BUCKET BRIGADES
A Self-Balancing Order-Picking System for a Warehouse

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Abstract

"Bucket brigades" are a new way of sharing work among pickers in a warehouse so that the statistics of the order stream elicit a spontaneous allocation of work to balance the effort. The result is increased pick rates without conscious intention of the workers, without guidance from management, without any model of work content, without any computation, indeed without any data-gathering at all.

We implemented order-picking by bucket brigade in the warehouses of a major chain retailer, where, among other benefits, pick rates increased more than 30%.

We believe that bucket brigades can replace zone-picking as the standard method of picking orders in high-volume retail trade.

Key words: *warehouse, order-picking, work-sharing, bucket brigade, zone-picking, self-organizing systems, dynamical systems*

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"Bucket brigades" are a way of coördinating workers who are progressively assembling product along a flow line. If the workers are stationed from slowest to fastest along the line (with respect to the direction of product flow), then a balanced allocation of work will spontaneously emerge.

We analyzed this surprising phenomenon in the context of manufacturing (Bartholdi and Eisenstein, 1996). Here we report on the translation of these ideas to the warehouse, where we confirmed the effectiveness of order-picking by bucket brigade at the central distribution center of a major chain retailer, at which we observed improvements that were immediate, substantial, and cost-free.

In the following we describe standard industry practice for order-picking, how we replaced it at one site with bucket brigades, and what happened. Finally, we explain the apparent superiority of bucket brigades.

1 Order-picking

In the stores of chain retailers, sales space for inventory is severely limited, and so the warehouses supporting them replenish stock-keeping units (*sku's*) frequently and in small, less-than-caseload amounts. This means that a typical store orders many sku's, but small numbers of each. Picking these many sku's in small amounts is very labor intensive.

Under these circumstances, the preferred mode of storage in the warehouse is generally flow rack, illustrated in Figure 1. Flow rack is arranged in aisles, through which runs a unidirectional conveyor system. The racks are divided into *bays*. Within each bay are shelves with rollers and the shelves are tilted to bring the cases forward. Each sku in the flow rack is stored as a *lane* of cases and individual items of each sku are picked from the forward-most case.

An *order* is a list of sku's for a single customer together with quantities to be picked. Paperwork describing orders to be picked waits at the start of the aisle. Each order sheet lists the sku's (and amounts to pick) in the sequence in which they will be encountered along the aisle.

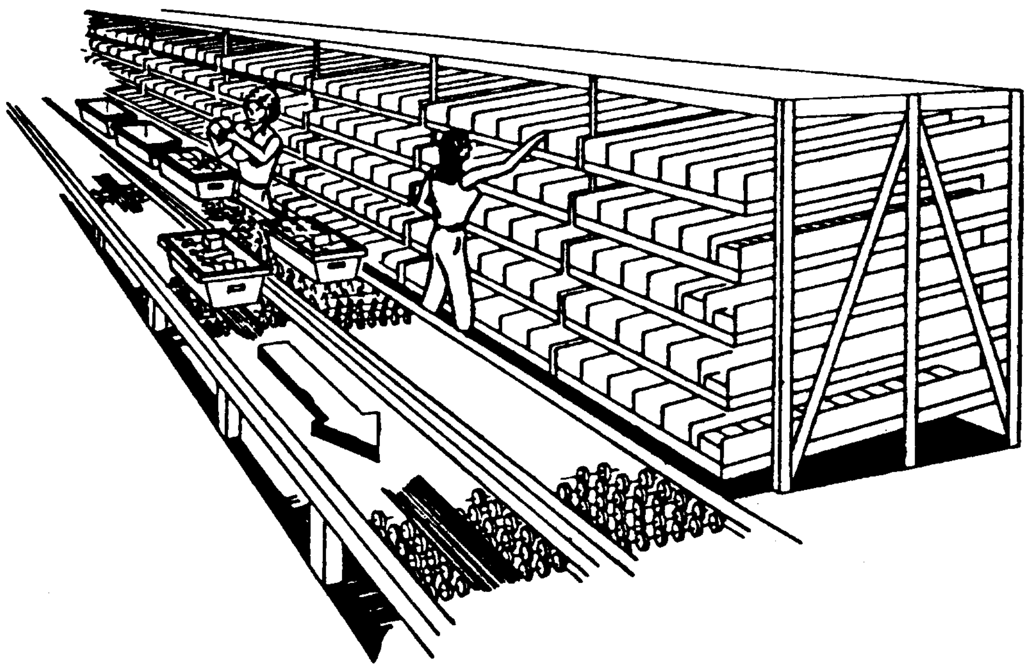

Figure 1: A team picking from an aisle of flow rack to a conveyor (from "Warehouse Modernization and Layout Planning Guide", Department of the Navy, Naval Supply Systems Command, NAVSUP Publication 529, March 1985, p 8-17). The "passive" conveyor (closer to the pickers) holds partially completed orders. The powered "take-away" conveyor transports completed orders to the shipping department.

Workers assemble each order progressively along the aisle, putting the sku's into *totes* (cartons), which travel together. Workers keep the orders in sequence, to avoid sorting at the shipping dock, where trucks are loaded in reverse order of delivery.

The aisles work in parallel to pick the orders of a common set of customers. This means the aisles must periodically synchronize their completions to correspond to the timed departure of a set of trucks. Otherwise the aisles operate independently of each other.

2 Sequential Zone-picking

Because broken-case order-picking is so labor-intensive, managers naturally want to keep all pickers busy. Standard practice is to attempt to balance the work by partitioning the bays into contiguous sections called *zones* and then restricting each picker to work within her[1] zone. The picker in the first zone takes a new order, opens a *tote* (box) and slides it along the passive lane of the conveyor as she moves down the aisle picking the sku's for that order. On reaching the end of her zone, she leaves the order on the passive conveyor for the next worker and returns to the beginning of her zone for more work. Each worker remains in her zone, moving totes forward while picking, and is idle if there are no orders waiting when she returns to the beginning of her zone. The last picker pushes the totes of a completed order onto the take-away conveyor, which takes them to the shipping department. The idea is that all workers will presumably remain busy if their zones have approximately the same total work. This style of order-picking is called *sequential zone-picking*. (For more about order-picking protocols, see "The warehouse manager's guide to effective order picking", Monograph M-8, Tompkins Associates, Inc., Raleigh, NC.)

Zones are fixed in advance of picking, based on some model of work content, but in practice require constant readjustment to maintain balance. There are three reasons for this.

[1] In our experience most pickers are female.

- Zones usually span integral numbers of bays so that zone boundaries are easy for the pickers to recognize; but the work might be distributed in such a way that no division by bay produces a good balance.
- The model of work content is unavoidably inaccurate. There are more factors that determine work content than can be economically modeled: In addition to the number and locations of the sku's to be picked, work content is also determined by heights of the locations (at waist level or inconveniently high?), weight and shape of the sku's (heavy? hard to handle?), and so on. Moreover, such models cannot account for inevitable disruptions such as disposing of an empty case, opening a new case, sealing a full tote, pulling stalled cases to the front of the flow rack, and so on. Even more importantly, such models never, in our experience, account for the inherent differences in the pick rates of individual workers, which typically range from 50% to 200% of work standard. It is not surprising that zones tend to underutilize the fastest workers, while frustrating the slower workers, who, under pressure to keep up, can introduce errors.
- Zones are static: They attempt to balance only the *total* work over, say, one day, but fail to maintain balance from order to order. The result is that every picker might accomplish the same total work at the end of the day; and yet no one have been fully utilized.

Some facilities have tried to improve balance by recomputing zones several times a day, and others have invested heavily to build more sophisticated models of work content. Many more firms try to ignore the problem by assigning each picker an identical number of contiguous bays of flow rack from which to pick, which implicitly assumes that all pickers are identical and all bays will be picked equally often (O'Brian, 1986, for example). None of these strategies overcome the inherent inefficiencies of zone-picking.

In summary, zone-picking requires constant supervision to ameliorate unavoidable imbalance — and is imbalanced nonetheless. The cost of imbalance is reduced pick rates due to incompletely utilized pickers and due to work-in-process, which interferes with picking.

3 Bucket brigade order-picking

We suggest that the pickers work as a *bucket brigade*: Each picker follows the rule “Pick forward until someone takes over your work; then go back for more”. When the last picker completes an order, she pushes it onto the take-away conveyor and then walks back to take over the order of her predecessor, who in turn takes over the order of her predecessor, and so on until the first picker begins a new order.

Workers are not restricted to zones, and so any worker can in principle pick from any location. There are no buffers, so the only work-in-process inventory is that in the hands of the pickers.

Pickers must maintain their sequence: No passing is allowed and so it can happen that a picker is blocked by her successor, in which case we require that she simply wait until she can resume picking, after her successor has moved out of the way. (Thus there is at least the possibility of wasted pick capacity due to blocking; later we shall show how to minimize this waste.)

We further require that the pickers be sequenced from slowest-to-fastest, so that the slowest picker is starting new orders and the fastest is finishing them. Then, as we shall show, pickers will spontaneously migrate to where the work is. The results will be increased pick rates, due to more effective work-sharing, and reduced management because the balanced allocation of work is spontaneous.

The idea of spontaneous reallocation of work in a manufacturing environment has been explored by Bartholdi and Eisenstein (1996) and by Bartholdi, Bunimovich, and Eisenstein (1995). Here we apply the essential ideas to warehousing, where we believe it has even greater potential. Some translation is necessary, however, for the issues in warehousing are somewhat different than in manufacturing. For example, a deterministic model of work was appropriate for apparel manufacturing, where successive units of work are identical, while here the location and amount of work vary from order to order. Nevertheless, the general conclusions are similar: When properly configured — that is, when workers are sequenced from slowest-to-fastest and are carrying appropriate amounts of work — a bucket brigade line will continuously and spontaneously balance the work to improve throughput.

We implemented order-picking by bucket brigade at a distribution center that supports over two thousand stores of a major US chain retailer[2]. This has subsequently been extended to additional, regional warehouses and now involves several hundred pickers. Previously, all sites had used sequential zone-picking.

One of the advantages of bucket brigades is that to implement them requires no special equipment and no changes to a typical warehouse management system. This made it easy to try one morning on a single pick-line. We described the idea to the workers in fifteen minutes, management sequenced the workers from slowest-to-fastest, and within a half-hour they were picking comfortably.

Another advantage of bucket brigades is that they are easy to adjust. This made it easy to experiment with settings, such as "bucket size" (the number of orders to be carried by each picker).

3.1 Bucket size

There are two opportunities for waste under bucket brigades: time lost when one worker is blocked by, but forbidden to pass, her successor; and time spent walking back to get more work. (There are similar opportunities for waste under zone-picking: time lost when a picker is starved for work; and time spent walking back to get more work at the beginning of a zone.) Our biggest design challenge was to reduce this waste; and the natural way to do this is to increase the size of the "bucket" (the number of orders carried by each worker). Larger buckets mean fewer walk-backs to get work. Larger buckets also mean reduced variance in the amount and location of work; and so there will be less opportunity for a

[2] Our client has requested anonymity to protect the competitive advantage afforded by bucket brigades; in deference to their wishes we refer to them herein as X, Inc.

faster but busy worker to block a slower one.

However, if the bucket is too large, the conveyor can become congested with totes. Then workers may find their totes pushed downstream by those of their predecessors and so they must walk to put sku's in the appropriate totes. This walking reduces the effective pick rate, and so throughput.

We had, in advance, estimated by simulation an adequate bucket size, which we then adjusted by experiment on the line. This was an easy adjustment that required merely that the first worker change the number of new orders she introduced into the line. The most effective bucket size depends on the statistics of the order stream and will differ from site to site, but was in this case four orders per worker.

We briefly considered releasing a variable number of orders to better smooth the work content per bucket; but this seemed unattractively complicated. Fortunately, it proved unnecessary because we found a bucket size that eliminated blocking without causing congestion.

Under zone-picking, congestion had been a frequent problem due to spot imbalances between zones; and this had been exacerbated by a policy of stationing the fastest worker first on the line, where she started as many new orders at one time as she wished (sometimes up to fifteen). In contrast, the bucket brigade protocol strictly controls work-in-process, and so congestion, by linking the start of new orders to the completion of previous orders. Furthermore, sequencing the workers from slowest-to-fastest still allows the fastest worker to pace the system, but by pulling work rather than by pushing it.

3.2 Results

The most striking benefit of order-picking by bucket brigade was the increase in pick rates, which reached sustained levels over 30% greater than the previous historical averages, while reducing management intervention (Figure 2). This was achieved at essentially no cost, and in particular, with no change to the product layout, equipment, or control system (except to render parts of the

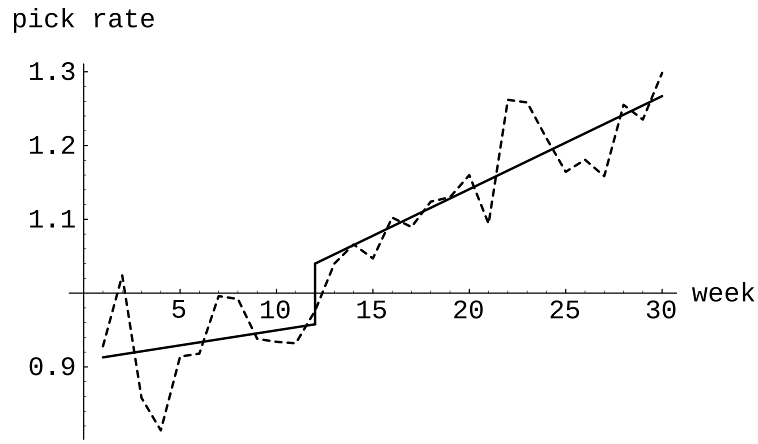

Figure 2: Average pick rate as a fraction of the work-standard. Zone-picking was replaced by bucket brigade in week 12. (The solid lines represent best fits to weekly average pick rates before and after introduction of the bucket brigade protocol.)

latter unnecessary).

To determine whether the increased throughput is an artifact of our tinkering or represents a genuine improvement in technology, we simulated both zone-picking and bucket brigade on the order stream of one aisle for a day and compared their relative performances (Figure 3). Bucket brigade was clearly superior, even though our simulation showed zone-picking at its most advantageous. In real life, the greater work-in-process of zone-picking means congestion and therefore both decreased pick rates and more opportunities to put sku's in the wrong tote. This suggests that the observed increase in pick rates under bucket brigade is real.

Picking by bucket brigade produced additional benefits, including the following.

- Spontaneous (re)balance of the work has freed management time. Previously each aisle was monitored by a manager who adjusted zones within the aisle to correct the inevitable spot imbalances and the resulting congestion or starvation. This level of supervision is no longer necessary because

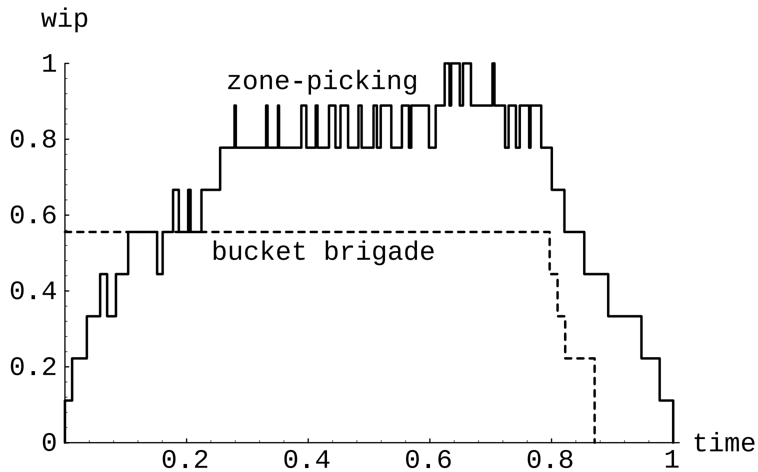

Figure 3: The (normalized) work-in-process under simulated zone-picking and under bucket brigade. Bucket brigade finished in 85% of the time required by zone-picking and had only half the peak work-in-process.

adjustments are spontaneous and continual.

Furthermore, differences in work rates are now visible and so it has become easier to recognize problems. For example, at X, Inc. each bay contains comparable amounts of work of each order and so, under the bucket brigade protocol, each worker tends to visit a length of aisle proportional to her pick rate. In one case, an unusually slow worker at the first position was repeatedly "pushed back" by her faster teammates: She was unable to pick quickly enough ever to leave the first bay of flow rack and so her teammates asked that she be removed. It was apparent to all that they could pick as fast without her and they preferred to split the incentive pay $n-1$ ways. Under zone-picking such imbalances were harder to recognize because they could be hidden by work-in-process.

- The synchronization of multiple aisles has become easier. A manager can now monitor the progress of an aisle by simply checking what order any worker is picking. Under zone-picking it was difficult to know the status of an aisle because of the considerable and variable work-in-process.

It has also become easier to move workers to maintain the balance among aisles. Under zone-picking, when one picker was moved, work was interrupted while management redefined the zones in each aisle; but under bucket brigades, the pickers in each aisle spontaneously adjust to account for the new configuration.

- A bucket brigade is extensible. For example, at X, Inc. there was a worker picking from carousels immediately upstream from one aisle; and she occasionally got ahead of the workers in that aisle. Under zone-picking she had to cease working until the congestion was cleared. Now she simply joins the bucket brigade to help them pick. After they have caught up, she returns to the carousels at the next walk-back.

- Reduced levels of work-in-process increased the accuracy of order-picking. Because the number of totes on the conveyor is strictly controlled, workers put sku's in the wrong totes less frequently.

- The pickers claim to be more satisfied because they prefer working in teams, with clear instructions about where to go and when. Furthermore, the simplified and regularized movements mean that temporary workers can become productive more quickly.

- The expense and inaccuracy of work content models is avoided. X, Inc. had calculated zones several times a day based on a sophisticated, computer-hosted model of work content. With bucket brigades, X, Inc. is able to forego this expense and still increase pick rates. Other sites in our experience use less sophisticated work-content models to determine zones and so we expect such sites to benefit still more from conversion to order-picking by bucket brigade.

4 Special conditions

Warehouses vary enormously in their details, even within the same company. Here we discuss some interesting special issues that arose at various sites.

4.1 Dynamic adjustment of bucket size

Under zone-picking pickers started and ended their day at staggered times because work was not simultaneously available for all. This complicated and extended the day for management. We found we could reduce the problem under the bucket brigade protocol: At the start of the day the fastest worker begins picking a *single* order from the very start of the aisle, followed by the next worker picking a single order, and so on, until every worker is picking a single order. Then, at each subsequent walk-back, the first picker increases the number of orders introduced, until reaching the standard bucket size.

Similarly, workers changed the bucket size at the end of the day. For example, in one aisle we had directed each worker to carry four orders. Initially this caused a problem at the end of the day because the first worker finished almost an hour before the last worker. To simplify employee scheduling, management introduced the following modification: When the first worker begins picking the final four orders of the day, she signals the last worker; then at the next walk-back the last worker takes over only two of the orders of her predecessor. At each subsequent walk-back, any worker with only two orders takes only two from her predecessor, until eventually everyone has exactly two orders. Then the first and last pickers are separated by half the work content as when everyone carried four orders, and so they will finish work within 30 minutes or so of each other. The extra time for the first workers is used to clean the work area and prepare for the next day.

4.2 Pick-to-light

X, Inc. had instrumented the flow rack in some aisles with a *pick-to-light* system, by which a central computer turns on a lighted display at each storage location to show exactly what and how many to pick from the next bay for a particular order. This is intended to reduce search time and paper-handling; but it also allows the bucket brigade protocol to work even more efficiently: Because all the locations to be picked within a bay are lighted at the same time, two workers can pick simultaneously, side-by-side, on the same order. This helps the bucket brigade protocol in two ways.

- It reduces time lost during hand-offs: During a walk-back each picker must take over the work of her predecessor; and because all the remaining picks in a bay are lighted simultaneously, both pickers can work side-by-side until the preëmpted picker reaches a convenient stopping point. Thus there is almost no time wasted in handing off work.

- It reduces time lost due to blocking. Because of variations in the amount and location of work among pickers there will occasionally be some blocking. We reduced consequent waste by requiring that, whenever a worker is blocked, she temporarily abandon her own work to help the picker who is blocking her. ("If blocked, help your teammate get out of your way.")

4.3 Any picker can start a walk-back

Bucket brigades may be even more productive if the protocol is amended to allow *any* picker who completes an order — not exclusively the last picker — to push her order onto the take-away conveyor and go back to take over the work of her predecessor. This avoids waste because no picker who has completed her order will ever be forced to wait.

Such a modification is useful at sites in which orders need not remain in sequence and where picks for each order are not typically required along the entire length of the pick ailse.

For instance, such a modified protocol is helpful at the national distribution center of Blockbuster Music, where part of their picking operation is organized so that workers push carts through one-way aisles of static shelving, which contain sku's with a wide range of pick activity. The most active of these sku's are concentrated in the first five of 23 aisles, so that many orders are completed within the first few aisles and are sent directly to shipping whenever they have been filled. The operations manager reported an increase in pick rate of over 50% within a day of changing from zone-picking to bucket brigade. An additional benefit from bucket brigades at this site is that, because pickers are not allowed to pass one another anyway, the aisles could be narrowed to the width of a single cart. This reduced space requirements by almost half, which reduced walking time and so further contributed to increased pick rates.

5 The effectiveness of bucket brigades

To better understand where bucket brigades will be effective, let us consider a simple model in which the amount and location of work varies. This model is intended to be tractable as well as representative, and so some of the assumptions, especially one on the distribution of work, are more strict than is necessary for bucket brigades to be effective in real life.

Let there be m discrete positions at which a worker may stand while picking. These positions partition the sku's into m disjoint sets. For example, the positions might correspond to the bays of flow rack; or possibly, in a more detailed representation, one foot intervals along the aisle.

Assumption 1 (Total ordering of positions) *Positions can be numbered according to their appearance in an* a priori *sequence $j = 1, \ldots, m$, so that, for any given order, any picks from position j will be completed before any picks from subsequent positions beyond j.*

Such an ordering is generally implicit in the layout (geometry) of storage and direction of material flow. For example, when sku's are stored along an aisle that must be traversed, it is natural to pick them in the order in which they are encountered. On the other hand, storage need not be restricted to a single aisle; for example, our model applies (and bucket brigades are being used) where the pickers walk through parallel aisles of shelves like shoppers in a grocery store.

An order is a m-tuple, the j-th entry of which represents the amount of standard work to pick from location j:

Assumption 2 (iid orders, exponentially distributed work) *Orders are independent and identically distributed random vectors, the components of which are independent; and the j-th component, representing the standard work at location j, follows an exponential distribution with common mean $1/\mu$.*

This assumption holds only approximately at X, Inc. Orders tend to be identically distributed because chain retail outlets experience the same seasonalities and are served by a common marketing plan. Also, all the orders within a day are generally destined for the same geographical region and therefore likely to reflect common regional tastes. Orders tend to be independent because they reflect the purchasing decisions of local customers, who presumably act independently.

Orders are to be picked by n pickers who can be ranked according to the speed at which they work:

Assumption 3 (Total ordering of the workers by velocity) *Each picker i is characterized by a work velocity v_i, and so the time for picker i to complete a pick is exponentially distributed with mean $1/(\mu v_i)$.*

This assumption is uncontroversial for order-picking, where the pertinent skills are simply dexterity and motivation. All the managers and workers we interviewed agreed that such a ranking could be quickly agreed upon by any pickers who had worked together. Indeed, it is typical in the industry that order-pickers are evaluated in terms of their "pick rate".

Finally, we assume that time spent walking is relatively small:

Assumption 4 (Insignificant walking time) *The time to pick a typical order is significantly greater than the time to walk the length of the aisle.*

5.1 Spontaneous emergence of teamwork

Based on our model of work, we can describe the behavior of a bucket brigade as a continuous-time Markov chain in which the state of the system is given by a vector $\{x_1, x_2, \ldots, x_n\}$, where $x_i \in \{1, 2, \ldots, m\}$ gives the position of worker i. This Markov chain is finite and all states communicate, so there is a unique limiting distribution to which the system converges (Ross, 1989, for example). Therefore, statistically predictable behavior will assert itself; and so we can evaluate the effectiveness of a bucket brigade line by measuring its production rate.

We claim that, under our model of work, a bucket brigade line will perform at its best (that is, at its highest production rate) if the pickers are sequenced from slowest-to-fastest along the direction of material flow. This makes intuitive sense, at least locally, because it reduces the probability of blocking. This, however, is a local argument and says nothing about the evolution of the system over time. Nevertheless, we have verified this claim for small lines, for which the Markov equations for the limiting distribution can be solved easily. We observed that the randomness of the orders does not qualitatively change the dynamics of the bucket brigade from those of the deterministic model analyzed by Bartholdi and Eisenstein (1996) and Bartholdi, Bunimovich, and Eisenstein (1995). Asymptotic behavior remains recognizably the same, except that the faithfulness of the reproduction depends on the variance of work among orders. For example, in Figures 4 and 5 the limiting distributions are concentrated over the stable (asymptotic) sets of the deterministic model (cf. Bartholdi, Bunimovich, and Eisenstein, 1995). In Figure 4 the pickers are sequenced from faster-to-slower. Here, the faster worker tends to stay close on the heels of the slower worker, and thus hand-offs alternate between the start and end of the line. In Figure 5 the pickers are sequenced from slower-to-faster, and hand-offs

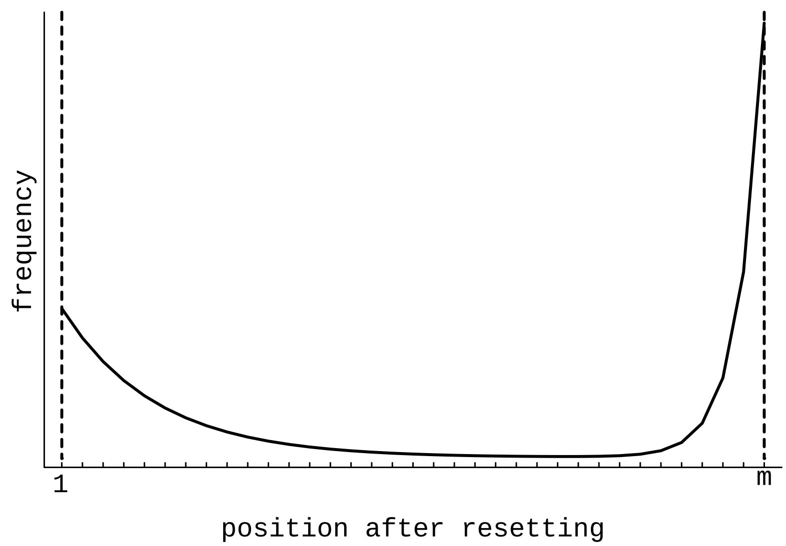

Figure 4: Faster-to-slower: Position of the second, slower, of two pickers immediately after walk-back. In the deterministic model of work, the second picker alternates between the first and last positions (dashed vertical lines).

are concentrated where the pickers will be pre-positioned to share effectively the work of the next order.

Now we can ask a theoretical question: How good is the production rate of bucket brigades in an absolute sense? In other words, can we guarantee that all pickers will always be busy? When work is probabilistic the answer is, of course, no; but we can recognize what factors reduce blocking and so improve the production rate.

For example, the chance of blocking is reduced when there is a large difference in the velocities of adjacent pickers. Figure 6 shows the limiting behavior of a two-picker line as the relative contribution of the last picker increases. More precisely, the production capacity remains constant: $v_1 + v_2 = 1$ and $\mu = m$; so the maximum production rate is 1 (the horizontal dashed line) while the relative contribution v_2 of the second picker changes. When the pickers are sequenced from faster-to-slower (the leftmost region), the production rate falls off rapidly as the relative contribution of the second picker decreases. However,

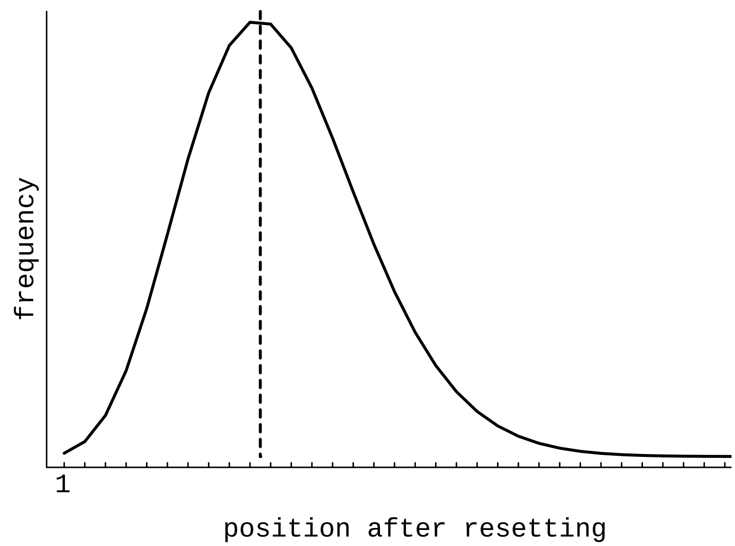

Figure 5: Slower-to-faster: Position of the second, faster, of two pickers immediately after walk-back. In the deterministic model of work, the second picker repeatedly returns to the position marked by the dashed vertical line.

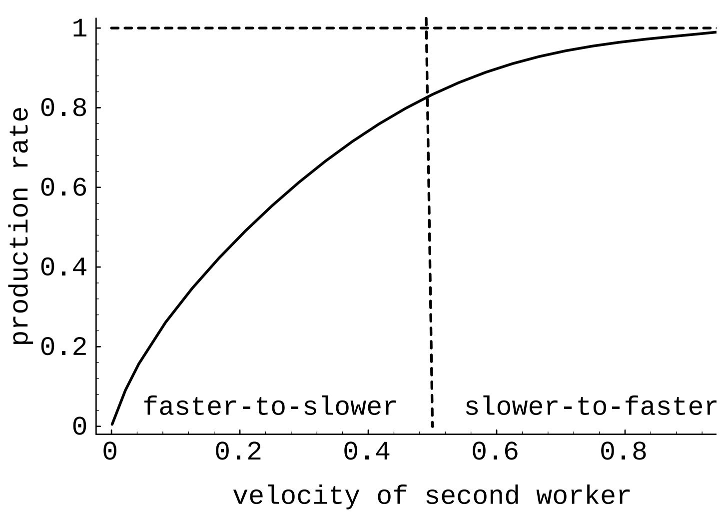

Figure 6: The production rate increases with the contribution of the second picker. Here, the velocity of the team remains constant, but the velocity of the second picker increases from 0 to 100 percent of the total work velocity of the team. Slowest-to-fastest is nearly optimal, despite variance in the work.

when the pickers are sequenced from slower-to-faster (the rightmost region), the production rate is nearly unbeatable (no blocking), even when the second picker is only a little faster than the first picker. This suggests that a workforce should be partitioned into bucket brigades so that each brigade contains a wide range of work velocities. This is consistent with analysis of the deterministic model in Bartholdi, Bunimovich, and Eisenstein (1995).

Another way to reduce the chance of blocking and improve the production rate is to reduce the variance of the work. As variance decreases, the behavior of the bucket brigade approaches that of the deterministic model analyzed in Theorem 3 of Bartholdi and Eisenstein (1996), in which the work is the same from order to order and is distributed uniformly and continuously through space. For this deterministic model the production rate converges to the highest possible because all blocking eventually ceases. In practice one can reduce the variance, as we did at X, Inc. , by increasing the bucket size (aggregating groups of four orders for batch picking). The chance of blocking can also be reduced by reducing the number of pickers, after which the team members will tend to be separated by larger and so less variable amounts of work.

The issues are more complicated when the intensity of work is allowed to vary among locations, so that work is no longer uniform. Bartholdi and Eisenstein (1996) show that when work is pathologically concentrated it can happen that blocking is endemic to bucket brigades. However, this is highly unlikely in practice because any extraordinarily busy items are generally picked separately, such as from floor storage on the shipping dock. In fact, our experience suggests that bucket brigades are effective even in the presence of rather severe variations in work intensity among locations.

6 Conclusions

We believe that bucket brigades are more productive than zone-picking for two reasons: First, bucket brigades constantly and spontaneously seek balance; and second, balance is based on actual, realized work content and not mere estimates of work content. Furthermore, the bucket brigades can achieve high production rate without resorting to high work-in-process because they absorb variance in the work by allowing the pickers to move to where the work is. Of course the strongest — and incontrovertible — evidence for the effectiveness of bucket brigades is experience in a commercial warehouse, such as we have reported.

The main benefits of order-picking by bucket brigade are increased pick rates and simplified management, including freedom from work-content models. These benefits were so substantial at X, Inc. that other, initial concerns, such as whether brigade members might shirk or free-ride, were dismissed as second order effects at best. There are thousands of warehouses, particularly those supporting high-volume retail sales, that could enjoy the same benefits we report here.

Our work may be seen to lie within two current streams of thought. Most immediately, it is a special case of *dynamic line-balancing*, wherein an intelligent controller adjusts the allocation of work in real time (for example, Ostolaza, Thomas, and McClain, 1990). For bucket brigades the allocation occurs spontaneously, which has the considerable advantage of requiring no controller at all! (In fact, our biggest problem in implementing bucket brigades has been to persuade workers that their *ad hoc* local "improvements" are generally not improvements at all and only interrupt the emergence of balance. We learned to insist on strict observance of the bucket brigade protocol[3].)

The second stream of thought into which our work fits is the hosting of computational processes on analogue devices. In our case the order-picking system is the computer of its own allocation of work. It might be said that we program this computer by sequencing the workers from slowest-to-fastest. There is no need to measure and input data because it is already encoded directly in the "hardware". The output is the balance.

[3] For which, incidentally, the metaphor of "bucket brigade", with its vivid sense of urgency, provides an effective training aid.

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