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Order-Picking by Cellular Bucket Brigades: A Case Study

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1. Introduction

Order-picking typically accounts for about 55% of the total operating cost of a distribution center (Frazelle, 2002) and is considered one of the most critical functions of a supply chain. As a result, the management of distribution centers often gives the highest priority to order-picking for productivity improvement. In an order-picking process, stock-keeping units (SKUs) are retrieved from storage to fulfill specific customer orders. Some critical issues in this process include:

1. Allocating work for workers (or order-pickers) such that their workload is balanced.
2. Reducing workers' travel as it accounts for more than 50% of the total order-picking time (Frazelle, 2002).

One way to address the first issue is to coordinate workers by forming a bucket brigade (Bartholdi & Eisenstein, 1996a; Bartholdi et al., 2001). In a bucket brigade, every worker follows a simple rule: Continue to pick SKUs along the order-picking line until either your work is taken over by your colleague downstream or you finish it if you are the last worker of the line; then you walk back to receive more work, either from your colleague upstream or from the start of the line if you are the first worker.

Under certain assumptions, Bartholdi and Eisenstein (1996a) show that if workers are sequenced from slowest to fastest according to their work velocities in the direction of work flow, then a bucket brigade will *self-balance* such that the hand-offs between any two neighboring workers will converge to a fixed location. As a result, every worker will repeatedly work on a fixed segment of the line. Furthermore, the system's throughput attains its largest possible value.

Bucket brigades are especially effective in coordinating workers for order-picking due to the following reasons (Bartholdi & Eisenstein, 1996b; Bartholdi et al., 2001):

1. The rule is easy for workers to remember and follow.
2. Neither a work-content model nor computation for work balance is required. Both are necessary for any static work-allocation policy.
3. Workers dynamically and constantly balance their work and thus, the system can restore balance spontaneously from temporary disruptions and is adaptive to SKUs' demand seasonality.

Bucket brigades are also used to produce garments, to package cellular phones, and to assemble tractors, large-screen televisions, and automotive electrical harnesses (Bartholdi & Eisenstein, 1996a; 1996b; 2005; Villalobos et al., 1999a; 1999b).

Despite their impressive performance, there is a way to remarkably improve the throughput of bucket brigades. To distinguish from this new way of coordinating workers, we call the traditional bucket brigades introduced by Bartholdi and Eisenstein (1996a) *serial* bucket brigades. Recall that the serial bucket brigade rule requires each worker to walk back to receive more work after he relinquishes his work to his colleague downstream or after he completes his work. The travel to get more work either from his colleague upstream or from the start of the line is unproductive. This waste of capacity is especially significant for a long order-picking line. For example, it is common to have an aisle covering more than a hundred of racks for order-picking in large distribution centers. The throughput of serial bucket brigades will be compromised in such environments because of workers' unproductive travel to get more work.

In this chapter, we discuss a new design of bucket brigades introduced by Lim (2011) that totally eliminates this unproductive travel. This is also to address the second issue in order-picking mentioned above. Our basic idea is to store SKUs on both sides of an aisle. A worker picks SKUs to fulfill customer orders from one side of the aisle while he proceeds in one direction. He picks SKUs, possibly for other customer orders, from the other side of the aisle while he proceeds in the reverse direction.

Since the new design requires workers to pick SKUs in both directions and to cross the aisle, we need new rules for workers to share work. Although the new design totally eliminates the unproductive travel inherent in serial bucket brigades, it introduces a new type of unproductive travel: Workers are required to walk from one side of the aisle to the other. Since this cross-aisle travel is small if the aisle is narrow, we expect the system to perform well under this new design for narrow aisles. We perform computer simulations based on data from a distributor of service parts in North America. Our results suggest that bucket brigade order-picking under the new design can be significantly more productive than a serial bucket brigade, even if the latter is equipped with wireless technology to reduce travel.

We outline the chapter as follows: After reviewing the literature in Section 2, we describe the new design of bucket brigades and discuss rules for workers to share work in order-picking in Section 3. We then perform simulations to compare the average throughput of a system under the new design with that of a serial bucket brigade based on data from a distribution center in Section 4. Finally, we give some concluding remarks in Section 5.

2. Related literature

Bartholdi and Eisenstein (1996a) provide the first theoretical analysis on serial bucket brigade assembly lines. In their model, the product has deterministic work content. Workers cannot overtake each other and so they remain in a fixed sequence along the line. Each worker has a work velocity representing his familiarity with work content. These work velocities are deterministic and finite. They assume workers walk back to receive work with an infinite velocity because the time to walk the entire line is negligible compared with the time required to assemble an item (an instance of the product).

The most interesting result of Bartholdi and Eisenstein (1996a) is that if workers are sequenced from slowest to fastest in the direction of production flow according to their work velocities, the hand-off points between any two neighboring workers will converge to a fixed location. Eventually, every worker will repeatedly work on a fixed portion of work content on each item produced. The system is said to self-balance. Mathematically, the system converges to a *fixed point* (see, for example, Alligood et al., 1996). Another important result is that if work content is continuously and uniformly distributed on the assembly line, then the throughput of the line on the fixed point is the sum of work velocities of all workers, which is the maximum possible for the system.

The self-balancing property of bucket brigades is attractive to managers because it creates several positive effects. For example, the skills of workers are reinforced by learning through repetition, each worker is constantly busy, and the output is regular, which simplifies the coordination of downstream processes. All these effects are created without the intervention of management or engineering.

Bartholdi et al. (1999) describe all possible dynamics of two- and three-worker bucket brigades. They analyze the system with workers not necessarily sequenced from slowest to fastest. Bartholdi et al. (2006) generalize the ideas of bucket brigades to a network of subassembly lines so that all subassembly lines are synchronized to produce at the same rate.

Bartholdi et al. (2001) investigate the behavior of bucket brigades when work content on each work station is stochastic. They find that the dynamics and throughput of the stochastic system will be similar to that of the deterministic system if there is sufficient work distributed among sufficiently many stations. They also report the effectiveness of bucket brigades in order-picking in a distribution center, which experienced a 34% increase in productivity after the workers began picking orders by bucket brigades.

Armbruster and Gel (2006) analyze a two-worker bucket brigade in which the work velocities of workers do not dominate each other along the entire line. Armbruster et al. (2007) study the behavior of bucket brigades when workers improve their work velocities as they learn. They observe that if workers are allowed to change their order along the line, the self-balancing property of bucket brigades is typically preserved.

Lim and Yang (2009) study policies that maximize the throughput of bucket brigades on discrete work stations. For the three-station, two-worker line they show that fully crosstraining the workers and sequencing them from slowest to fastest outperforms all other policies for most work-content distributions on the stations. They also find that the policy that only partially cross-trains the workers and sequences them from slowest to fastest performs equally well in many situations.

In contrast to the normative model studied by Bartholdi and Eisenstein (1996a), some work has been done based on the assumption that workers spend significant time to walk back for more work. Bartholdi and Eisenstein (2005) consider the case where each worker spends a constant walk-back time and a constant hand-off time to get a new item from his colleague upstream. They assume different workers may have different walk-back times and different hand-off times. Bartholdi et al. (2009) assume each worker has a constant, finite walk-back velocity. Workers are allowed to overtake or pass each other. The authors show that the system may behave chaotically, according to rigorous mathematical definitions, if it is not configured properly. This chaotic behavior causes the inter-completion times of items to be effectively random, even though the model is purely deterministic.

Lim (2011) first introduces the ideas of *cellular* bucket brigades to totally eliminate the unproductive travel inherent in serial bucket brigades. Based on a model where work content is continuously and uniformly distributed, the author analyzes the dynamic behavior and the throughput of a cellular bucket brigade. The author shows that a cellular bucket brigade can be substantially more productive than a serial bucket brigade.

Inspired by the ideas of Lim (2011), Lim and Wu (2011) introduce simple rules for workers to share work on U-shaped lines with discrete work stations. The authors study the dynamics and determine the long-run average throughput of the system.

This chapter complements the theoretical work of Lim (2011) with a case study on the order-picking operation of a distribution center. We describe how the ideas of cellular bucket brigades proposed by Lim (2011) can be implemented in order-picking and introduce simple rules for workers to share work under this new design in practice. We evaluate the system's performance under the new design using computer simulations based on real data from the distribution center.

Eisenstein (2008) analyzes the optimal design of discrete order-picking technologies. Gue et al. (2006) study the effects of pick density on order-picking in narrow aisles. For a recent review of order-picking literature, see de Koster et al. (2007). van den Berg (1999) provides a nice survey on planning and control of warehousing systems.

3. Order-picking by cellular bucket brigades

3.1 A basic model

Our method can be used in carton-picking or piece-picking (Bartholdi & Hackman, 2010) that occurs along an aisle, where jobs are released from one end of the aisle. Workers may or may not travel with handling equipment such as order-picker trucks or carts. To facilitate the analysis, we consider an order-picking line that consists of s sections of shelving shown in Fig. 1. Each section of shelving is represented by a *pick point* that is located at the center of the section. We assume all SKUs in the section are retrieved from this pick point.

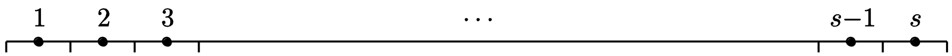


Fig. 1. **An order-picking line**. The line consists of *s* sections of shelving. Each section of shelving is represented by a pick point located at its center.

An order is a list of *pick lines* for a customer. Each pick line requests a piece of a SKU from a specific pick point. If multiple pieces of the same SKU are requested by the customer then multiple pick lines are printed. We assume *b* orders are batched into a *job*. The average number of pick lines per job increases with the job size *b*. Every job is released from the start of the order-picking line (left end of Fig. 1). SKUs requested by a job are progressively picked along the line until the job is completed.

Each worker carries a single job and walks with a finite, constant velocity *w* along the order-picking line. He stops at the next pick point to pick SKUs for his job. The time required to retrieve a SKU from a pick point depends on the worker's experience and dexterity. We assume the *k*-th slowest worker in a team takes T_k seconds to retrieve a piece of a SKU from a pick point, where

$$T_k = T\, e^{-\beta(k-1)}, \tag{1}$$

$k = 1, \ldots, n$, and $T, \beta > 0$. We also try other functions where T_k decreases with *k*. The simulation results are generally similar. Thus, we only report the results based on Equation (1) in this chapter.

After all orders of a job are picked, they are brought to the shipping department where they are sent to the customers. The objective is to maximize the average number of pick lines (or, equivalently, the average number of orders) picked per unit time.

3.2 A new design

Consider a new design of bucket-brigade order-picking to reduce unproductive travel of workers inherent in serial bucket brigades. The idea is to fold the entire order-picking line at its midpoint so that the two halves of the line form an aisle in between. Fig. 2 shows such a design. The work flow of the two halves runs in opposite directions. Each job is initiated at the start of the first half. SKUs requested by the job are picked in the forward direction until the end of the first half, where the job is transferred to the second half of the line. SKUs from the second half of the line are then picked for the job until the job is completed. Thus, the first half is called the *forward line*. The second half, which continues the jobs in the reverse direction, is called the *backward line*. The aisle width between the forward and the backward lines is *a*.

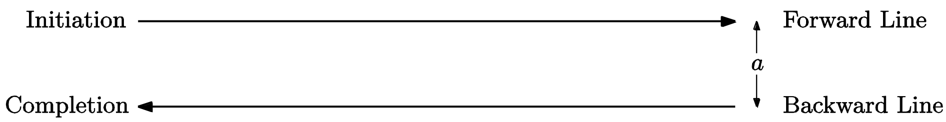


Fig. 2. **A new design**. Each job is initiated at the start of the forward line. The SKUs requested by the job are progressively picked until the end of the forward line, where the job is transferred to the backward line. The SKUs for the job are then picked in the backward direction until the job is completed. The width of the aisle between the two lines is *a*.

To uniquely determine the coordinate of each worker along the aisle, we conceptualize the aisle as a real line and define its left end as the origin. Let x_i denote the coordinate of worker i along the aisle, for $i = 1, \ldots, n$. We require workers to remain in a fixed ordering along the aisle from 1 to n so that $x_1 \leq x_2 \leq \ldots \leq x_n$. This requirement is reasonable for narrow aisles where workers cannot overtake or pass each other. This will not be a limitation of our model as the new design is effective only if the aisle is sufficiently narrow. As a result, only worker 1 can initiate and finish a job at the start of the aisle, and only worker n can transfer a job from the forward line to the backward line at the end of the aisle. We call workers $i-1$ and $i+1$ the *predecessor* and the *successor*, respectively, of worker i.

Since workers work in both directions along the aisle, a hand-off between any two workers now becomes an exchange of work. A worker i continues to work on the forward line until a hand-off occurs at point p along the aisle where he meets his successor, who is working on the backward line. A hand-off is not instantaneous now: The two workers first relinquish their jobs at point p and then walk across the aisle with velocity w, which takes time a/w. After they exchange their work, worker i works on the backward line with the job from his successor, while his successor works on the forward line with the job from worker i. Note that if the picked SKUs are carried by trucks (or carts), then each truck (or cart) follows its associated job. In this case, the two workers exchange not only their jobs, but also their trucks (or carts).

When worker n finishes his work at the end of the forward line, the system *resets* itself: Worker n transfers his job from the forward line to the backward line. He continues to work on his job on the backward line until he meets worker $n-1$, who is working forward. After a hand-off, worker $n-1$ works backward on the job that he receives from worker n. Worker $n-1$ then meets and exchanges work with worker $n-2$, who in turn meets and exchanges work with worker $n-3$, and so on until worker 1 completes the job at the end of the backward line. Worker 1 relinquishes the completed job, crosses the aisle, and initiates a new job. Each reset triggers a job completion and each job completion is followed by a job initiation. Thus, the work-in-process is bounded by the number of workers in the system.

3.3 Extended rules

A worker's coordinate along the aisle remains unchanged when he is crossing the aisle. To keep workers in the same ordering along the aisle, we need to introduce additional rules to handle situations in which a worker, working on the forward (backward) line, catches up with his successor (predecessor) while the latter is crossing the aisle. If worker i, who is working forward, catches up with worker i+1, who is crossing the aisle, then worker i must *wait* for worker i+1. We set $x_i = x_{i+1}$. If worker i, who is working backward, catches up with worker i−1, who is crossing the aisle, then worker i must wait for worker i−1. We set $x_i = x_{i-1}$.

Under the new design each worker independently follows these rules:
Work forward: Continue to pick SKUs for your job on the forward line until

1. you exchange work with your successor, then **work backward**; or
2. you reach the end of the forward line if you are the last worker, then transfer your job to the backward line and **work backward**; or
3. you catch up with your successor, who is crossing the aisle, then **wait**.

Work backward: Continue to pick SKUs for your job on the backward line until

1. you exchange work with your predecessor, then **work forward**; or
2. you complete your job at the end of the backward line if you are the first worker, then initiate a new job and **work forward**; or
3. you catch up with your predecessor, who is crossing the aisle, then **wait**.

Wait: Stay with your job,

1. if you are on the forward line, remain idle until your successor finishes crossing the aisle, then **work forward**; or
2. if you are on the backward line, remain idle until your predecessor finishes crossing the aisle, then **work backward**.

Fig. 3 illustrates the movement of workers in the new design. Let x^t_i be the hand-off point along the aisle between worker i and his successor due to the t-th reset. The two workers exchange their work and cross the aisle with velocity w. After the hand-off, worker i works backward until he meets worker i−1, who is working forward, at point x^t_{i-1}. After a hand-off between the two workers at point x^t_{i-1}, worker i works forward again.

Meanwhile, worker i+1 picks SKUs for the job that he receives from worker i on the forward line. He meets worker i+2, who is working backward, at point x^{t+1}_{i+1}. After a hand-off, worker i+1 works backward again. The next hand-off between workers i and i+1 occurs at point x^{t+1}_i. We call this a cellular bucket brigade because the workers move in cells.

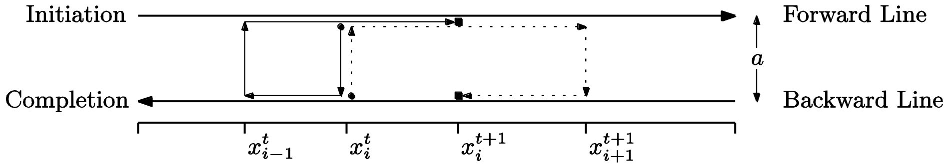


Fig. 3. **Movement of workers in a cellular bucket brigade**. This figure illustrates the movement of worker i (represented by the solid arrows) and worker i+1 (represented by the dotted arrows) between two successive hand-offs that occur at points x^t_i and x^{t+1}_i between the two workers in a cellular bucket brigade. The start and the end of a worker's path are represented by a circle and a square respectively.

A worker is *blocked* by his successor (predecessor) on the forward (backward) line if the former catches up with the latter while the latter is picking SKUs at a pick point. When a worker is blocked, he remains idle until his successor (predecessor) works forward (backward) again.

4. Comparing with serial bucket brigades: A case study

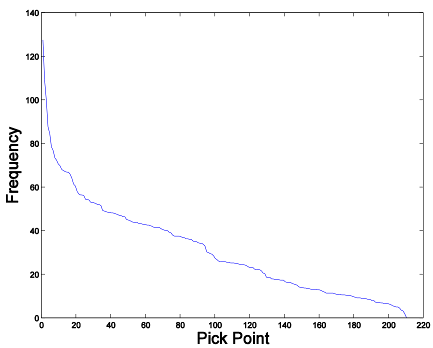
We use data from a distribution center to test the performance of cellular bucket brigades under realistic order-picking settings. Our simulation results suggest that cellular bucket brigades can be significantly more productive than their traditional counterparts even if the latter are equipped with wireless technology to reduce travel.

4.1 Order-picking in a distribution center

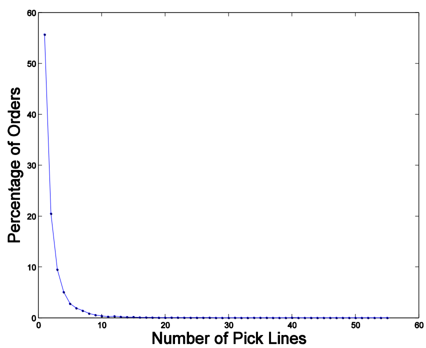
We perform simulations based on data from a major distributor of service parts in North America. In their order-picking facility, there are 214 pick points. The *pick frequency* of a pick point is the number of times SKUs are retrieved from the pick point. Different SKUs face different demand and therefore, different pick points may have different pick frequencies. Fig. 4(a) shows the daily pick frequency of each pick point. The figure shows that some pick points are visited over 120 times daily and some are visited no more than twice a day.

Fig. 4(b) shows that the number of pick lines per order is typically small for the distribution center. Eighty percent of the orders contain only 3 pick lines or fewer. The average is 2.18 pick lines per order. Thus, it makes sense to batch many orders into a job to reduce travel.

Since most of the SKUs in the distribution center are small parts, each worker carries a tote while they pick the SKUs. A job is passed together with its associated tote from one worker to another in the order-picking process. No other handling equipment is needed in this case.



(a)



(b)

Fig. 4. **Demand pattern**. (a) Daily pick frequencies of different pick points distribute over a wide range. The highest frequency is 127.5 and the lowest is 1.5. (b) The number of pick lines per order is typically small.

4.2 Order-picking policies

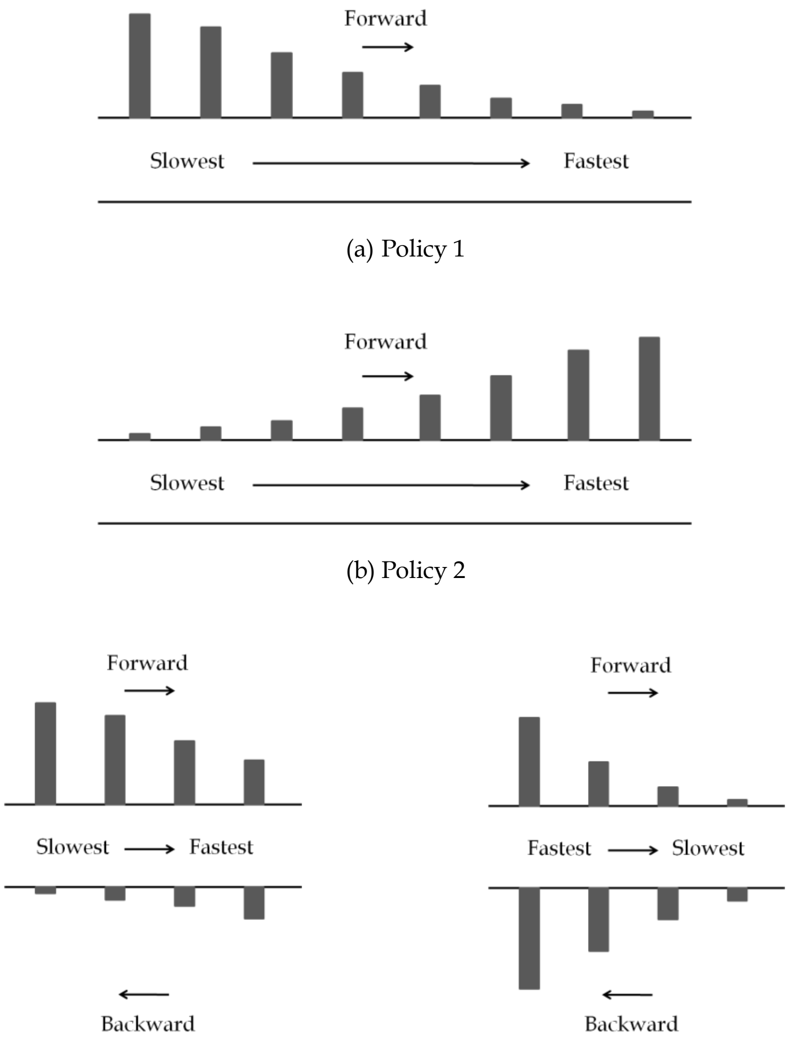
Several factors may impact the productivity of bucket brigades in this distribution center. For example, the distribution of SKUs along the order-picking line will affect the throughput of bucket brigades. Furthermore, the distribution center may consider using wireless technology to reduce travel of workers. With wireless technology, each job is transmitted to electronic devices held by workers so that workers can start picking SKUs for the job without traveling to the start of the line. We consider the following four different order-picking policies:

1. **Serial bucket brigades without wireless technology** – Pick points are distributed from highest to lowest pick frequencies on one side of an aisle such that the pick point with the highest frequency is located nearest to the start of the aisle. All jobs are initiated at the start of the aisle. Workers follow the serial bucket brigade rule and are sequenced from slowest to fastest in the direction of work flow along the aisle. Fig. 5(a) illustrates this policy.

2. **Serial bucket brigades with wireless technology** – Pick points are distributed from lowest to highest pick frequencies on one side of an aisle such that the pick point with the lowest frequency is located nearest to the start of the aisle. We assume the facility is equipped with wireless technology such that all jobs are initiated at their first pick points along the aisle. For example, if the first SKU requested by a job is located at section 23, then we start the job from section 23. Workers follow the serial bucket brigade rule and are sequenced from slowest to fastest in the direction of work flow along the aisle. See Fig. 5(b) for an illustration.

3. **Cellular bucket brigades with slowest-to-fastest ordering of workers** – Pick points are distributed on both sides of an aisle. A forward line is on one side of the aisle and a backward line is on the other side (see Fig. 5(c)). Pick points are distributed, from highest to lowest pick frequencies, first on the forward line and then on the backward line such that both pick points with the highest and the lowest frequencies are located nearest to the start of the aisle. All jobs are initiated at the start of the forward line. Workers follow the cellular bucket brigade rules and are sequenced from slowest to fastest in the direction of the forward line.

4. **Cellular bucket brigades with fastest-to-slowest ordering of workers** – Pick points are distributed, from highest to lowest pick frequencies, alternatively on the backward and the forward lines: The pick points with the highest frequency, 3rd-highest frequency, 5th-highest frequency, and so on are distributed on the backward line. They are sequenced in this ordering in the reverse direction of the backward line such that the pick point with the highest frequency is located nearest to the start of the aisle (see Fig. 5(d)). On the other side of the aisle, the pick points with the 2nd-highest frequency, 4th-highest frequency, 6th-highest frequency, and so on are sequenced in this ordering along the forward line such that the one with the 2nd-highest frequency is located nearest to the start of the aisle. All jobs are initiated at the start of the forward line. Workers follow the cellular bucket brigade rules and are sequenced from fastest to slowest in the direction of the forward line.



(a) Policy 1

(b) Policy 2

(c) Policy 3

(d) Policy 4

Fig. 5. **The four different order-picking policies**. The heights of the shaded bars represent the pick frequencies of the corresponding pick points. (a) SKUs are distributed on one side of an aisle. Workers are sequenced from slowest to fastest along the aisle. (b) Same as (a), but pick points are distributed from lowest to highest pick frequencies. (c) SKUs are distributed on both sides of an aisle. Workers are sequenced from slowest to fastest along the aisle. (d) Pick points with high pick frequencies are close to the start of the aisle. Workers are sequenced from fastest to slowest along the aisle.

The disadvantage of Policy 1 is that the faster workers near the end of the aisle spend a lot of time walking rather than picking SKUs. This does not fully utilize system capacity as we want fast workers to spend more time picking rather than walking. Policy 2 overcomes this problem by distributing pick points with high pick frequencies near the end of the aisle. Thus, SKUs with high demand are picked by faster workers. Furthermore, it uses wireless technology to reduce unproductive travel of workers. We expect Policy 2 to be more productive than Policy 1.

Policy 3 distributes SKUs in a way to reduce the probability of blocking in both directions. It corresponds to a cellular bucket brigade with more work content on the forward line than the backward line. Following the results of Lim (2011), workers should be sequenced from slowest to fastest in the forward direction. On the other hand, the backward line has more work content than the forward line under Policy 4. According to Lim (2011), workers should be sequenced from slowest to fastest in the backward direction (fastest to slowest in the forward direction). Policy 4 will keep the faster workers busy because pick points with high pick frequencies are located near the start of the aisle.

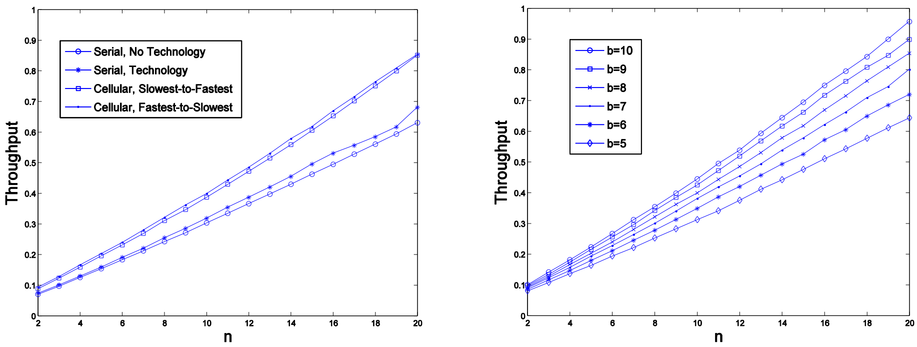
4.3 Performance of different policies

We compare the performance of all policies through simulations. Fig. 6(a) shows the average throughput (number of pick lines picked per second) under different policies. For all policies, the throughput increases with the number of workers n. Policy 2 outperforms Policy 1, while Policy 4 is more productive than Policy 3. The results suggest that the throughput of cellular bucket brigades is significantly higher than that of serial bucket brigades. The improvement in throughput by cellular bucket brigades can be as large as 25% (for $n = 20$).

Note that a cellular bucket brigade with fewer and slower workers can be significantly more productive than a serial bucket brigade, even if the latter is equipped with wireless technology to reduce travel. For example, the distribution center currently employs 14 workers for order-picking. Fig. 6(a) suggests that a team of 12 workers (slower on average) under Policy 4 is about 6% more productive than a team of 14 workers (faster on average) under Policy 2. This implies that even with 14% reduction in labor, the throughput can still be improved by about 6% using cellular bucket brigades. Thus, cellular bucket brigades not only fulfill customer orders more efficiently, but also save the costs of labor and wireless technology.

Fig. 6(b) shows the average throughput of Policy 4 with different job sizes. As the job size b gets larger, there are more pick lines per job and so there is less unproductive travel. This results in higher average throughput. We observe similar results under other policies.

Since workers pick SKUs in both forward and backward directions in a cellular bucket brigade, a worker may be blocked by his successor (when the worker works forward) or by his predecessor (when the worker works backward). The chance of blocking increases with the time required to retrieve a SKU from a pick point. To simulate situations in which blocking occurs more frequently, we increase the value of T in Equation (1).



(a) (b)

Fig. 6. **Throughput of different policies**. (a) The average throughput of each policy increases with the number of workers. Policy 4 outperforms all other policies. For this graph, we set b = 8. (b) The average throughput of Policy 4 increases with the job size b. For both graphs, a = 3 (ft), w = 3 (ft/sec), T = 15 (sec), and β = 0.1.

Fig. 7(a) shows that when T = 30 seconds, Policy 3 outperforms Policy 4 as the team size n increases. This is because under Policy 4, pick points with high frequencies are located near the end of the backward line. As the time to retrieve a SKU from a pick point increases, blocking occurs more frequently near the end of the backward line. Furthermore, blocking is more likely to occur when there are more workers in the system. As a result, Policy 4 becomes less productive than Policy 3 as the team size n increases. However, cellular bucket brigades (Policies 3 and 4) are still more productive than serial bucket brigades (Policies 1 and 2).

Fig. 7(b) shows the average throughput of all policies when T = 60 seconds. Policy 3 remains the most productive among all policies. However, the problem of blocking under Policy 4 becomes so severe that the policy is outperformed by Policy 2 as the team size gets larger. Fig. 6 and 7 suggest that Policy 4 is preferred if the time required to retrieve a SKU from a pick point is short. Otherwise, Policy 3 should be used. The results of this case study suggest that the ideas of cellular bucket brigades are promising for boosting productivity and reducing the costs of an order-picking system.

5. Conclusion

The main contribution of this chapter is to investigate the effectiveness of cellular bucket brigades in a realistic order-picking setting. Under the design of cellular bucket brigades, SKUs are stored on both sides of an aisle. Workers pick SKUs to fulfill customer orders from one side of the aisle as they proceed in one direction. They pick SKUs, possibly for other customer orders, as they proceed in the reverse direction. This totally eliminates workers' unproductive travel to receive more work inherent in traditional (serial) bucket brigades.

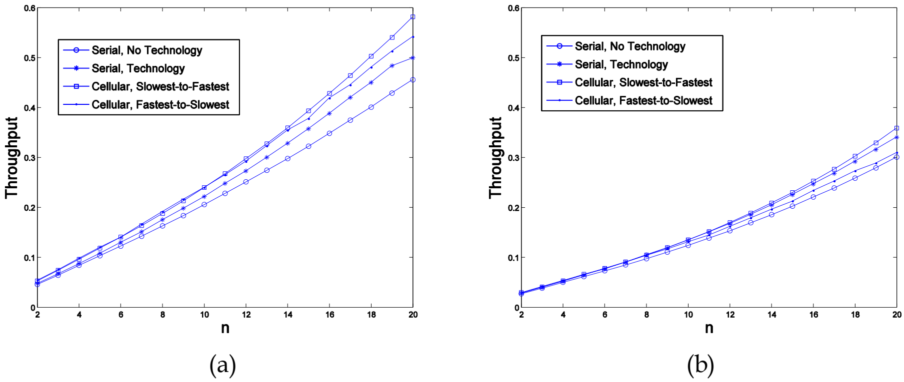


Fig. 7. **Cellular bucket brigades remain productive when pick time increases**. (a) When T increases to 30 seconds, cellular bucket brigades are still more productive than serial bucket brigades. (b) When T increases to 60 seconds, Policy 3 gives the highest throughput. Policy 2 outperforms Policy 4 when the team size is large. For both graphs, b = 8, a = 3 (ft), w = 3 (ft/sec), and β = 0.1.

Since workers work in both directions and they are required to walk across the aisle in a cellular bucket brigade, we discuss extended rules to coordinate the workers so that they can share work in an effective way. The extended rules remain easy for workers to remember and follow. Thus, it is straightforward to implement them in practice.

We compare the average throughput of cellular and serial bucket brigades through computer simulations based on data from a distributor of service parts in North America. Our results suggest that cellular bucket brigades generally attain higher throughput than serial bucket brigades. The improvement in throughput by a cellular bucket brigade can be as high as 25% over a serial bucket brigade for a team of 20 workers. Even with fewer and slower workers, cellular bucket brigades can be more productive than serial bucket brigades that are equipped with wireless technology to reduce travel. For example, the throughput of a cellular bucket brigade with 12 workers can be 6% higher than that of a serial bucket brigade with 14 workers equipped with wireless technology. This suggests that cellular bucket brigades not only can boost productivity, but also can save the costs of labor and wireless technology.

Our method of order-picking can be extended to a setting with multiple aisles, where SKUs are stored on both sides of each aisle. A global pick-path that traverses through all the aisles can be constructed. Workers pick SKUs from one side of the path when they travel in one direction, and they pick from the other side of the path when they travel in the reverse direction.

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