Reducing Labor Costs in an LTL Crossdocking Terminal

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Abstract

Handling freight in a crossdocking terminal is labor-intensive, and therefore costly, because workers must unload, sort, and transfer a wide variety of freight from incoming to outgoing trailers. The efficiency of workers depends, in large part, on how trailers are assigned to doors around the dock; that is, on its layout. A good layout reduces travel distances without creating congestion, but, until now, no tools have been available to construct such layouts. We describe models of travel cost and three types of congestion typically experienced in crossdocking terminals; and we use them to construct layouts that minimize the labor cost of transferring freight. We report on the use of our models in the less-than-truckload trucking industry, including an implementation at a terminal in Stockton, CA that improved productivity by more than 11 percent.

Profits for less-than-truckload (LTL) motor carriers are traditionally thin because logistics costs have been a major focus for all manufacturing and distribution firms for the past decade. Carriers are also having to provide better service as shippers demand that pickups and deliveries be made at precise times, rather than on precise days. Furthermore, encroaching competition from truckload and package carriers have caused LTL carriers to look for analytical methods to reduce costs and improve service.

Operational costs for a carrier have 3 major components: costs for drivers and vehicles making local pickups and deliveries, linehaul costs for transporting freight between terminals, and handling costs for sorting and consolidating freight. Research in pickup and delivery problems includes variations on the well-known Vehicle Routing Problem and, more recently, work on stochastic dynamic vehicle routing (see Powell et al. 1995 for example). Linehaul costs are addressed in the network configuration literature, such as Powell and Sheffi (1989) and Roy and Delorme (1989). We address the less-studied component of handling costs.

Handling freight in an LTL terminal is labor-intensive, and therefore expensive, because workers must quickly sort a variety of freight. An inexpensive way to remove work from the system is to assign destination trailers to the right doors of the terminal to take advantage of patterns of freight flow. For example, if much of the freight flowing through the terminal is bound for Miami, the Miami trailers should probably be parked in a convenient location. The challenge is to formalize the notion of "convenient."

Layout for LTL terminals is similar in some ways to the problem of gate assignments in airports, for which some analytical work exists. For example, Mangoubi and Mathaisel (1985) and Bihr (1990) propose mathematical programming and heuristic approaches to the problem. Mathaisel (1996) and Su and Srihari (1993) describe expert systems designed to manage airport operations, including assigning flights to gates. Our problem differs from aircraft gate assignment in several ways:

- Unlike those for aircraft, arrival times for incoming trucks are not known. At best, drivers call ahead to estimate an arrival time, but normal traffic congestion prevents precise planning.
- LTL terminals experience more serious internal congestion problems than do airports.
- The LTL problem is an order of magnitude larger because the airport problem is partitioned into independent subproblems by carrier.
- Unlike people and baggage in airports, freight in an LTL terminal is very heterogeneous and requires multiple material handling systems for transport.

The problem of crossdock design is similar in spirit to that of the more general and much-studied problem of facility layout, which was recently surveyed by Meller and Gau (1996). Both share the goal of positioning activities within a facility to minimize the costs of material handling. However, the problem of crossdock design is easier in one way and harder in another: In facility design, researchers have mostly optimized simple measures of material movement subject to complicated spatial constraints to produce a two-dimensional layout (Meller and Gau, 1996). In contrast, we optimize a much richer measure of performance; and we can do this because the spatial constraints are simpler in a crossdock: All we need do is assign trailers to fixed dock doors. Our measure of performance includes models of work content based on specific types of material-handling systems and work-rules common to crossdocks. Moreover, we also model the several types of congestion to which crossdocks are subject.

Optimization models to lay out crossdocks have usually been based on door-to-door distance, which is well-defined and so lends itself to the more formal methods of mathematical programming. For example, Tsui and Chang (1990, 1992) model the problem of assigning trailers to doors on a dock as a bilinear program, with the objective of minimizing the weighted distance between incoming and outgoing trailers. Peck (1983) models the layout problem in a similar way but also takes into account different types of freight and material handling systems.

Unfortunately, for many LTL terminals, the accuracy of these approaches is an illusion because shortest door-to-door distance is not a good measure of travel time. Actual travel time across the dock depends on, among other things, the type of freight (for example, heavy enough to require a fast forklift or light enough for a slow but immediately available palletjack?) and the local work rules that determine how each piece of freight should be moved.

Worse, minimizing weighted door-to-door distances can exacerbate congestion. As more activity is squeezed into a smaller area of the dock, there will be delays as, for example, forklifts interfere with each other. Congestion on the dock leads to excessive labor cost and can result in shipments missing service commitments. In extreme cases, congestion can halt operations entirely. For example, managers at one terminal reported occasional traffic jams requiring more than 10 minutes to clear.

We describe a set of models that guide a local search routine in assigning destination trailers to terminal doors so that the total labor cost is minimized, which requires balancing the cost of moving freight from incoming trailers to outgoing trailers with the cost of delays due to different types of congestion.

Distinctive features of our layout tools include:

- Models of the standard types of material handling systems in LTL terminals;
- Models of several types of congestion to which a dock is susceptible; and
- Explicit effort to minimize the *total* labor costs, accounting for both travel and congestion costs.

Work reported on facility design has concentrated on facilities in support of manufacturing; but, because manufacturing facilities are so varied in their requirements, testability and transportability of results is diminished. However, there are thousands of crossdocks just in the U.S. and this has allowed us to refine and validate our models on an assortment of facilities. As of this writing we have applied our models to nine terminals belonging to four different LTL carriers, and have found the layouts produced by our models to be significantly better than industry practice. We report in detail on the most complicated of those applications, a terminal in Stockton, California operated by the regional carrier Viking Freight, that documented an 11.7% improvement in performance.

1 LTL crossdocking terminals

1.1 Operations

Firms in the LTL industry are *common carriers*, meaning they transport shipments between other firms, and individual trucks contain goods from many shippers. Because shipments are smaller than a truckload quantity, LTL carriers seek economies of scale by consolidating shipments with similar destinations through a network of terminals. Networks of national LTL carriers are typically configured in a hub-and-spoke design. Regional carriers ship most of their freight directly to destination terminals in order to meet overnight service commitments.

The largest LTL carriers operate more than 300 terminals each, in almost every state of the nation. Regional carriers typically serve 10–20 states with fewer than 100 terminals. Terminals range in size from fewer than 10 doors to more than 500 doors; a typical terminal has 20–80 workers moving freight on a shift.

All terminals conduct *outbound* and *inbound* operations, so named because of the type of freight handled. Outbound freight is that to be sent outside the geographical area of responsibility of a terminal; and inbound freight is that arriving from outside the area of responsibility.

For *end-of-line* or *satellite* terminals, inbound and outbound operations are separated in time: Outbound freight, which was picked up by pickup-and-delivery (P&D) drivers during the day, is moved in the evening; and inbound freight, arriving from other terminals, is moved early in the morning. At other times, the terminal is inactive. For *hub* terminals, inbound and outbound freight arrives throughout the day, so the operations are separated in space, with the dock divided into inbound and outbound sides. Hub terminals also operate a *breakbulk* operation, in which trailers arrive from other terminals with freight bound for terminals other than the hub. Here, the hub operates as a transfer and consolidation point.

Most terminals are laid out as long, narrow warehouses with doors around the perimeter. Figure 1 illustrates a typical terminal. In this figure, small shaded rectangles represent incoming trailers with freight to be unloaded, and small clear rectangles represent destination trailers.

[Figure 1 about here.]

Inside a terminal, a variety of material handling methods is used to transport freight. Forklifts and palletjacks carry heavy or bulky items, and carts transport smaller items. In addition, large terminals may have draglines, which circulate carts around the inside perimeter of the dock.

There are two types of doors in a terminal: *strip doors*, where full trailers are parked to be unloaded, and *stack doors*, where empty trailers are put to collect freight for specific destinations. Once established, the designations of these doors do not change, although the trailers parked at them will. A stack door always receives freight for the same destination. A strip door may be occupied by any incoming trailer, regardless of its origin or contents.

Arriving trucks may deliver their trailers directly to an unoccupied strip door; or, if none is available, they may place them in a queue. After the trailer is backed into a strip door, a worker unloads the freight. After unloading all the items of a shipment onto a cart, the worker walks to the destination trailer and loads the items into that trailer; or he places the cart on the dragline, if the terminal is so equipped. To handle pallet loads, the worker uses a palletjack, or hails a forklift driver, or finds a forklift and delivers the load himself, if union rules permit.

After a trailer has been completely stripped, a driver replaces it with another incoming trailer from the queue of trailers waiting to be stripped. After an outgoing trailer has been filled, a driver replaces it with an empty trailer to be filled with freight for the same destination.

1.2 Freight flow

The patterns of freight flow within a terminal — and therefore the work — are determined by:

Layout by which we mean the specification of doors as either strip or stack doors and the assignment of destinations to the stack doors.

Geometry The shape of a terminal determines the location of the doors, and thus the travel distances between them. The shape of the terminal also affects congestion: for example, narrow docks tend to be more congested because workers have less room to manœuver.

Material handling systems For example, palletjacks are slower than forklifts, but they may be more available; draglines reduce walking time, but can impede forklift travel.

Freight mix For example, terminals having a higher mix of pallet freight require more forklift travel than those receiving a majority of carton freight.

Scheduling In real time, the dock supervisor determines freight flow patterns by assigning incoming trailers to strip doors.

Changing the geometry or material handling systems of a terminal is expensive; changing the freight mix is a marketing decision with implications outside the terminal. The two remaining ways to take work out of the system — change the layout or change the scheduling — are inexpensive. Gue (1998) addresses scheduling in a separate paper; here we describe technology for tuning the layout and show, by implementation at real terminals, that it produces significant savings.

2 Modeling flow

An important determinant of travel and congestion cost is the rule used by the supervisor to assign incoming trailers to strip doors. One might assume that supervisors strive to place incoming trailers near the destinations for which they have the most freight, but in practice, they often do not; instead, they make assignments based on

- the scheduled departure times of outgoing trailers;
- the mix of freight on the incoming trailers (For example, if there is much pallet freight on the dock, the forklifts will be very busy and so the supervisor may choose to unload a trailer containing primarily carton freight.); and
- the experience level of available workers. (Supervisors try to match more motivated workers with difficult loads.)

The result is that, with respect to travel distances, supervisors use a First-Come, First-Served (FCFS) policy. The FCFS policy is especially common among end-of-line terminals, because they must move freight quickly to avoid missing service guarantees, and therefore cannot afford to double handle trailers by parking them in the yard.

For FCFS scheduling, the flows through each strip door tend, over time, to resemble the aggregate flows through the terminal. For example, if 12% of the monthly freight passing through the terminal is bound for Miami, then about 12% of the monthly freight passing through any strip door will be bound for Miami. Accordingly, we model each incoming trailer as an "average trailer," which contains a shipment for each destination j with weight w_j, where w_j is the average weight of freight bound for destination j per incoming trailer during some historical period (typically one month).

3 A cost model

We estimate the cost in man-hours of moving freight from strip doors to stack doors. The two main costs in our model are worker travel-time and worker waiting-time due to congestion.

3.1 Travel time

Let f_{ijm} represent the weight of freight flowing between strip trailer i and destination trailer j using material handling system m. Let c_{ijm} be the cost in man-hours to move a pound from trailer i to trailer j using material handling system m. The cost c_{ijm} accounts for the locations of trailers i and j and the travel path and speed of material handling system m. For example, let $m = 1$ represent forklifts; then d_{ij1} should be the round-trip rectilinear distance between trailers i and j (rectilinear because staged freight on the dock generally forces this pattern of travel). Then if s_1 is the average speed of a forklift, and h_1 the average weight per trip carried by a forklift,

$$c_{ij1} = \frac{d_{ij1}}{s_1 h_1},$$

and c_{ij1} has units of man-hours per pound. We include the return trip in the distance d_{ij1} because workers generally unload the same incoming trailer until it is empty.

The total labor cost due to travel is $\sum_{i,j,m} c_{ijm} f_{ijm}$, where the summation is over all incoming trailers i, destination trailers j, and material handling systems m.

3.2 Three types of congestion

3.2.1 Interference among forklifts

When a forklift makes a delivery to a stack door it must turn and manœuver its way in. Since loads are frequently bulky and hard to manipulate, and there is usually freight sitting in the center of the dock, the forklift blocks other forklifts trying to pass by that stack door, as in Figure 2. This phenomenon, which we call *interference*, is most noticeable on docks that are operating close to capacity.

[Figure 2 about here.]

We describe a steady-state congestion model that estimates *average* waiting time due to interference. We model the interference at door j as a single server queue having two types of customers: *delivering* forklifts and *passing* forklifts. Delivering forklifts are "served" at a stack door in time that we model as an exponential random variable with mean $1/\mu$. Passing forklifts require no service at a stack door but must wait to pass until there are no delivering forklifts in front of them in the queue.

Exponential service times match our measurements on the dock and it is consistent with the observation that most deliveries take little time, but occasionally a forklift driver has trouble placing an awkward load, such as a roll of carpet.

Again, based on dock measurements, we assume that delivering forklifts arrive at door j according to a Poisson process with arrival rate λ_j. We determine the arrival rate λ_j by estimating the average number of loads delivered to door j per time.

For example, let $k = 1$ represent forklifts, h_1 the average weight per trip carried by a forklift, and t the average time required to strip a trailer (1.5–2 hours). The total flow into door j is $\sum_i f_{ij1}$. The average arrival rate for delivering forklifts to door j is

$$\lambda_j = \frac{\sum_i f_{ij1}}{h_1 t}.$$

The intensity of flow is itself partly determined by congestion, but this is a second-order effect because a real, operating terminal is approximately correct. In practice, congestion obliges greater labor requirements to realize a certain flow but does not significantly reduce that flow.

We assume that forklifts pass door j according to a Poisson process with rate $\bar{\lambda}_j$, which we compute in a manner similar to the calculation of λ_j. The flow of forklifts passing door j is $2\sum_{i,k} f_{ik1}$, where the summation is over all (i,k) pairs that have flow past door j, and the multiplier 2 accounts for the return trip of each forklift. To determine if an (i,k) pair has flow past door j, we assume that, if a forklift must cross the dock to deliver its load, then it crosses immediately after exiting the strip door. In practice, forklifts cross wherever they can find an aisle in the freight in the center of the dock. Our assumption is reasonable if there is approximately the same number of strip doors on each side of the dock and flow across the dock is balanced. This is usually the case, because designers tend to avoid obvious imbalances, and solutions to our model are also approximately balanced due to approximate symmetry of terminals.

The average arrival rate for passing forklifts at door j is

$$\bar{\lambda}_j = \frac{2\sum_{i,k} f_{ik1}}{h_1 t}.$$

Consider an $M/G/1$ queue with arrival rate $\lambda_j + \bar{\lambda}_j$ and service time distribution

$$S = \begin{cases} X & \text{for a delivering forklift} \\ 0 & \text{for a passing forklift,} \end{cases}$$

where X is an exponential random variable with mean $1/\mu$. The service time distribution S of an arriving forklift f has first moment

$$\begin{aligned} E\{S\} &= E\{S \mid f \text{ requires service}\} \Pr(f \text{ requires service}) + \\ &\quad E\{S \mid f \text{ is passing}\} \Pr(f \text{ is passing}) \\ &= E\{S \mid f \text{ requires service}\} \left(\frac{\lambda_j}{\lambda_j + \bar{\lambda}_j}\right) \\ &= \frac{1}{\mu}\left(\frac{\lambda_j}{\lambda_j + \bar{\lambda}_j}\right), \end{aligned}$$

and second moment

$$\begin{aligned} E\{S^2\} &= E\{S^2 \mid f \text{ requires service}\} \Pr(f \text{ requires service}) + \\ &\quad E\{S^2 \mid f \text{ is passing}\} \Pr(f \text{ is passing}) \end{aligned}$$

$$
\begin{aligned}
&= E\{S^2 \mid f \text{ requires service}\}\left(\frac{\lambda_j}{\lambda_j+\bar{\lambda}_j}\right)\\
&= \frac{2}{\mu^2}\left(\frac{\lambda_j}{\lambda_j+\bar{\lambda}_j}\right).
\end{aligned}
$$

By Little's law and the Pollaczek-Khintchine formula for average waiting time in an $M/G/1$ queue, the expected queue length is

$$
\begin{aligned}
L_j &= \frac{(\lambda_j+\bar{\lambda}_j)^2 E[S^2]}{2(1-(\lambda_j+\bar{\lambda}_j)E[S])}\\
&= \frac{\lambda_j(\lambda_j+\bar{\lambda}_j)}{\mu(\mu-\lambda_j)}.
\end{aligned}
$$

The queue length L_j can be interpreted as the expected man-hours per time spent waiting at door j. To incorporate this expression into the cost model, we compute the total man-hours spent waiting at door j during the average time t to unload an incoming trailer. This gives the expected cost of interference in man-hours:

$$
\frac{t\lambda_j(\lambda_j+\bar{\lambda}_j)}{\mu(\mu-\lambda_j)} = \frac{t\lambda_j^2}{\mu(\mu-\lambda_j)} + \frac{t\lambda_j\bar{\lambda}_j}{\mu(\mu-\lambda_j)}.
$$

The first term in this expression is the fixed cost of waiting for delivering forklifts in front of their destination doors. The second term is the variable cost of delays incurred by passing forklifts. Because the fixed cost is independent of the layout, we incorporate into our cost model only the term expressing variable cost,

$$
\frac{t\lambda_j\bar{\lambda}_j}{\mu(\mu-\lambda_j)},
$$

which is measured in man-hours.

In reality, there are two physical queues in front of a door, one from each direction, as in Figure 2. We chose to model these as a single queue by assuming that delivering forklifts enter service at the door first-come, first-served. In practice, this discipline is only loosely followed, as a matter of driver courtesy. The single-queue model fails to capture the behavior of the physical queues in that passing forklifts could leave a queue in the two-queue physical system earlier than they would in the single-queue model (see Gue 1995 for an example). Nevertheless, we use the single-queue model because the analysis is simpler and our measurements show that it is sufficiently accurate. This is based on experience at a client terminal, which recorded the details of more than 300 forklift cycles (pickup, travel, delivery). Our model had predicted that drivers at this terminal would spend about 21.8% of their time waiting in queues due to congestion; we measured 21.1%.

3.2.2 Dragline congestion

We describe a steady-state model that estimates the average waiting time to transfer all dragline freight from strip trailers to destination trailers.

A worker interacts with the dragline by pulling empty carts off the line and placing full carts on the line. Depending on the number of full and empty carts passing his door, he may have to wait during either of these operations. The flow of full carts passing a door depends on the freight flow from upstream strip doors to downstream stack doors, and on the number of times each cart passes its destination before a worker, called a *linepuller*, removes it from the line.

A worker at strip door i typically places his full cart on the line and then takes an empty cart off the line. We define his total waiting time w_i to be

$$w_i = w_i^{place} + w_i^{pull},$$

where w_i^{place} and w_i^{pull} are the times spent waiting to place the full cart on and pull the empty cart off the line respectively. Let ν_d be the travel rate of the dragline in spaces per time, and ν_{ia} the average rate of all carts passing door i (whether empty or full). Because no door is a net consumer or producer of carts, ν_{ia} is the same for all i, and we let $\nu_{ia} = \nu_a$, for all strip doors.

Let $m = 2$ represent the dragline, h_2 the average weight per trip carried by a cart on the dragline, and t the average time to unload an incoming trailer. The average rate $\bar{\nu}_i$ at which full carts pass door i on the dragline is

$$\bar{\nu}_i = \frac{1}{h_2 t} \left(u \sum_q \sum_r f_{qr2} + \sum_{q<i} \sum_{r>i} f_{qr2} \right), \tag{1}$$

where u is the average number of times a cart passes its destination door without being removed by the linepuller, and t is the average time required to unload a trailer. (The inequalities $q < i$ and $r > i$ reflect the circular ordering determined by a unidirectional dragline.) The first term is the fixed flow past door i due to the linepuller's inability to pull every cart at its destination door the first time it arrives there; the second term is the variable flow due to the layout.

Consider a worker at strip door i waiting to place a cart in an empty space. The time for a cart to circumnavigate the dragline is significantly longer than the time a worker spends waiting for a cart. Therefore we can ignore as unlikely the situation in which a worker sees the same dragline spaces repeatedly; and so we may reasonably treat the stream of carts passing door i as probabilistic. For each dragline space that passes, the worker finds

- an empty cart, with probability $p_e = (\nu_a - \bar{\nu}_i)/\nu_d$,
- a full cart, with probability $p_f = \bar{\nu}_i/\nu_d$, or
- an empty space, with probability $p_s = (\nu_d - \nu_a)/\nu_d$.

We view each space that passes as a Bernoulli trial with parameter p_s, and model the worker's waiting time with a geometric random variable W_s having parameter p_s. The waiting time per space is then $1/\nu_d$, and the expected waiting time to place a full cart in an empty space is

$$w_i^{place} = E\{W_s\}\frac{1}{\nu_d} = \frac{1}{p_s \nu_d} = \frac{1}{\nu_d - \nu_a}. \tag{2}$$

After placing the full cart on the line, the worker must wait for an empty cart, instead of an empty space. We model this waiting time with a geometric random variable W_e having parameter p_e. The expected waiting time to pull an empty cart is

$$w_i^{pull} = E\{W_e\}\frac{1}{\nu_d} = \frac{1}{p_e \nu_d} = \frac{1}{\nu_a - \bar{\nu}_i}. \tag{3}$$

Combining equations 2 and 3,

$$w_i = \frac{1}{\nu_d - \nu_a} + \frac{1}{\nu_a - \bar{\nu}_i}.$$

As we should expect, if $\nu_a \to \nu_d$, waiting time increases because there are few empty spaces and the worker must wait to place a full cart on the line. If

$\bar{\nu}_i \rightarrow \nu_a$, waiting time increases because there are few empty carts passing and the worker must wait a long time to find an empty cart.

While unloading an incoming trailer in strip door i, a worker makes approximately $n_i = \sum_j \lceil f_{ij2}/h_2 \rceil$ trips to the dragline during which he waits for time $n_i w_i$. In practice, it is more common that workers have difficulty finding an empty cart than an empty space on the line, because empty spaces are controlled, for the most part, by the total number of carts the supervisor allows on the dock. The number of empty carts passing by a door depends on the total number of carts and the layout. Because the layout affects only waiting for an empty cart, we add to the cost model

$$\frac{n_i}{\nu_a - \bar{\nu}_i}.$$

We can add this term directly because it has the same units (man-hours) as travel cost.

Note that if the linepuller is very inefficient (for example, if $u \geq 2$), then the fixed term in equation 1 dominates the variable flow term. However, because of the nonlinear relationship between $\bar{\nu}_i$ and b_i, the variable flow (that due to the layout) still affects waiting time. Therefore, the model suggests that layout is important in reducing dragline congestion, even if the linepuller is inefficient.

3.2.3 Congested floor space

Sometimes workers cannot load a shipment directly into a stack door, but must park it temporarily on the floor nearby. Workers may *dock freight* because

- A different type of freight is needed to achieve a tight packing of the trailer; or
- the freight must wait for companion items to maintain shipment integrity; or
- it will not fit because the trailer is too close to weight or volume limits and so it must wait for the next trailer.

Docking freight is undesirable because that freight must be double-handled. Furthermore, accumulated freight aggravates forklift congestion by creating bottlenecks in front of stack doors with high levels of flow.

We adopt the industry metaphor that describes crowded floor space as having high *pressure*. Let the *force* $F_j = \sum_{i,m} f_{i,j,m}$ on the door j be the total freight flow bound for destination j, and let the area A_j be the area in front of door j when the dock is partitioned by a Voronoi diagram based on the centroids of the doors, as in Figure 3.

[Figure 3 about here.]

Define the *pressure* P_j at door j to be $P_j = F_j / A_j$, so that doors with high flow and small floor space have high pressure. Now we can control door pressure and so constrain the set of allowable layouts by requiring that for all stack doors j, P_j is within acceptable bounds.

3.3 Solution procedure

We construct an effective layout by a simulated annealing procedure that interchanges pairs of trailers: Imagine each door as being occupied by an abstract strip or destination trailer. By changing the positions of those trailers, we change the designations of their doors; and we use our cost models to evaluate the resulting layout. We choose this method of solution for three reasons:

- The nonlinearity of the objective function precludes the use of established integer programming methods.
- Pairwise interchange allows the user to easily enforce ad hoc restrictions, such as requiring that a particular destination be assigned to a particular door or that certain doors be grouped together.
- Local search confers flexibility. It has been essential to our success that the user be able to adjust a design incrementally.

We construct an initial layout by assigning doors based simply on travel distance; and then we refine that layout with simulated annealing, evaluating each change by the total cost, including congestion.

Initially we assign strip trailers and the highest-flow destination trailers to the "best" doors. We do this by sorting destination trailers from greatest to least flow and then merging this list with a list of the strip trailers, alternating, to produce a list of the form `[destination trailer of greatest flow, strip trailer, destination trailer of next greatest flow, strip trailer, ...and so on]`. Then we sort all doors according to the sum of rectilinear distances to all other doors, from smallest sum to largest. Finally, we repeatedly assign the next trailer on the list to the next door. The result is a reasonably good layout with regard to total weighted distance.

Our implementation of simulated annealing uses the cooling schedule of Connolly (1990) as modified by Paulli (1993), who reports excellent results for quadratic assignment problems (QAPs), which are similar in structure to our problem. Connolly also reports that a local search routine that swaps pairs sequentially — as in our algorithm — is superior to one that swaps randomly for the QAP.

4 Characteristics of efficient layouts

In the LTL industry layouts are constructed by intuition and experience, not, up to now, by analytical models. We have applied our model to nine LTL terminals, and here describe how our layouts have differed from current practice.

4.1 Current practice

Layouts in the industry generally group strip doors and stack doors independently. Strip doors are usually located in groups near the center of the dock, because managers believe that this minimizes travel distances. Stack doors are often grouped logically, such as by geographic region or by required departure time. A typical industry layout is given in Figure 4.

[Figure 4 about here.]

The problems are several:

- High-flow stack doors are concentrated in the corners, which contributes to floor space congestion.
- There is no opportunity to cross-dock freight, because strip doors are opposite strip doors.
- High-flow stack doors are next to one another, leading to forklift congestion.

4.2 What our layouts look like

Layouts based on our interference model, as in Figure 5, concentrate activity in the center of the dock, but, as expected, not "too much," especially when flow intensities are high.

[Figure 5 about here.]

Another characteristic of our solutions is that the highest-flow regions on either side in the center are slightly offset. This improves efficiency in two ways: First, it reduces congestion in the center of the dock; and second it supports crossdocking.

A third recognizable feature of our solutions is that the corners of the terminal tend to be occupied by stack doors of little activity. This makes sense because we can be sure such doors will have light flow of freight, while a strip door might experience high freight flows, depending on what trailer is parked there; and a busy stack door will certainly have high freight flows. Placing low-flow doors in the corners also reduces floor space congestion.

In practice terminal managers concentrate on reducing forklift travel because forklifts are an expensive resource and often in short supply; but, in our experience, they frequently miss opportunities to reduce labor costs associated with the dragline.

A common problem among terminals with draglines is having to shut down the line and clear it of carts when it reaches saturation, thus wasting labor and interrupting the continuity of operations. Figure 6 shows the layout of a terminal containing a dragline operated by the former Carolina Freight Carriers.

[Figure 6 about here.]

This displays some of the problems of the terminal of Figure 4; but in addition, this layout wastes dragline capacity because of the concentration of strip doors in two places. The effect is that upstream strip doors take all the empty carts and then fill all the empty spaces on the dragline so that downstream strip doors are underserved.

For this terminal our model produced the layout of Figure 7. Here the large groups of strip doors have been broken up by inserting high-flow stack doors among them, thus balancing the flow of carts passing by the strip doors. This results in an estimated 12% reduction in labor costs due to travel and waiting.

[Figure 7 about here.]

Finally, we observe the following result, which helps explain the tendency of our layouts to concentrate activity unimodally in the center of a terminal.

Theorem 1 *A layout that minimizes the sum of weighted distances has stack doors arranged unimodally with respect to their flows.*

Proof Suppose there exists an optimal layout with door flows not unimodal on a side. Then there are stack doors i, j, and k on one side of the dock containing trailers a, b, and c respectively, such that $f_a > f_b < f_c$. Divide the dock into four regions, numbered 1 through 4, separated by lines drawn across the dock through doors a, b, and c. Assign a trailer directly across from a, b, or c (through which a line was drawn) to either of the two possible regions arbitrarily. Let S_i denote the set of strip doors in region i, and let d_{jk} denote the rectilinear distance between door j and door k.

Consider the interchange of destination trailers a and b. The change in flow cost ΔC_{ab} is

$$\begin{aligned}\Delta C_{ab} &= \sum_{r\in S_1}(d_{ri}(f_b-f_a)+d_{rj}(f_a-f_b))+\sum_{r\in S_2}(d_{ri}(f_b-f_a)+d_{rj}(f_a-f_b))\\ &\quad +\sum_{r\in S_3}(d_{ri}(f_b-f_a)+d_{rj}(f_a-f_b))+\sum_{r\in S_4}(d_{ri}(f_b-f_a)+d_{rj}(f_a-f_b))\\ &= -|S_1|d_{ij}(f_b-f_a)+\sum_{r\in S_2}(d_{ri}(f_b-f_a)+d_{rj}(f_a-f_b))\\ &\quad +|S_3|d_{ij}(f_b-f_a)+|S_4|d_{ij}(f_b-f_a)\\ &\leq (-|S_1|+|S_2|+|S_3|+|S_4|)d_{ij}(f_b-f_a)\end{aligned}$$

Since the layout is optimal, $\Delta C_{ab} \geq 0$ and $f_b - f_a < 0$ implies

$$-|S_1|+|S_2|+|S_3|+|S_4| \leq 0.$$

An identical argument for ΔC_{bc} yields

$$|S_1|+|S_2|+|S_3|-|S_4| \leq 0.$$

This implies $2(|S_2|+|S_3|)=0$ and so $|S_2|=|S_3|=0$, and $|S_1|=|S_4|$. But an equal number of strip doors on either side of the group of stack doors i, j and k with no strip doors in between means that we can swap the trailers in those doors without changing the cost; or else the solution is not optimal, a contradiction. □

5 Implementation at a Viking terminal

Viking Freight System is one of the largest regional carriers in the West, operating nearly 50 terminals spread over a dozen western states. The Viking terminal in Stockton, California serves as both a breakbulk and an end-of-line terminal. As an end-of-line terminal, the outbound operation runs from about 1600h to 2200h each evening, when freight arrives from local pickup and might be delivered to any door on the dock. The outbound operation shuts down at

2200h as activity picks up for the breakbulk operation, which runs to about 0200h.

Initially, Stockton ran the end-of-line and breakbulk operations on different ends of the dock, as shown in Figure 8. Trailers arriving from local pickup during the day were assigned to doors at one end of the terminal, unless they contained an unusually large load for a breakbulk destination.

[Figure 8 about here.]

To reduce travel distances, we superimposed the outbound and breakbulk docks onto the same set of doors, such that outbound destinations would become strip doors after their activity ceased. This meant that our program had to make an additional tradeoff: One destination trailer might have a stronger claim to convenient location during breakbulk operations but another might have a stronger claim during outbound operations. Which should get the convenient location?

We handled this by generating two layouts simultaneously, one for the outbound operation (before 2200h) and one for the breakbulk operation (after 2200h), required them to remain consistent, and modified our search procedure to respect this consistency.

Another complication was that the freight mix on arriving trailers was highly inhomogeneous, with each trailer containing one of four distinct freight mixes. Trailers arriving from local P&D runs contained freight for all destinations; but incoming breakbulk trailers arrived in three varieties corresponding to their origin terminals: Rocky Mountain trailers contained only freight for Central California destinations, Central California trailers contained only freight for Rocky Mountain destinations, and other trailers contained freight for any breakbulk destination. We modeled this by creating (in software) the appropriate number of each type of trailer such that the total breakbulk freight on the dock was a scaled representation of the breakbulk freight handled in an average shift. Each trailer was assumed to contain the average mix of freight typical of its type.

5.1 Implementation and results

Figure 9 shows the two layouts developed by our model (subsequent to slight adjustments by terminal managers). The flows in the figures reflect only the flows received during the respective operation, before 2200h and after; and doors corresponding to outbound points in the outbound layout become strip doors in the breakbulk layout. The logic of the layout is perhaps not obvious because the model is balancing so many objectives: different flow values for each destination during the two operations, the conversion of some doors from stack to strip, and localized flows in the breakbulk layout. Nevertheless, one can observe centralization of activity, interspersed strip and stack doors, and crossdocking.

[Figure 9 about here.]

In addition, the breakbulk layout forms regions of localized flow, with Central California destinations located toward one end, and Rocky Mountain destinations at the other.

Our cost models predicted a 49% reduction in labor cost due to travel. An internal study at Viking (Hein, 1999) indicates that travel is typically 20% of total labor cost, which leads to predicted total labor cost savings of about 10%. To test our prediction, we recorded Stockton's existing performance metric for one month before and three months after implementation (see Figure 10).

[Figure 10 about here.]

Viking's performance metric is based on work sampling and time studies that account for the quantity and types of freight crossing the dock and the man-hours used. Each night, managers enter into the model freight characteristics, such as number of pallets, pounds of carton freight, and so on, and the model returns the "standard labor hours" allowed. The performance measure is simply actual labor hours divided by standard hours.

According to Stockton's measurements, labor productivity increased 11.7% after implementing our layout, which corresponds to an annual labor cost savings of approximately $67,000. The savings are more impressive when one considers that we affected only half of Stockton's dock costs (the outbound operation), and Stockton is only 1 of 48 terminals in the Viking system.

In addition to cost savings, managers in Stockton realized several unexpected benefits with the new layout. There was a noticeable improvement in seal times each night, and this led to better service to other terminals and reduced costs for linehaul drivers otherwise delayed because their trailers were not ready. The terminal manager stated that workload for hostlers (drivers who move trailers between the dock and the yard) went down dramatically because the dock is effectively smaller. He also stated that because activity on the dock is more concentrated than before, supervisors have been much more effective, leading to improved safety performance, noticeably fewer damage claims, and greater adherence to procedures.

6 Conclusions

Changing the layout of a terminal is a simple way to reduce labor costs without investing in new systems or worker training. Benefits accrue immediately, as workers spend less time traveling the moment they step onto the dock. And because it is expensive to handle freight, even a small percentage reduction in labor cost at the terminals can have a significant effect on profits.

Our models reduce labor costs by properly balancing travel distances and congestion. We have shown that accounting for congestion can significantly improve the performance of a terminal — and it is easy to reap this benefit. All that is required is to change the designations of the terminal doors.

Finally, an immediately useful product of our models is the following list of guidelines for efficient layouts.

- Intersperse high-flow stack doors with strip doors in the center of the dock to reduce both travel time and congestion.
- Slightly offset high-flow sections in the center to reduce congestion and promote crossdocking.

- Put strip doors opposite busy stack doors to enable crossdocking and efficient use of forklifts.
- Put the least busy doors in the corners to avoid congestion due to docked freight.
- Locate doors to balance the dragline and so increase its effective capacity.
- Establish regions of localized flow when trailers have different types of freight mixes.

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List of Figures

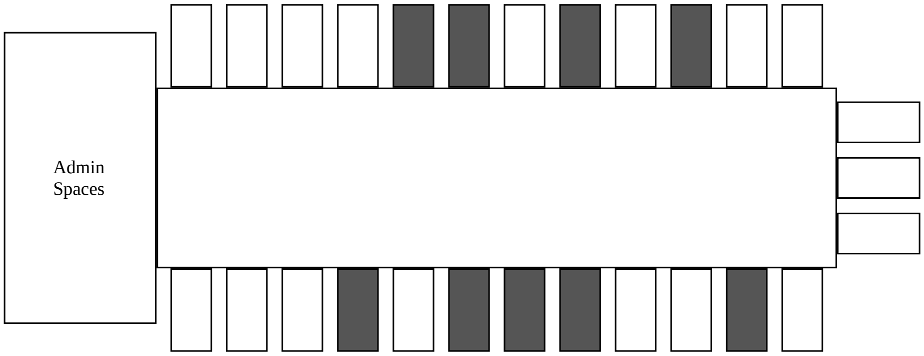

Figure 1: A typical LTL crossdock. Shaded rectangles represent trailers to be unloaded; clear rectangles represent destination trailers to be filled.

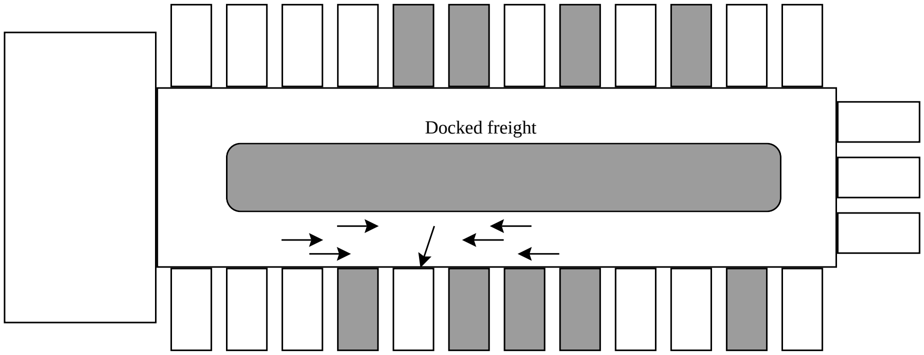

Figure 2: A forklift impeding others as it manœuvers its load into a trailer.

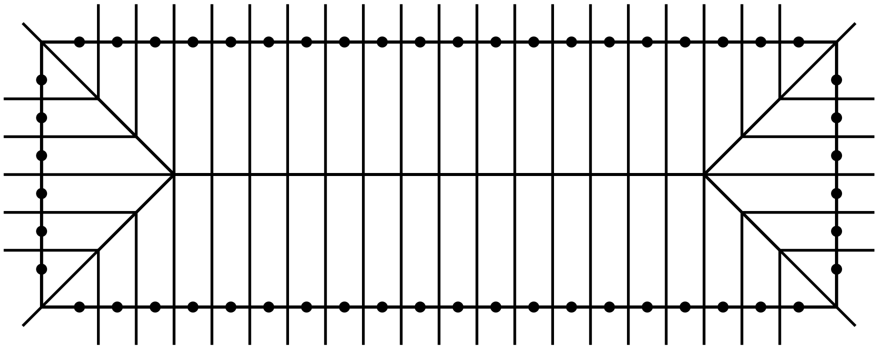

Figure 3: Partition of the dock according to which door is closest. Doors in the corner of a terminal have less space in which to dock freight.

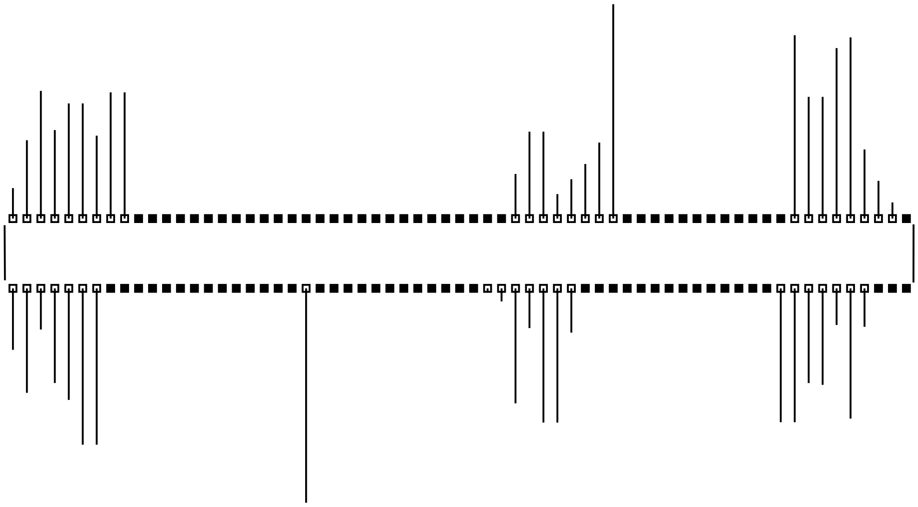

Figure 4: A layout designed by engineers at the Southeastern Atlanta terminal. (Lines extending from the stack doors represent the relative flows to those doors.)

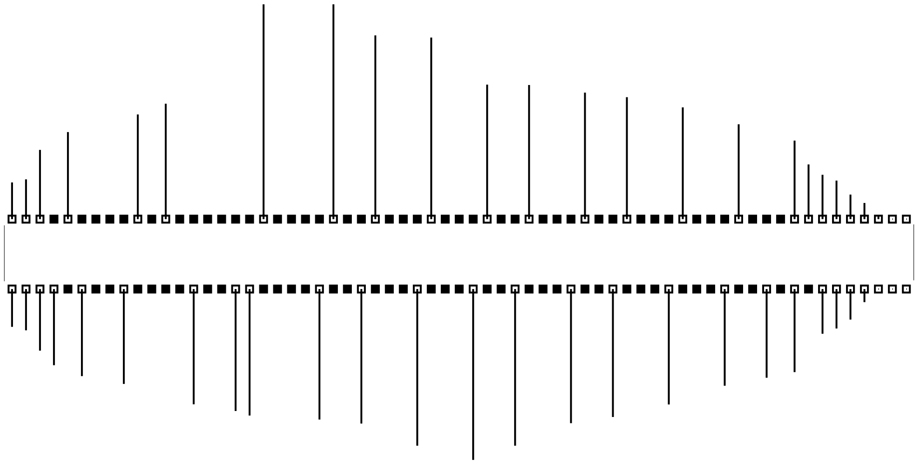

Figure 5: A typical layout produced by our model, in this case for Southeastern Freight Lines, Atlanta terminal.

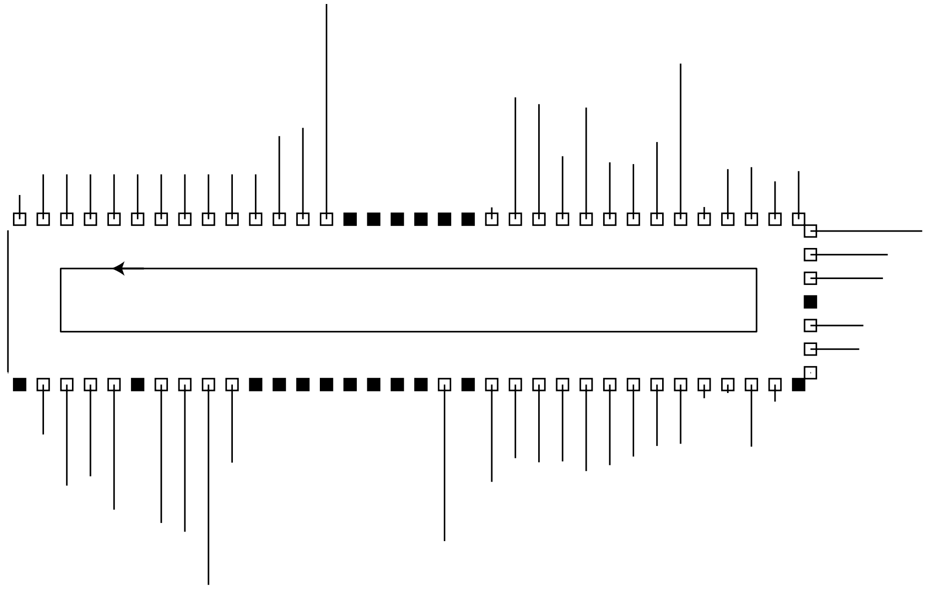

Figure 6: The layout of the Carolina Freight terminal near Atlanta.

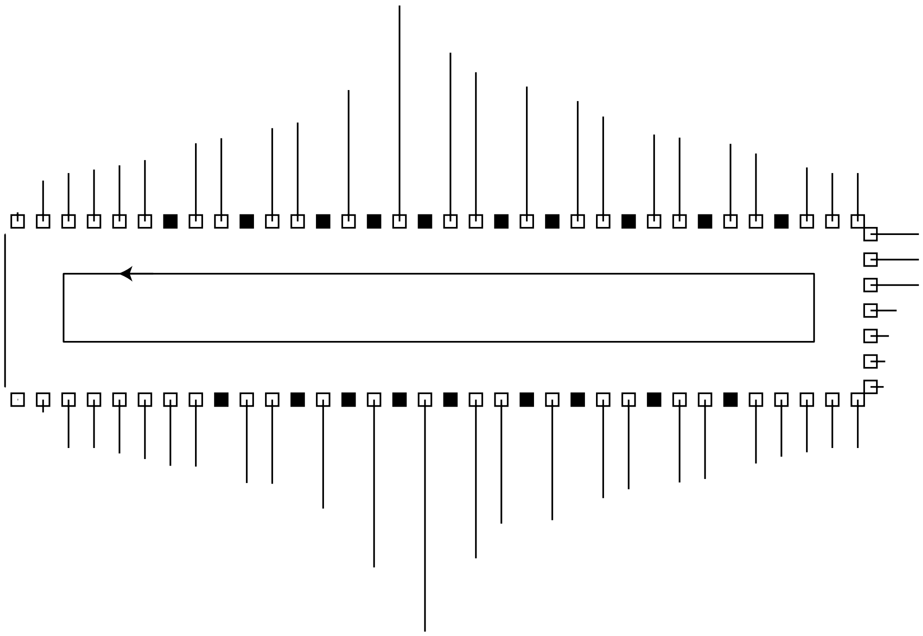

Figure 7: A layout that improves dragline capacity.

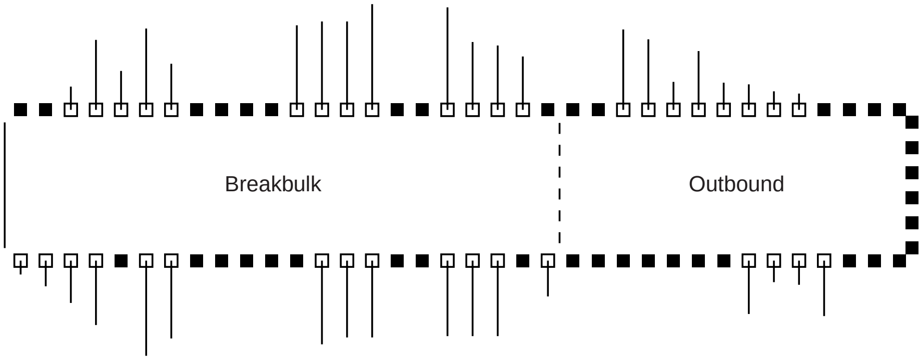

Figure 8: Stockton terminal before the implementation.

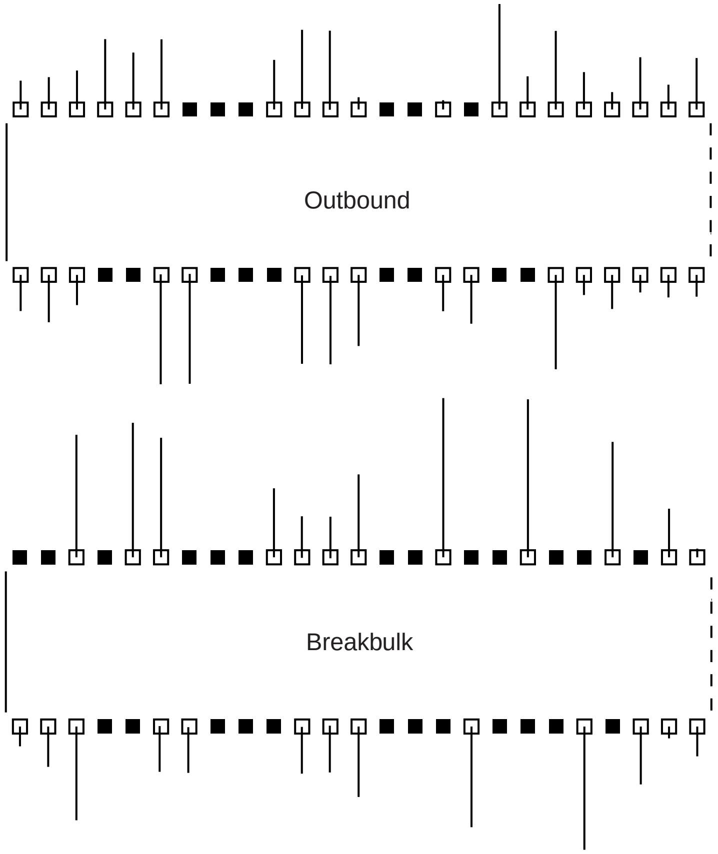

Figure 9: Stockton outbound and breakbulk layouts after the implementation.

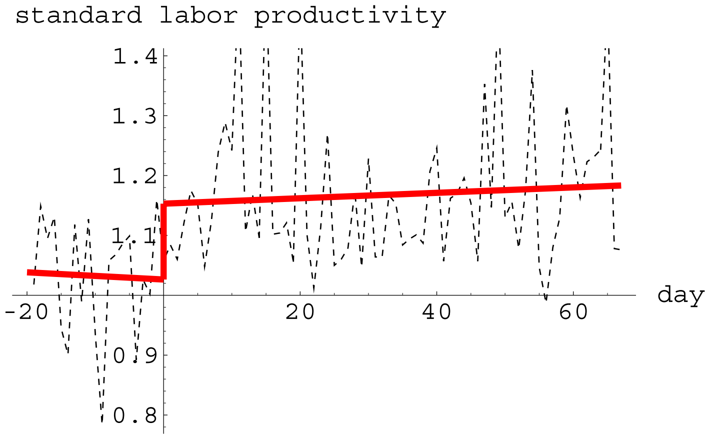

Figure 10: Performance of the Stockton terminal before and after implementation of the layout suggested by our model. Average performance after the implementation is 11.7% greater than before.