required to return their home bases after each pick. They propose an optimal policy for the concurrent problems of product location, picker home base location, and the allocations of products to pickers so that the expected order cycle time is minimized. They also present a dynamic programming algorithm, which determines the optimal product location and picker home base location, for fixed product locations. Parikh and Meller (2008) address the selection problems between batch and zone order picking strategies. They develop a cost model to estimate the cost of batch picking and zone picking systems, which is composed of the cost of labor, equipment, workload imbalance, and sorting. Le-Duc and De Koster (2005) present a procedure to find the optimal number of picking zones by using mixed integer programming (see De Koster et al. (2007) and Gu et al. (2007) for more comprehensive review on order picking).

As Bartholdi and Eisenstein (1996) indicate, the balanced workload model in zone picking has some problems in practice. Firstly, the workload is often calculated based on historical or forecasted order data. However, the historical or forecasted demand may not remain the same in the future, especially under today's fast changing market environment. Secondly, the model attempts to balance the total work over a long period of time. Even though it may appear balanced on average, the allocation of the works can be quite unbalanced in real operational situations, because the items in each order change from order to order. Thirdly, the static balancing method is hard to adjust to uncertainties such as equipment break down, employee absenteeism, and other various interventions. Lastly, the work speed of each picker is different from each other, which is not considered in assigning items to zones. With different work speeds, the performance of zone picking systems is determined by the slowest worker. To solve these problems, an order picking system with bucket brigades is introduced as an alternative to zone picking.

3 Bucket brigades in order picking

3.1 Bucket brigades

Operations of the bucket brigades imitate the cooperative behavior of ants when brood, food, or other resources are moved (Anderson et al. 2002). The following shows how the bucket brigades work: *Each worker carries a product towards completion. When the last worker finishes his product he sends it off and then walks back upstream to take over the work of his predecessor, who walks back and takes over the work of his predecessor, and so on. After relinquishing his product, the first worker walks back to the beginning of the line to start a new product. Workers are sequenced from slowest-to-fastest so that the slowest worker introduces a new job into the flow line, while the fastest finishes the job at the end of the line.*

In bucket brigades, each worker is assigned the works dynamically (Bartholdi and Eisenstein 1996). Workers must maintain their sequence. No passing is allowed and so it can happen that a worker is blocked by his successor, in which case he simply waits until his successor moves out of the way. There are no buffers; so, the only work-in-process (WIP) inventory is that in the hands of the workers. Bartholdi and Eisenstein (1996) present theoretical studies on the bucket brigades. They start by using several simplifying assumptions and by modeling a self-balancing line as a Markov chain. Then, they enrich the initial model by relaxing some assumptions (Bartholdi et al. 2001, 2006, 2008). They apply bucket brigades to warehouse order picking systems (Bartholdi et al. 2001) and manufacturing assembly lines (Bartholdi and Eisenstein 2005), and report many successful results. Bratcu and Dolgui (2005) investigate the application areas of BB picking and extensively review the research works of bucket brigades.

Bartholdi and Eisenstein (1996) present a normative model, which represents ideal conditions sufficient to guarantee that bucket brigades achieve the maximum possible performance. The normative model is based on the following three assumptions:

Assumption 1. Insignificant walking time: the total time to perform a job is significantly greater than the time to walk the length of the flow line.
Assumption 2. Total ordering of workers by work velocity: each worker $i = 1, \ldots, n$ is characterized by a distinct constant work velocity v_i. The work velocity for each worker is deterministic.
Assumption 3. Smoothness and predictability of work: the work content required by an order, which is normalized to one, is spread continuously and uniformly along the line.

In a flow line where products of a kind is produced repetitively under the normative model, there is a unique balanced partition of the effort wherein worker i performs the following interval of work no matter where a given set of workers start.

$$\left[\sum_{j=1}^{i-1} v_j \Big/ \sum_{j=1}^{n} v_j, \sum_{j=1}^{i} v_j \Big/ \sum_{j=1}^{n} v_j\right]$$

That is, worker i takes a new job from worker $(i-1)$ at $\sum_{j=1}^{i-1} v_j / \sum_{j=1}^{n} v_j$ and hands off his job to worker $(i+1)$ at $\sum_{j=1}^{i} v_j / \sum_{j=1}^{n} v_j$. Bartholdi and Eisenstein (1996) prove that if the workers are sequenced from slowest to fastest, the works are spontaneously and constantly reallocated to reach this balance; and the production rate converges to $\sum_{i=1}^{n} v_i$ items per unit time, which is the maximum possibly attainable from the given set of workers. Since all the workers keep busy all the time under the normative model, there is no balancing loss in the line. Bucket brigades have some benefits over static workload balancing methods such as zone picking. These include the following:

- It is a pull system; so WIP inventory is strictly controlled. With the minimal WIP inventory, secondary labor is reduced and quality is improved.
- It is adaptive. It will spontaneously reallocate effort in response to changes in the logistics systems.
- The system becomes more flexible and agile, because bucket brigades tune themselves, without cumbersome endeavors of workload balancing.
- There is a reduced need for central planning and management, because bucket brigades make the flow line self-balancing.
- Throughput is increased, because bucket brigades spontaneously generate the optimal division of work.

3.2 Bucket brigade order picking

Bucket brigade order picking (BB picking) utilizes the concept of bucket brigades in order picking operations. Unlike the zone picking systems, the BB picking system does not restrict the pickers within specified work areas. The benefits attainable from the BB picking systems are maximized when the assumptions under the normative model are satisfied. However, in real order picking environment, the assumptions made in the normative model are not usually satisfied. The following are some of the BB picking's characteristics that are different from the assumptions made in general BB picking:

1. Each order has a different line of items to be picked. With the different order contents, we canot normalize the production time to a constant value, of one.
2. The work content is not usually spread continuously in an oder picking system. Even though a picker downstream becomes available, he may wait for his predecessor to finish his current picking job for an item. In this case, there may be some hand-off losses.
3. Since the order contents are different from order to order, the picking locations change over orders. Therefore, hand-off locations will never converge.
4. Blocking may happen, even though all the pickers have the same work speed. In general, no passing is allowed, and so it can happen that a picker is blocked by his successor, in which case he simply waits until he can resume picking, after his successor moves out of the way.

Because of these characteristics, there exist two kinds of losses in BB picking, blocking and hand-off losses. Figure 2 shows a situation where a blocking happens. Worker 1 is performing a picking operation for the $(i + 1)$th order while worker 2 for the ith order. The $(i + 1)$th order includes items a1, a2, and a3, while the ith order includes item b1, b2, b3, and b4. Suppose worker 1 finishes picking item a1 and should go forward to pick the next item, a2, while worker 2 is performing picking operation for b2 on the way to the location of a2. When passing is not allowed, worker 2 blocks

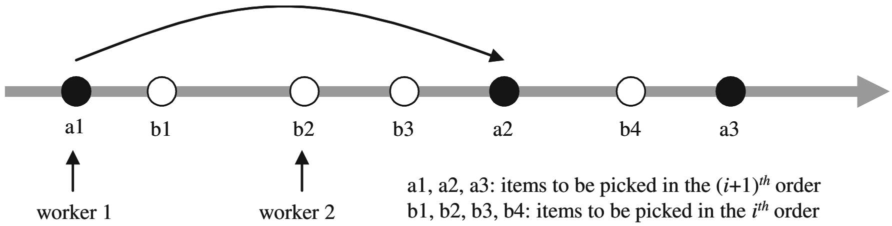


Fig. 2 Blocking in BB picking

worker 1 from going forward to pick item a2. Then, worker 1 should wait until worker 2 finishes picking both the items b2 and b3. Here, we can see that the blocking occurs because of the locations of the items in the orders. (Note that, in the previous work performed in Bartholdi et al. (2001), it is assumed that the blocking is only caused by the different work speed.)

Figure 3 shows a situation where a hand-off loss happens. Worker 2 becomes available and is ready to take a new order from worker 1 at time t_2, but worker 1 is in the middle of picking an item. Then, worker 2 should wait until worker 1 finishes his current job. The waiting time of worker 2 for the hand-off is $t_3 - t_2$.

We now predict the performance of workers when the hand-off times are present. Consider an order picking system that handles the orders whose pick list contains n items on average. Performing a picking operation for item $j(1,\ldots,n)$ takes a task time t_j. Then, the total picking time for an order is $T = \sum_{j=1}^{n} t_j$. When a picker performs all the tasks for an order, pick rate r during a unit time is $r = 1/T$. When m pickers work along the picking line (as in zone picking) and they are utilized 100%, then the pick rate of the line is $r = m/T$. However, in BB picking line, there could be a hand-off loss, resulting in less pick rate than maximum. Let $\bar{t}$ be the average picking time, $\bar{t} = T/n$. Then, the average hand-off time would be $\bar{t}/2$. When there are m pickers (zones), an order experiences the hand-offs $(m-1)$ times. Then the hand-off loss time for a product is $(m-1)\bar{t}/2$. Let E_o be the efficiency of pickers. Then E_o can be calculated as follows

$$E_\mathrm{o} = \frac{T}{T + (m-1)\bar{t}/2} \tag{1}$$

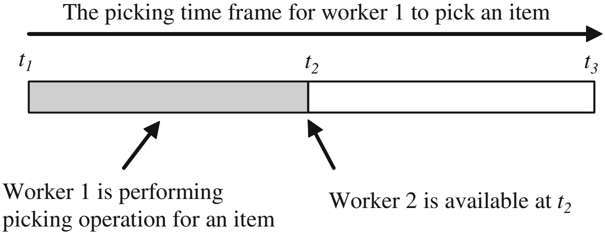


Fig. 3 Hand-off loss in BB picking

With the picker efficiency E_o, the pick rate r done by one picker during a unit time is as follows

$$r = \frac{E_o}{T} = \frac{1}{T + (m-1)\bar{t}/2} \tag{2}$$

Then, the pick rate performed by m pickers in a picking line during a unit time is mr.

From Eqs. 1 and 2, it can be seen that the system performance becomes worse due to the hand-off losses as the number of pickers increases in BB picking systems.

3.3 A new bucket brigade order picking: zoned BB picking

The blocking and hand-off losses may overshadow the benefits from the inherent flexibility of the bucket brigades. To reduce the blocking and hand-off losses, we introduce a new BB picking protocol in which zone picking and general BB picking are combined. We will call this protocol "zoned BB picking". In zoned BB picking, each worker is allowed to work within an extended zone. Figure 4 shows the work areas for the pickers in zoned BB picking. There is no work area restriction for each picker in the upstream line so that all the workers are allowed to go back to the beginning of the flow line to take a new job. However, there is a downstream work area limit for each picker, beyond which he cannot perform a picking job. There are $(m-1)$ interface buffers each of which is located at the end of a picker's work area. When the next picking job for a picker is located beyond his work area, the job is put in the interface buffer located at the end of his work area. When a next picker is available and there is at least one job in the interface buffer before him, he picks the job out of the interface buffer and starts performing picking operations (like in zone picking). If there is no job put in the interface buffer, he goes upstream and takes a new job from his predecessor (like in general BB picking). In Fig. 4, picker 1 puts his current order in interface buffer A when he reaches this point without handing his current order over to the picker 2, and then picker 2 later picks the order out of the buffer to start picking operations.

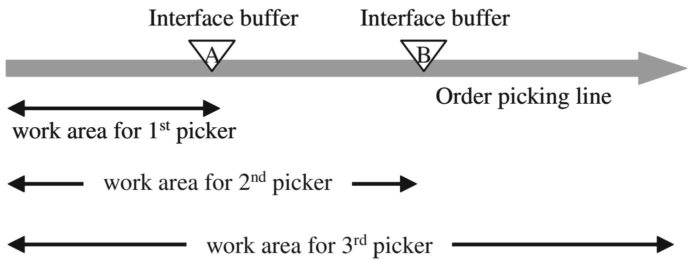


Fig. 4 Work area for each worker in zoned BB picking

In zoned BB picking, each picker follows the operational protocol described below when he finishes a picking operation for an order

Step 1.	Check if the location of the next item is within the allowed work area. If the next item is located out of the allowed work area, go to Step 5. Otherwise, go to Step 2.
Step 2.	Check if the next picker is available. If the next picker is available, hand the job over to the next picker and then go back for another job. Otherwise, go to Step 3.
Step 3.	Check if the next item is stored before the current location of the next picker. If yes, start a picking operation. Otherwise, go to Step 4.
Step 4.	This is the case where a picker is blocked when the next picker is in the way to the next item to be picked. Blocking is resolved after the next picker goes beyond the location of the next item to be picked. When blocking is resolved, go to Step 2.
Step 5.	Put the job in the interface buffer for the next picker, and then go back for another job.

The zoned BB picking protocol is a combination of zone picking and BB picking. With the interface buffers in zoned BB picking, it is expected that we have less blocking and hand-off losses: when the next picker is available later and finds the interface buffer with at least one order, he takes the order immediately out of the interface buffer and starts picking operations for the order. In this case, the picker does not experience any hand-off loss for this order. The blocking loss is also reduced, because each picker has a work area limitation beyond which he cannot perform picking operations. The next section examines the performance of the general and zoned BB picking systems through simulation experiments under various logistics settings.

4 Experimental analysis

We examine the performance of bucket brigades with a warehouse system, slightly adjusted from original data of Jane (2000) for experimental analysis. The warehouse under consideration stores cosmetics and daily necessities for a direct-sales company. There are 150 kinds of products kept in the manual pick area. Currently, a zone picking policy is adopted where the pick area is divided into three serial zones. Every day, about 800 orders are placed by customers. In each order, a variety of products (6–12 kinds) with a small amount (1–3 units) of each product are requested. For the zone picking policy, the products numbered from 1 to 50 are assigned to zone 1, the products numbered from 51 to 100 to zone 2, the products numbered from 101 to 150 to zone 3. In this way, the workload for each zone is balanced. It is assumed that the pickers have the same speed of work. It is also assumed that once a picker starts a picking operation for an item, he should finish the current picking job before handing the order over to the next picker. In the zone picking systems, the number of boxes waiting at the buffer area between two zones may be restricted because of the space restriction.

In the simulation experiments, a random number r, $6 \leq r \leq 12$, is generated to represent the number of products in an order. Then, r different products in an order are generated with equal possibility for all items. The time it takes to pick an item follows an exponential distribution with a mean of 10 s. Since an order has 6–12 items to be picked, it takes 90 s on average to complete an order under ideal conditions. The simulation runs are made for 1 month (20 days). Since the order picking system is empty at the beginning of the simulation, there is a period of transient state. The statistics during this period (5 days) are discarded. (*Note that there are three pickers in the line. Each order has nine items to be filled on average. It takes 10 s to fill an item. On average, each picker spends 30 s* (*0.5 min*) *for an order. Each picker has 480 working minutes for a day. Since an order is filled every 0.5 min, the maximum pick rate will be 960 orders per day. In addition, the minimum lead time will be 1.5 min.*)

4.1 Performance of general BB picking and zone picking

Table 1 shows the performance of general BB picking and zone picking. Pick rate, and lead time are used as performance measures. Lead time is defined as the time period it takes for an order to be filled in the order picking system after it is released to the system. Pick rate is the amount of the orders that are completed during the planning horizon (here, a day) to be filled in the order picking system. The table shows that zone picking provides better performance than BB picking in terms of pick rate, while BB picking provides better performance than zone picking in terms of lead time. Here, for the zone picking systems, we assume that there are infinite buffer between zones so that a worker can put an order (box) in the buffer whenever he finishes picking the items within his zone. With the infinite buffer, there is little chance for a picker to be idle due to a shortage of orders to be filled. This makes it possible for a picker to keep busy in the zone picking system, which results in high pick rate. However, the infinite buffer leads to a very long lead time.

The poor performance of general BB picking in terms of pick rate is due to blocking and hand-off losses, which have been discussed in the previous section. Table 2 shows the losses due to blockings and hand-offs in the BB picking system. Pickers 1 and 2 experience the blocking losses, while pickers 2 and 3 experience hand-off losses. In our example with general BB picking, the pickers are utilized only 73.9% on average with 10.5% hand-off and 15.6% blocking losses.

When we see the lead time in Table 1, we can find that BB picking provides far shorter lead time than zone picking. By Little's law, the lead time is proportional to the WIP inventory level. In general BB picking, the WIP inventory level is always

Table 1 Comparison of general BB picking and zone picking

	BB picking	Zone picking
Pick rate (orders/day)	670.8	904.8
Lead time (minutes)	1.9	79.3

Table 2 Hand-off and blocking losses for each picker in BB picking

Picker Number	Picking %	Hand-off %	Blocking %
1	73.0	0.0	27.0
2	66.9	13.2	19.9
3	81.7	18.3	0.0
Average	73.9	10.5	15.6

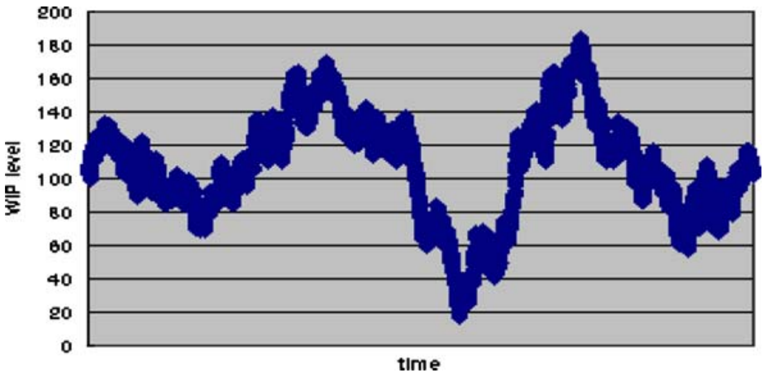


Fig. 5 WIP levels over time

three, while it fluctuates over time in zone picking. Figure 5 shows the WIP levels over time (20 days) when the zone picking policy is employed. The high WIP levels in zone picking are due to workload imbalance over time.

In Fig. 5, the maximum WIP level is 185, which is very high. There are some shortcomings associated with the high WIP levels. With a large number of boxes on a conveyor, there is congestion, and workers are likely to put items in the wrong boxes. Sometimes, there is not enough space on the conveyor for a large number of boxes. The buffer size directly affects the WIP inventory levels. So far, it has been assumed that buffers with an infinite size are located between adjacent zones in zone picking. However, this may not be allowed in practice. Table 3 shows the performance of zone picking systems when the buffer size is restricted. It is seen that as the buffer size decreases, both the pick rate and the lead time decrease in the zone picking systems. With the buffer size of zero, a picker hands over the job to his successor directly at the zone interface without any buffer. Suppose we have five buffer spaces between the adjacent zones. Then, we have 4.8 min of lead time and 803.6 orders of pick rates. We can observe that the lead time is reduced at the cost of less pick rate, compared with the results from the zone picking system without a buffer restriction.

Table 3 Effect of buffer sizes in zone picking

Buffer size	Pick rate (orders/day)	Lead time (min)
0	572.2	2.1
1	675.0	2.6
2	731.8	3.1
5	803.6	4.8
10	843.6	7.4
20	874.3	12.9
Inf.	904.8	79.3

4.2 Performance of zoned BB picking

As mentioned previously, the poor performance of general BB picking is due to blocking and hand-off losses. We have introduced zoned BB picking in the previous section to reduce blocking and hand-off losses. In this experiment, the interface buffer between pickers 1 and 2 is located just after the 50th item, while the interface buffer between pickers 2 and 3 is located just after the 100th item, as in zone picking. Table 4 shows the performance of zoned BB picking systems with various buffer spaces. As in zone picking, both the pick rate and the lead time decrease as the buffer size decreases. We can see the performance improvement of zoned BB picking over general BB picking: the maximum pick rate is 904.8 under zoned BB picking, while it is 670.8 (see Table 1) under the existing BB picking.

Figure 6 compares the performance of zone picking and zoned BB picking when the same buffer size is assumed. In the zoned BB picking system, when a picker finishes his picking jobs within his zone but the interface buffer downstream is full, he should wait until the buffer has at least one empty space. It is seen that zoned BB picking provides better performance than zone picking in terms of pick rate, especially when the buffer size is small. In terms of lead time, the two picking methods provide similar performance, as seen in the right-hand side graph in Fig. 6.

Figure 7 compares the losses due to blockings and hand-offs in the general BB picking and zoned BB picking systems. It is observed that the hand-off and blocking losses are dramatically reduced in the zoned BB picking system. The hand-offs are reduced from 10.5 to 1.9% and blocking is reduced from 15.6 to 6.6%. The low hand-off and blocking losses in zoned BB picking result in high worker utilization. The low

Table 4 Performance of zoned BB picking with various buffer sizes

Buffer size	Pick rate (orders/day)	Lead time (min)
1	720.6	2.7
2	770.5	3.2
5	830.9	4.8
10	863.1	7.4
20	883.3	12.7
Inf.	904.8	62.1

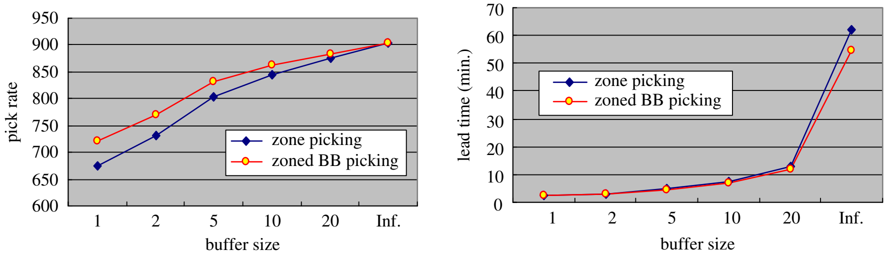
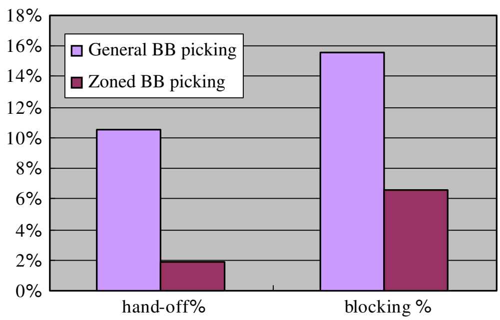


Fig. 6 Performance of zone picking and BB picking over various buffer sizes

Fig. 7 Hand-off and blocking losses for each picker in zoned BB picking



hand-off % in zoned BB picking indicates that the pickers downstream take the new jobs from the interface buffers in most cases, which does not require any hand-off time. Blocking happens only due to workers downstream in general BB picking, while it happens due to workers downstream and interface buffer of limited capacity in zoned BB picking. Out of the 6.6% blocking loss in zoned BB picking, 0.9% is due to the blocking caused by the picker downstream and 5.5% is due to full interface buffers. We can see that blocking due to workers downstream is dramatically reduced. We also identify that with larger buffer size, we can further reduce the blocking losses. The low hand-off and blocking losses in zoned BB picking lead to high pick rate, 830.9, which is 23.8% more than in general BB picking and 3.4% more than in zone picking with the same buffer size.

4.3 Impact of interface buffer location

We have assumed so far that the interface buffers in zoned BB picking are situated at the same location as in the zone picking system. The first and second buffers are located just after the 50th and the 100th items, respectively. To examine the impact of the locations of the interface buffers on the system performance, we have done simulation experiments with different locations of the interface buffers. Figure 8 shows

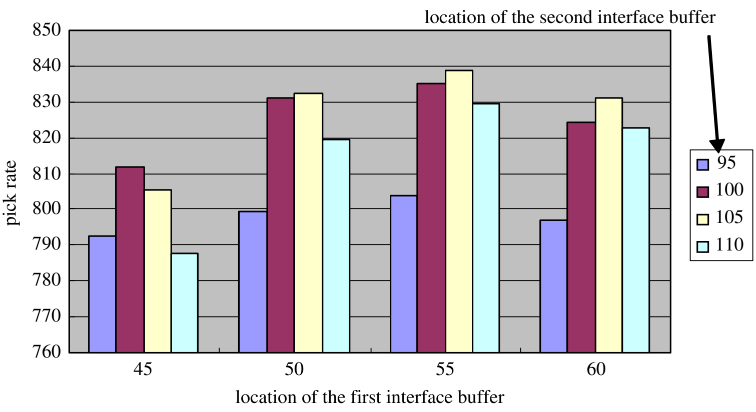


Fig. 8 Impact of the interface buffer locations on pick rate

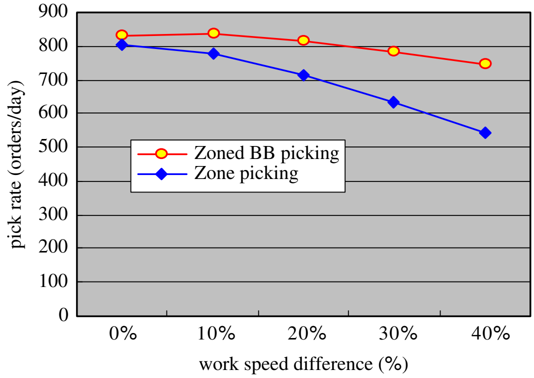


Fig. 9 The effect of work speed on the performance of order picking

the pick rates in zoned BB picking with different interface buffer locations. The best performance is achieved when the first and second interface buffers are located just after the 55th and the 105th items, respectively. From the experiments, we can tell that the locations of the interface buffers affect the performance of zoned BB picking. It is interesting to see that the performance increases first and then decreases as the work areas for the first two pickers increase. The results show that it is important for each picker to be assigned appropriate work area in zoned BB picking.

4.4 Effect of different work speed

The work speed may vary picker by picker. Figure 9 shows the results when each picker has a different work speed. Here, it is assumed that both picking methods have the same buffer size of five. The numbers on the x-axis indicate the work speed difference. For example, 20% means that there is a speed difference of 20% among workers, i.e., the speed of the slowest picker is 0.8, the speed of the fastest picker is 1.2, and the speed of the average picker is 1.0. The slowest picker is located at the beginning and the fastest picker at the end of the line. The figure shows that the work speed difference affects the performance less in zoned BB picking than in zone picking. This result says that BB picking works well especially for the system with different work speeds.

5 Conclusions

This paper describes bucket brigades applied to order picking in warehouses. We have discussed some characteristics of order picking systems when bucket brigades are applied. Two types of efficiency losses, blocking and hand-off losses, have been identified. To reduce these losses, we introduce a new bucket brigade order picking (BB picking) protocol, where zone picking and general BB picking are combined. We investigate through simulation experiments the performance of the general BB picking system and the new BB picking system under various logistics settings. Some of the observations are as follows:

- When general BB picking (discussed in Bartholdi et al. 2001) is applied, it provides worse performance than zone picking in terms of pick rate but better performance in terms of lead time.
- In general BB picking, blocking and handoff losses often cause the pickers to be idle for some time, which results in lower performance.
- The new BB picking system, zoned BB picking, provides less hand-off and blocking losses than general BB picking, resulting in higher pick rate.
- With appropriate decisions about the location of the interface buffers, the performance of the zoned BB picking protocol can be further improved.
- The capacity of the interface buffers affects the performance of zoned BB picking.
- Zoned BB picking works better than zone picking especially when the workers have different work speeds.

There are some prerequisites that should be considered when bucket brigades are applied in order picking. Since the workers under the BB picking systems cover more work areas than in zone picking, they should have knowledge about more items. Since each worker does not have his own work area, there may be some confusions and congestions in practice. Schultz et al. (2003) have identified several negative side effects that occur in systems that rely on flexible work assignment. They insist that the side effects may partially or completely offset the advantages of the flexibility. Close attention should be paid for a meaningful productivity gain when BB picking is applied.

Much research works remain to be done. Different results may be obtained in other logistics settings. For example, in some situations, where orders have different order frequency from each other or where each order has a very small or large list of items, some additional considerations should be taken. Analytical performance models for BB picking with blocking is another interesting research topic to be addressed. The zoned BB picking protocol presented in this paper may be only one of many possible BB picking variants, for example, suppose another BB picking protocol that allows any worker to leave his partially completed order in a buffer when he is blocked and walk back to take over the work of his predecessor. Bartholdi and Eisenstein (1998) insist that this BB protocol deteriorates the performance of bucket brigades. Their claim may be true when the product (order) should visit all the stations like in product assembly lines. However, as we have identified some distinct characteristics in BB picking, we think this claim may not be true in an order picking environment. It would be interesting to study some more promising BB picking variants.

Acknowledgments This work was supported by the Korea Research Foundation Grant, funded by the Korean Government (MOEHRD) (KRF-2006-D00575).

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