The Best Shape for a Crossdock

John J. Bartholdi, III
The Logistics Institute
School of Industrial & Systems Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0205
`john.bartholdi@isye.gatech.edu`

Kevin R. Gue
Graduate School of Business & Public Policy
Naval Postgraduate School
Monterey, CA 93943
`kevin.gue@nps.navy.mil`

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Abstract

Within both retail distribution and less-than-truckload transportation networks crossdocks vary greatly in shape. Docks in the shape of an I, L, or T are most common, but unusual ones may be found, including those in the shape of a U, H, or E. Is there a best shape? We show that the answer depends on the size of the facility and on the pattern of freight flows inside. Our results suggest that many large crossdocks in practice suffer from poor design that increases labor costs on the dock.

Crossdocking

Of the four major functions of warehousing — receiving, storage, order picking, and shipping — the middle two are typically the most costly: storage because of inventory holding costs, and order picking because it is labor-intensive. Crossdocking is a logistics technique that eliminates the storage and order picking functions of a warehouse while still allowing it to serve its receiving and shipping functions. The idea is to transfer shipments directly from inbound to outbound trailers without storage in between. Shipments typically spend less than 24 hours in a crossdock, sometimes less than an hour.

Crossdocking is an important logistics strategy for many firms in the retail, grocery, and other distribution industries. Stalk et al. (1992) report that the retailer Wal-Mart considers crossdocking a core capability, and that the practice was a major reason it surpassed its competitor K-Mart in total sales in the 1980s. Because Wal-Mart was able to reduce total system inventory with crossdocking, it could offer the "everyday low price" for which it is now famous. In the grocery industry, crossdocking has allowed firms to reduce inventories and transportation costs in the midst of fierce price competition. Crossdocking is also a mainstay practice of less-than-truckload (LTL) trucking firms, which seek to consolidate shipments to achieve transportation economies.

Advanced information systems and improved supply chain coördination have drastically lowered transaction costs, which until now have been the traditional justification for large order quantities and higher inventory levels. Lower transaction costs, in turn, have led to smaller shipment sizes and a need to consolidate to regain transportation economies.

For example, Home Depot operates a crossdock in Philadelphia that serves more than 100 stores in the Northeast. Home Depot's culture allows store managers a great deal of autonomy with regard to product selection, inventory levels, and so on. In the past, each store ordered from vendors separately, and orders were sent in LTL shipments directly to the stores. Home Depot now uses crossdocking to reduce costs from the vendor by consolidating orders among its stores and ordering in truckload quantities from vendors.

Here is how the new system works: Each of the 100+ stores places orders for each vendor on a specific day of the week. The vendor consolidates all orders and sends truckloads of product to the crossdock in Philadephia. There, workers transfer products to trailers bound for individual stores (or 2 stores on a few multi-stop routes), so that outbound trailers contain products for very few stores from many vendors. Transportation costs are lower because shipments into and out of the crossdock are in truckload quantities.

Crossdocking is economical as long as handling costs do not overwhelm transportation and inventory savings, and it is handling costs that we address. Material handling in a crossdock is labor intensive for at least three reasons. First, freight is often oddly shaped (particularly in the LTL industry), so automation is difficult. Second, even in retail crossdocking where freight is more uniform, automated material handling systems are not as flexible as a labor force with respect to costs and throughput. Flexibility is especially important for retail firms because they often suffer severe seasonalities. Third, automation requires a huge fixed cost, which many firms are reluctant to incur.

Labor costs in a crossdock depend on the assignment of trailers to doors (the layout), the mix of freight flowing through the facility, available material handling systems, how arriving trailers are scheduled into doors, and the shape of the facility. Layout and material handling systems for crossdocking have been addressed by Peck (1983), Tsui and Chang (1990, 1992), and Bartholdi and Gue (2000). Gue (1999) reports on the effects of scheduling trailers into doors on the layout of a crossdock. In this paper, we study how the shape of crossdocks affects labor costs.

Some work has been reported on the related problem of the best shape for an airport terminal. Research in airport design is driven by the two categories of passengers: arriving-or-departing passengers, who travel between a gate and the entry point of the terminal, and transferring passengers, who travel from gate to gate. de Neufville and Rusconi-Clerici (1978) argue that pier-finger designs, in which a terminal has two or more piers extending from it, are appropriate when the percentage of transferring passengers exceeds about 30%. Robusté (1991) and Robusté and Daganzo (1991) describe geometric relationships for airport terminals, and show that optimal shapes with respect to walking distance depend on the proportion of each type of customer the airport serves. Robusté and Daganzo (1991) show that for large terminals with transferring passengers only — the case most analogous to a crossdock — the best design is a closed loop with equally long radial piers extending from its exterior, which the authors call a "sun" design. BANDARA and WIRASINGHE (1992) point out that, by design, transferring passengers tend to connect to another flight of the same airline and that flight is likely to be at a gate in the same pier as arrival, or at least nearby.

Crossdock design differs from airport design in a number of ways: First, almost all freight in a crossdock is transshipment freight, which is analogous to transferring passengers. Almost no freight begins or ends its travel at a crossdock as an arriving-or-departing passenger might do at an airport. Second, airport models minimize total distance between all pairs of gates (for transferring passengers) or gates and the terminal (for arriving-or-departing passengers) and therefore they implicitly assume comparable passenger activity at all gates. This is a reasonable assumption for airports because each gate hosts planes arriving from many origins and departing to many destinations over the course of a day. As a result, passenger flow tends to be more evenly distributed than in a crossdock, where it is typical for doors to be permanently assigned to either receiving or shipping; and for shipping doors to be permanently assigned to destinations. Furthermore, the material flows to particular shipping doors vary widely, typically by a factor of 2–10. Third, because of wingspan of the planes, gates at an airport are much further apart than are doors at a crossdock. As a result, floor congestion in front of the gate is less a problem than is floor congestion on a crossdock. Finally, and perhaps most significantly, inefficiencies in an airport are inflicted upon passengers, not upon the operating authority. In a crossdock, inefficiencies directly increase operating costs.

It is also worth remarking that the crossdocking facilities we consider face a different set of problems than package-handling terminals such as those of UPS or FedEx. Package-handling terminals restrict their business to packages of uniform size and weight to enable extensive use of conveyors. Consequently, in package-handling terminals, labor costs are not a direct function of travel between doors.

In the following section we discuss fundamental issues in crossdock design and our observations on current practice. Section 2 describes the methodology we use to evaluate different shapes. We report the results of our experiment in Section 3, and present conclusions in Section 4.

1 Crossdock design

Because crossdocking is a relatively new practice in the retail and distribution industries, the LTL trucking industry still operates most of the crossdocks in the United States. Code (2000) reports that there are more than 10,000 crossdocks in the United States and Canada. Most crossdocks are long, narrow rectangles (I-shape) but we have also seen crossdocks shaped like an L (Yellow Transportation, Chicago Ridge, IL), U (Consolidated Freightways, Portland, OR), T (American Freightways, Atlanta, GA), H (Central Freight, Dallas, TX), and E (unknown owner, Chicago). How can one account for this variety? Which shape is best?

Firms acquire their crossdocks in a variety of ways and do not always have the luxury of building new ones. If they lease or convert an existing facility they may be heir to someone else's bad design. Even if they design new facilities, the lead designers are likely to be civil engineering or commercial real estate firms, which are experts in topics like ingress and egress from the facility, parking lot construction, and building codes; but they are not likely to pay close attention to internal performance measures like travel cost or congestion.

Sometimes the dock shape is determined by simple constraints such as the size and shape of the lot on which it will stand. Commercial real estate in the most desirable locations is often very expensive or hard to find, forcing a distribution firm to trade off location for lot size and shape. Engineers at Yellow Transportation report that some of their L- and T-shape crossdocks were constructed to accommodate lot restrictions (Hammeke, 2000). Other issues complicate the placement of a crossdock on a lot, such as parking requirements, the turning radius of trucks, and the need for office or maintenance buildings. All these issues force compromises in the design of a crossdock. However, we ignore these particular complications to focus here on a single issue, shape, and how it affects crossdock performance.

We shall measure the performance of crossdock shapes by estimating the total travel between doors according to two models of work. The first is the simplest and most conservative: It looks only at the distances between doors. In particular, it assumes nothing about which trailers are parked at which doors nor anything about the intensities of freight flows. While only approximate, this nevertheless provides a general way of evaluating a dock; and in particular it can reveal regions of a dock that might create travel inefficiencies for freight that is unloaded or loaded at those doors. (This method is similar to that used to evaluate alternative designs for airports as cited above.)

The more detailed evaluation assumes a typical pattern of freight flows, then assigns trailers to doors to minimize travel, and then reports the total travel required.

1.1 Number of doors

The first design decision and the most important fact about a crossdock is the total number of doors, of which there are two types: *receiving* doors (also called strip or breakout doors) and *shipping* (or load) doors.

The number of shipping doors is relatively easy to determine because the firm usually knows how many destinations the crossdock must serve. If each destination requires one door, then the number of shipping doors equals the number of destinations. A high-flow destination may require more than one door in order to provide sufficient "bandwidth" to the destination. (The extreme in our experience is a crossdock in Dallas that allocates 10 doors to Houston to accommodate the 25–30 trailers of freight bound there every night.)

There are more issues involved in determining the number of receiving doors. In some retail crossdocks one side of the facility is devoted to receiving doors and the opposite side to shipping doors, and their numbers are equal. This configuration supports orderly staging of pallets and value-added processing, such as packaging, pricing or labeling. For LTL crossdocks, which generally do no value-added processing, Little's law provides a simple way to estimate the number of receiving doors by multiplying the required throughput of trailers by the average time to unload a trailer. At the LTL carrier Yellow Transportation, the average crossdock (hub, not end-of-line satellite terminal) has about 180 doors and ranges in size from 63 to 300 doors. The percentage of receiving doors ranges between 21–67 percent (Trussell, 2001).

To reduce footprint, crossdocks place doors as close together as possible while accounting for safety in backing trailers to the door. As a result, on most docks the doors are equally spaced and generally with a 12-foot offset. Consequently, it is common for the size of a dock to be summarized simply by giving the number of doors. We adopt this convention here.

1.2 Why the I?

Short, across-the-dock travel is important because crossdocking operations are labor-intensive and most of the variable cost of labor is devoted to travel between doors. Accordingly, most smaller crossdocks are I-shaped, because this design offers the chance to move freight directly across the dock from receiving door to shipping door.

1.2.1 The most convenient doors

There are several ways to measure the convenience of a door. The simplest and most conservative is to compute the average distance to all other doors on the dock. It is easy to see that by this measure doors in the center of an I-shaped dock are the most convenient; and this measure of convenience decreases linearly from the center doors to the doors at each end of the dock. The doors at the very ends of the dock have, like all other doors, a few close neighbors to either side; but the more distant doors are quite far away, at the opposite end of the dock. For convenience, we will say that the door with smallest average distance to all other doors is the "best door," because it is the one to/from which freight can be expected to move with least travel.

1.2.2 The economics of travel make docks narrow

Distribution managers prefer narrow docks because they reduce labor costs. Their intuition seems to be based on idealized freight flows in which product is conveyed directly across the dock; but in the docks we visited this "straight across the dock" travel constituted a surprisingly small fraction of total travel, less than half. Instead, the majority of the the distance traveled by freight is along the length of the dock. Nevertheless, despite the questionable intuition, the conclusion is correct:

Observation 1. *For a given number of doors, a narrower dock realizes a smaller average distance between doors.*

See Appendix A for a proof.

1.2.3 The minimum width of a dock

Crossdocks are impelled to be narrow by considerations of travel distance and therefore labor cost; but a minimum width is determined by the need to stage freight, especially in front of shipping doors. Freight must be staged because it does not arrive at the outgoing trailer in the sequence in which it must be loaded. The loading sequence may be determined by several factors, including the needs

- To build tightly-packed loads;
- To place fragile freight on top;
- To load in reverse order of delivery for multiple stops;
- To build "nose loads", so that the freight at the front of the trailer does not need to be sorted at intermediate crossdocks.

If there is too little staging area the dock becomes congested and throughput decreases. This is especially problematic when a company is growing or is at a seasonal sales peak. Consequently it is standard practice to reserve space directly in front of each door to dock freight for that door. The amount of space in front of each door, and therefore the width of the dock, depends on the estimated need to dock freight, which in turn depends on the freight mix, number of stops per trailer, amount of palletized freight, and so on. Consequently the appropriate dock width is, to some extent, particular to the operation. In our experience, crossdocks in the LTL trucking industry are 60–120 feet wide, which is equivalent to 5–10 door-widths. (Retail crossdocks are sometimes wider to allow for value-added processing.) The 5–10 door-widths rule is so common in practice that we assume that this dimension has been determined, is small and remains fixed throughout the remainder of the discussion.

Because the width is small and fixed, the efficiency of an I-shape is determined by its longer dimension:

Definition 1. *The* diameter *of a crossdock is the largest distance between any pair of doors.*

1.2.4 "Growing" the dock

We are interested in how the economics of travel across the dock change as the dock size (number of doors) increases.

The problem with the I-shape is that it loses efficiency as the number of doors increases because the diameter increases quickly. This means that some freight might have to travel quite far from arriving trailer to departing trailer. For example, on a dock of 250 doors, the distance between opposite ends of an I-shaped crossdock is almost one quarter-mile.

We can measure this tendency as follows: For I-shaped docks, adding four additional doors (two to each end) increases the diameter of the dock by two door offsets, so the rate of growth of the diameter is $4/2 = 2$ doors per door offset.

Definition 2. *The* centrality *of a crossdock is the number of doors required to increase its diameter by one door offset.*

A large value of centrality is good because the maximum travel distance does not grow too quickly as the number of doors increases.

1.3 Alternative shapes

It is to avoid such deterioration in efficiency for larger docks that other designs, such as T, or H, have been considered. These designs differ from the standard I-shape in having greater centrality, so the farthest doors are not as distant as for an I; but they achieve this at the cost of additional corners — and, as we shall show, corners reduce the labor efficiency of a crossdock.

We distinguish between inside corners and outside corners, because each incurs a different kind of cost. An inside corner, such as shown in Figure 1, renders some doors unusable because it would be unsafe or impossible for trailers to use them. For standard 48-foot trailers parked at a dock with 12-foot door offsets, at least $48/12 = 4$ doors on each side of an interior angle are unusable; and, for the sake of safety, in practice this number is generally chosen to be more conservative, 4–6. Therefore, for each inside corner a dock must have 8–12 *additional* door positions to offer the same number of *usable* doors. This increases the size of the dock and so the total travel time to move freight across the dock.

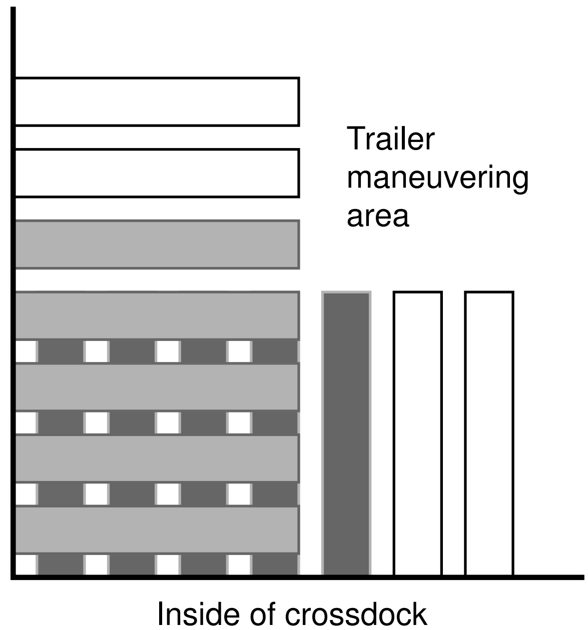

Figure 1: An inside corner constricts parking space for trailers and so makes some door positions unusable (marked in light and dark gray). As a result a dock with an inside corner must be larger to provide the desired number of usable doors.

In L, T, H, and X-shapes the inside corners are particularly wasteful because they are near the center of the dock and so the door positions that are rendered unusable are among the most centrally located. These are exactly the doors that one wants most to use, because they have many near neighbors and so create opportunities to reduce travel across the dock.

An outside corner exacts a different cost: Doors around an outside corner have less floor space available to dock freight and therefore are more susceptible to congestion within the dock. This may be seen in Figure 2, where a Voronoi diagram partitions the dock into (mostly) uniform shares of floor space. This is a natural way of assigning floor space to doors for the docking of freight. As suggested by Figure 2, it is easy to confirm the following.

Observation 2. *If a dock is w door positions wide then each outside corner loses $w/2$ doors' worth of floor space.*

We can conclude that for a typical crossdock (six doors wide, hosting 48-foot trailers, with doors at 12-foot offsets) each outside corner forfeits 3 shares of floor space and each inside corner forfeits at least 8 door positions.

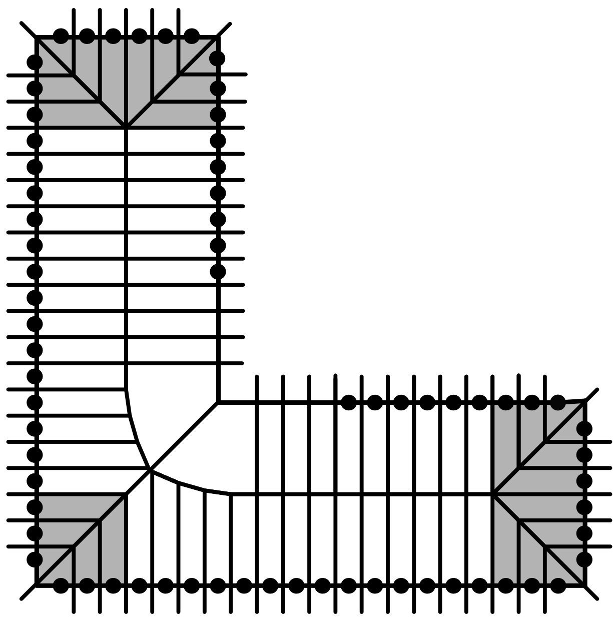

Figure 2: A natural division of floor space among doors for staging freight. The six doors around each outside corner have only three shares of floor space and therefore are more susceptible to congestion.

Shape	*#-Inside corners*	*#-Outside corners*	*Centrality*
I	0	4	2
L	1	5	2
T	2	6	$6/2 = 3$
X	4	8	$8/2 = 4$
H	4	8	$8/2 = 4$

Table 1: Properties of some dock shapes. Each inside corner forfeits about 8 door positions and each inside corner forfeits 3 door-shares of floor space. These represent fixed costs that can help achieve greater centrality.

Table 1 summarizes the key characteristics of various dock shapes. This table makes it clear why, for example, an L-shape is generally inferior, from an operational point of view, to an I-shape: The L-shape has centrality 2, like the I. This means the inside corner, which adds at least 8 door positions, increases the diameter by at least $8/2 = 4$ door offsets. In addition, the L-shape incurs the cost of the additional outside corner, which forfeits 3 door-shares of dock space.

We say that the L-shape is "generally inferior" because it does offer some small compensatory benefit that might not be obvious at first glance. Referring again to Figure 2, all the doors on the outside horizontal wall are slightly closer to all the doors along the inside vertical wall than they would be in the I-shaped dock with the same number of doors. Similarly, all the doors on the outside vertical wall are slightly closer to all the doors along the inside horizontal wall. As we show in Section 3, this characteristic of the L-shape gives it a slight design advantage in the presence of some patterns of freight flow.

Figure 3 further illustrates this compensatory benefit. It shows the distance from the best doors on an I and L (a middle door on the I, and a door closest to the inside corner on the L) to their neighboring doors, sorted from closest neighbor to farthest neighbor. The I has closer immediate neighbors, but its neighbor doors farther away are not as close as comparable doors on the L. Note that this is only a small benefit; other doors on the L are strictly inferior to their counterparts on the I, and so categorical statements about the dock

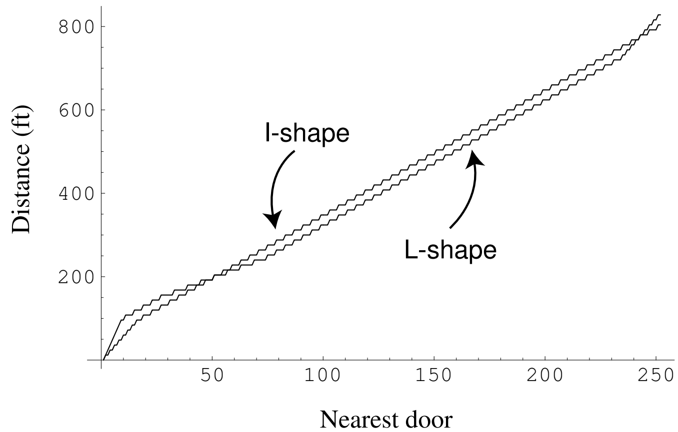

Figure 3: A comparison of the best doors on I- and L-shaped docks of 252 doors. The plot shows the distance from the best door on each dock to its neighboring doors, sorted from closest neighbor to farthest neighbor.

as a whole are not possible — in fact, determining how these attributes affect crossdock performance is the point of our computational experiment.

Table 1 also shows that the T-shape has two inside corners, which add $(2)(8) = 16$ door positions to increase the diameter by $\lceil 16/3 \rceil = 6$; and there are two additional outside corners. But the greater measure of centrality means that the dock can add more doors before the diameter becomes excessive. The additional corners are a sort of fixed cost to enable the greater centrality, which begins to pay off for larger docks. This effect is greater still for the H and X-shapes: The additional corners represent a still greater fixed cost to achieve a still greater centrality.

Performance of an H-shape depends directly on the length of the center segment, or crossbar. Our experiments indicated that the H is best when the center segment is as small as possible. How small can it be? The answer depends on many things, including the length of the trailers it must accommodate, the skill of drivers, whether drivers will be using a standard road tractor or a special yard tractor called a *hostler*, and, for 48- and 53-foot trailers, the placement of the rear axle (which determines pivot points and therefore the turning radius). One engineer reported that if the crossdock hosts exclusively 28-foot trailers, there need be only about 100 feet between piers (Hein, 2001). For 48- and 53-foot trailers he estimated the distance to be about 180 feet. Therefore in our computational experiments we assumed conservatively 8 trailers in the center segment plus the lost door positions due to inside corners, resulting in a distance of 16 door positions or 192 feet between piers.

2 Experimental design

To determine which shapes are best under which conditions we conducted computational experiments with several candidate shapes. We evaluated each shape by varying several characteristics and recording a surrogate for expected labor cost.

2.1 Candidate shapes

We evaluated the I, L, T, H, and X-shapes. We have seen the first four shapes in practice, and we proposed the X suspecting that it would perform well for larger docks. We assumed that all docks are eight doors, or 96 feet wide.

2.2 Estimate of labor cost

We evaluated each shape according to its *average travel distance*, which we define to be the total distance between inbound and outbound trailers weighted by the corresponding intensity of freight flow, divided by the total flow:

$$\frac{\sum_{i \in I} \sum_{j \in J} f_j d_{ij}}{\sum_{j \in J} f_j},$$

where I and J are the sets of receiving and shipping doors, respectively, d_{ij} is the distance between doors i and j, and f_j is the flow (in pounds) to the destination at door j. We take average travel distance to be an approximation of the total travel cost across the dock, and therefore an estimate of the variable labor cost to move freight through the facility.

There are other objectives in design, such as reducing congestion and providing adequate storage space. We comment on these criteria, but restrict our computational experiment to the more easily quantified measure of average travel distance.

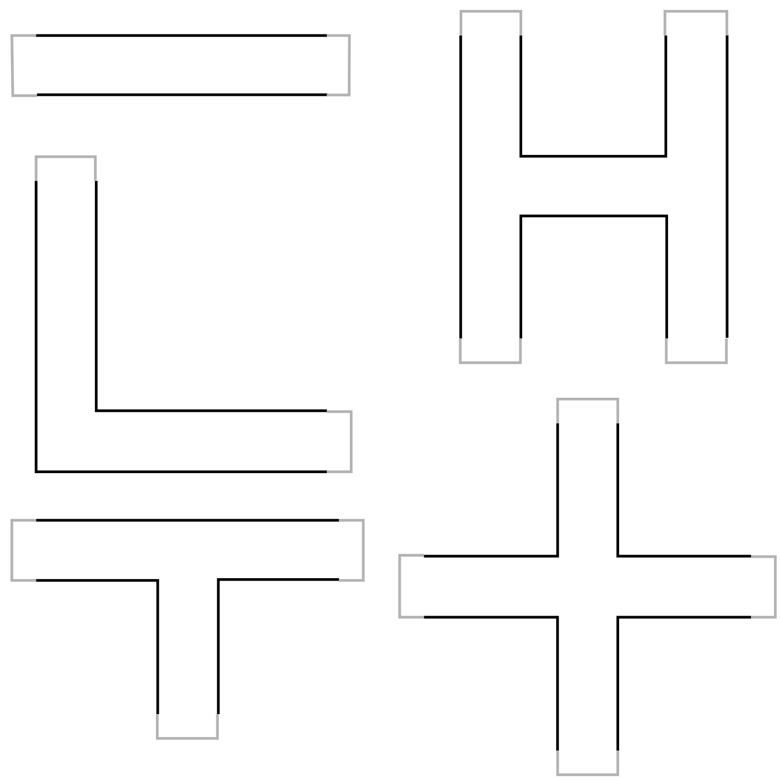

Figure 4: We grew each dock by adding two door positions at each end and studied how the costs of moving freight changed with increase in size.

2.3 Characteristics

For each dock shape, we explored four characteristics: size, layout, concentration of flows, and fraction of doors devoted to receiving.

2.3.1 Size

We varied dock size from 40 to 350 doors because this covers most of the crossdocks in industry. To “grow” a shape, we add two door positions at each end as suggested by Figure 4.

To grow an H, we extended both vertical arms of the H, at both the top and bottom, by two doors simultaneously. We did not extend the horizontal pier within the H. Our experiments indicated that this strategy for growth was superior to extending the horizontal pier along with the outer piers.

2.3.2 Layout

We can compute a more accurate estimate of the average travel distance to move freight over a crossdock if we know which destinations are assigned to which doors. Elsewhere we have referred to this as the "layout" of the dock; and choosing the best layout is itself a difficult combinatorial problem (Bartholdi and Gue, 2000).

We established the material flows of each design with good but suboptimal layouts produced by a one-pass interchange heuristic, which is a simplified version of the algorithm developed in Bartholdi and Gue (2000). The heuristic is as follows:

1. Construct an initial layout:
   (a) Assign the incoming trailers to the "best doors" — that is, to the doors having the smallest average distance to all other doors. It is easy to confirm that, for all the shapes we consider, these are the most central doors.
   (b) Assign the destinations receiving the most freight to the next best doors, successively.
2. Search for improvements by interchanging pairs of trailers.

See Figure 5 for an example of a layout produced by the heuristic. We chose not to run the heuristic all the way to a local optimum. First, we did not think it necessary after we benchmarked some test cases and found that this simple heuristic was generally within a few percent of the local optimum. Second, it would not have been possible to run all the experiments within a practical amount of time. Even with the simple heuristic our computational runs consumed an estimated total 2–3 years of CPU time scaled to a high-end personal computer.

2.3.3 Patterns of freight flows

We evaluated each shape under two patterns of freight flows:

Uniform freight flows in which every inbound trailer sends equal amounts of freight to every outbound trailer. This is an extreme case but we use it to test the robustness of

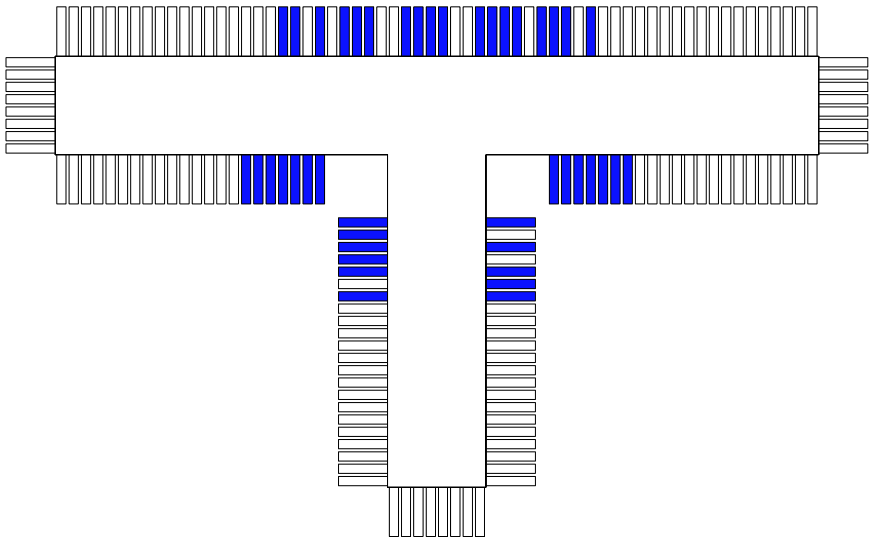

Figure 5: Results of the one-pass interchange heuristic applied to the T-shape. Dark rectangles represent inbound trailers. The heuristic tends to intersperse the highest-flow destinations among centrally located receiving doors.

our conclusions: Uniform flows magnify the weaknesses of any dock because it is hard to avoid regions of bad design by careful assignment of trailers to doors.

Exponential freight flows follow an "ABC" rule in which most of the freight of each inbound trailer is bound for the same few outbound trailers. This model is suggested by Figure 6, which shows the relative amounts of product moving out of stores of The Home Depot in the northeastern U.S. In this model, we assume that when a trailer arrives from a vendor at the crossdock, it contains proportionally more product for a larger store than for a smaller store. For convenience in computational testing we approximate the disproportionate nature of flows with an analytic expression giving the flow f_j to the j^{th} of n destinations as

$$f_j = (u - l)e^{-12.8j/n} + l,$$

where u is the maximum flow, and l is the minimum flow. The flows that result from our choice of parameters are representative of data from several crossdocks from which we have data.

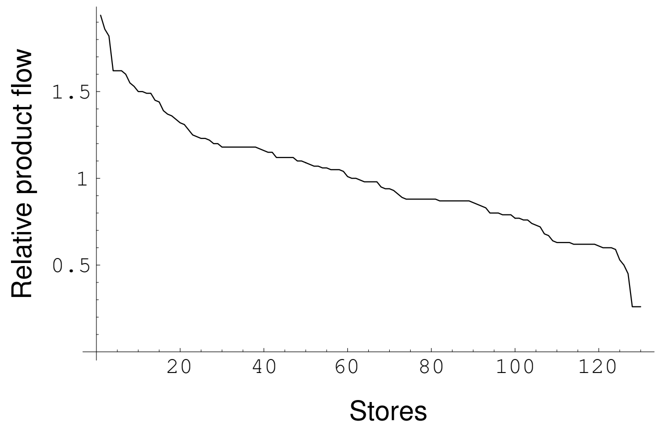

Figure 6: The approximate distribution of freight flows to stores through a major retail crossdock (Data courtesy of L. Kapiloff, The Home Depot).

2.3.4 Fraction of doors devoted to receiving

In practice, the fraction of doors devoted to receiving varies among crossdocks. This fraction depends on several issues, including:

- The relative numbers of incoming and outgoing trailers each day, and
- The relative times to unload a typical incoming trailer and to load a typical outgoing trailer.

In our experiments we varied the fraction of doors devoted to receiving from 0.1 to 0.5 in increments of 0.1. This range of values includes all crossdocks known to us.

In all, we evaluated 50 different combinations of dock shape and pattern of freight flow; and we examined each of these combinations over hundreds of dock sizes, for a total of several thousand instances.

3 Results

Figure 7 summarizes how the best shape depends on the distribution of flows and the fraction of doors devoted to receiving.

Our main result is

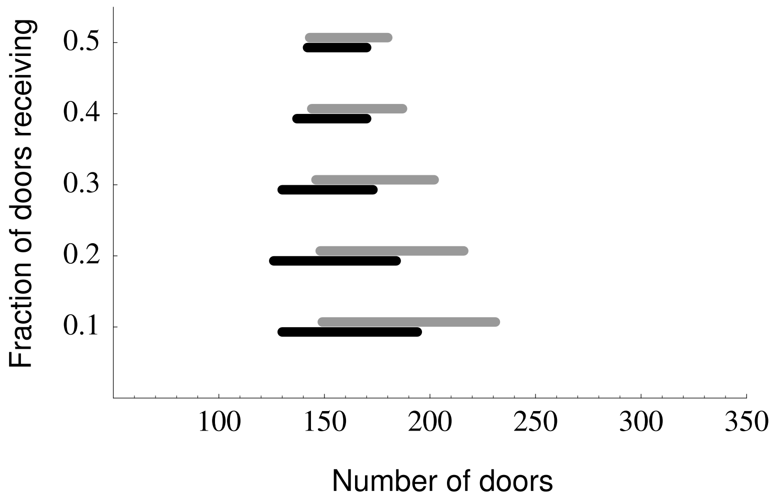

Figure 7: The black bars indicate regions for which the T-shape is most labor-efficient when freight flows are uniform, and gray bars show the same for exponential freight flows. To the left of the bars the I-shape is best and to the right the X is best.

As size increases, the most labor-efficient shapes for a crossdock are I, T, and X, successively.

Our experiments suggest that an I-shape is the most efficient for docks of fewer than about 150 doors. A T-shape is best for docks of intermediate size; and for more than about 200 doors an X-shape is best. Interestingly, there are many I-shaped crossdocks with 150–200 doors — they would probably have lower labor costs had they been built in the shape of a T. Our results suggest that I-docks larger than about 220 doors incur about 10% additional labor cost. We are not aware of any X-shaped docks in practice.

More details on the computational results are shown in the Appendix. These support the following additional observations.

- *It is not always easy to predict which shape is better.* For example, at first glance it seems that an I-dock would always be better than an L-dock of the same number of doors because the L-shaped dock has two additional corners but no greater centrality. Yet there are instances in which the L-shape was slightly preferable to the I. This arose because, as discussed in Section 1.3, the L-shape changes the distances between doors, and some pairs of doors are closer than they otherwise would be. Occasionally, just the right patterns of freight flow perfectly matched this altered distribution of distances so that the total labor cost was slightly less than that for an I-shape. Such events were extreme cases and rare in our testing. Consequently we believe that, as a practical matter, an I-shaped dock is always preferable to an L-shaped dock of the same number of usable doors.

Similarly, the H-shaped dock performed slightly better than an X in a few extreme cases even though, as a practical matter, the X is superior to the H.

- *The sizes at which T is preferred to I, and X preferred to T, depend on the number of receiving doors and the concentration of flows.* The observation suggests that both aspects of material flows are important when determining the best shape for a cross-dock. To the best of our knowledge this information is not currently used in deciding on a shape.

- *Alternative shapes (T and X) are more attractive when flows are uniform.* Notice from the plots in Figure 7 that the black bars, corresponding to uniform freight flows, are generally to the left of the gray bars (exponential flows). This is because the best doors for a shape assume greater importance when flows are more concentrated. Because the T and X sacrifice the best doors near the center to improve the quality of the worst doors, the dock must be larger to make these shapes attractive.

- *Alternative shapes (T and X) tend to yield greater savings when flows are uniform.* In Figure 8 (see the Appendix) the cost curves dip lower for cases with uniform freight flows than for those with exponential flows, suggesting that there is more to gain by using alternative shapes in those cases. In other words, crossdocks appear to be more sensitive to shape when flows are more uniform. We believe the reason is that the layout, which is a manipulation of flows, is less able to affect average travel distance when flows are uniform. When freights flows are exponential, it is possible to compensate to some extent for a bad dock shape by a careful assignment of trailers to doors.

- *The T-shape is preferred over a smaller range of doors when the fraction of doors devoted to receiving is higher. Moreover, this effect is more pronounced when freight* *flows are exponential.*

4 Conclusions

Shape matters.

Freight must be moved across the dock and total distance traveled is a good estimate of labor costs. With respect to labor costs the best shape for small to mid-sized crossdocks is a narrow rectangle or I-shape, which gets maximum use of its most central doors. Shapes that are topologically equivalent, such as L or U, should be avoided if possible because of the cost of additional corners.

For larger docks, alternative shapes are more attractive. The best shapes for larger docks have piers branching out from a central area, reminiscent of the "sun design" of Robusté and Daganzo (1991). These designs have more corners, for which they pay a cost; but they achieve greater centrality, and so more distant doors are closer to other doors. For example, the T-shape is best for dock sizes between about 150 and 200 doors, depending on the pattern of material flows. Even though the T forfeits some of its best door positions to the two inside corners, its worst doors are closer to the center of the dock than for the I-shape and this reduces total travel. In practice, there are many I-shaped docks in this size range but we believe this to be a poor design choice.

For docks larger than about 200 doors, the X-shape is best. Despite having four inside corners near the center of the dock, the X has the lowest expected material handling costs because its worst doors are not far from the center. On a large dock the worst doors in an I or T are too inconvenient to make these shapes competitive. There are docks of 200–300 doors in practice but none that we know of that are X-shaped. This shape should be considered.

When freight flows are concentrated among few destinations the point will be deferred at which a more complicated design, such as T or X, becomes attractive. This is because the labor will be concentrated on a subset of the dock and so the dock is, in effect, a smaller dock. Our results also show that the point at which a more complicated shape becomes preferable also depends on the fraction of doors devoted to receiving (see Figure 7).

Our results also suggest a natural strategy for expanding existing crossdocks: When an

I-shape approaches about 150 doors, it should be expanded with a segment in the center, creating a T. Should the dock grow again, the T should be made an X. Of course, exact points for transition depend on the material flows.

In focusing only on inside-the-dock labor costs we are necessarily ignoring other issues that can affect dock shape. For example, we argued that the X-shape is slightly preferable to the H. But the H-shape has one advantage not addressed in our research: It requires less travel for hostlers, who move trailers to and from the dock. For the X, no matter which doors the hostler is traveling between, he must effectively trace the perimeter of the dock because the four areas between the piers would almost certainly be used for parking trailers. For the H, hostlers would occasionally be able to shortcut from the end of one pier to the end of another, thereby avoiding having to trace the perimeter of the dock for every move.

Finally, it is worth remarking that there are some crossdocks of unusual shapes that we have not considered: A crossdock in Phoenix forms an obtuse angle, like a dogleg left; another in Seattle is a near-perfect square; and a terminal in Chicago is shaped like an E. As might be expected, these shapes are artifacts of history rather than thoughtful design.

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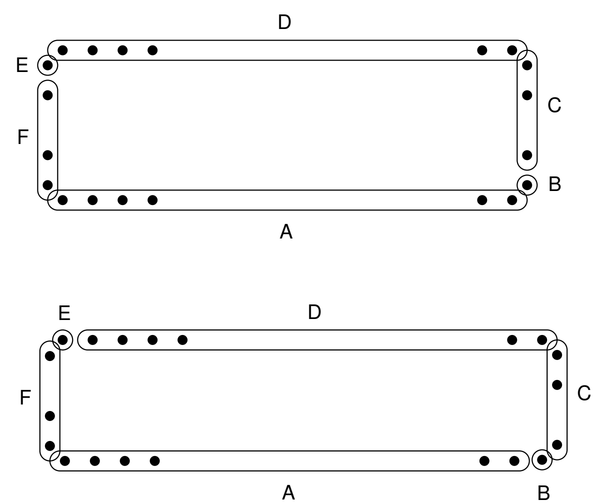
A Proof

Observation 1. *For a given number of doors a narrower dock realizes a smaller average distance between doors.*

Proof. Consider a dock of length l and width w, such that $l \geq w$ and $w \geq 2$ (otherwise the dock is as narrow as possible), and a narrower dock having dimensions $l+1$ and $w-1$, as in the figure. Note that there are l doors in regions A and D and $w-1$ doors in regions C



and F. Doors (or, more precisely, door centers) in regions A and F do not move between the two docks; doors regions D and C move one unit to the right and one unit down; doors in regions B and E move one-half unit to the right and one-half unit down. To determine the difference in average rectilinear distance Δd between doors for the two docks, consider each pair of regions: Doors in regions A and B are the same distance apart, so there is no change in distance. Doors in region C are also the same distance away from those in region A, so there is no change in distance. For doors in regions A and D there is a change: For any door in region A of the top figure, doors in region D above and to the right of that door are the same distance away in the bottom figure (having moved a unit closer and one unit further away); doors to the left of that door are 2 units closer. The rightmost door in region A has $l-1$ doors to the left, the next door has $l-2$, and so on, therefore the change in distance $\Delta d = -2((l-1)+(l-2)+\ldots+1+0) = -l(l-1)$. Similarly, we get

Regions	Δd	Regions	Δd
A $\rightarrow$ B	0	B $\rightarrow$ F	$w-1$
A $\rightarrow$ C	0	C $\rightarrow$ D	0
A $\rightarrow$ D	$-l(l-1)$	C $\rightarrow$ E	$w-1$
A $\rightarrow$ E	0	C $\rightarrow$ F	$(w-1)(w-2)$
A $\rightarrow$ F	0	D $\rightarrow$ E	0
B $\rightarrow$ C	0	D $\rightarrow$ F	0
B $\rightarrow$ D	$-l$	E $\rightarrow$ F	0
B $\rightarrow$ E	0		

Accounting for flow in opposite directions, the change in total distance between doors is $2(w^2 - w - l^2) < 0$, so the average distance between doors for the narrow dock is less. $\square$

B Summary of experiments

Figure 8 shows the results of the experiment for each shape-material flow combination. To better highlight the distinctions between shapes, the figure illustrates the cost of each shape *relative to* the I-shape, for every size between 96 doors (the smallest reasonable size for an H) and 350 doors, which is larger than almost all docks known to us (Central Freight operates a crossdock in Dallas that has 553 usable doors).

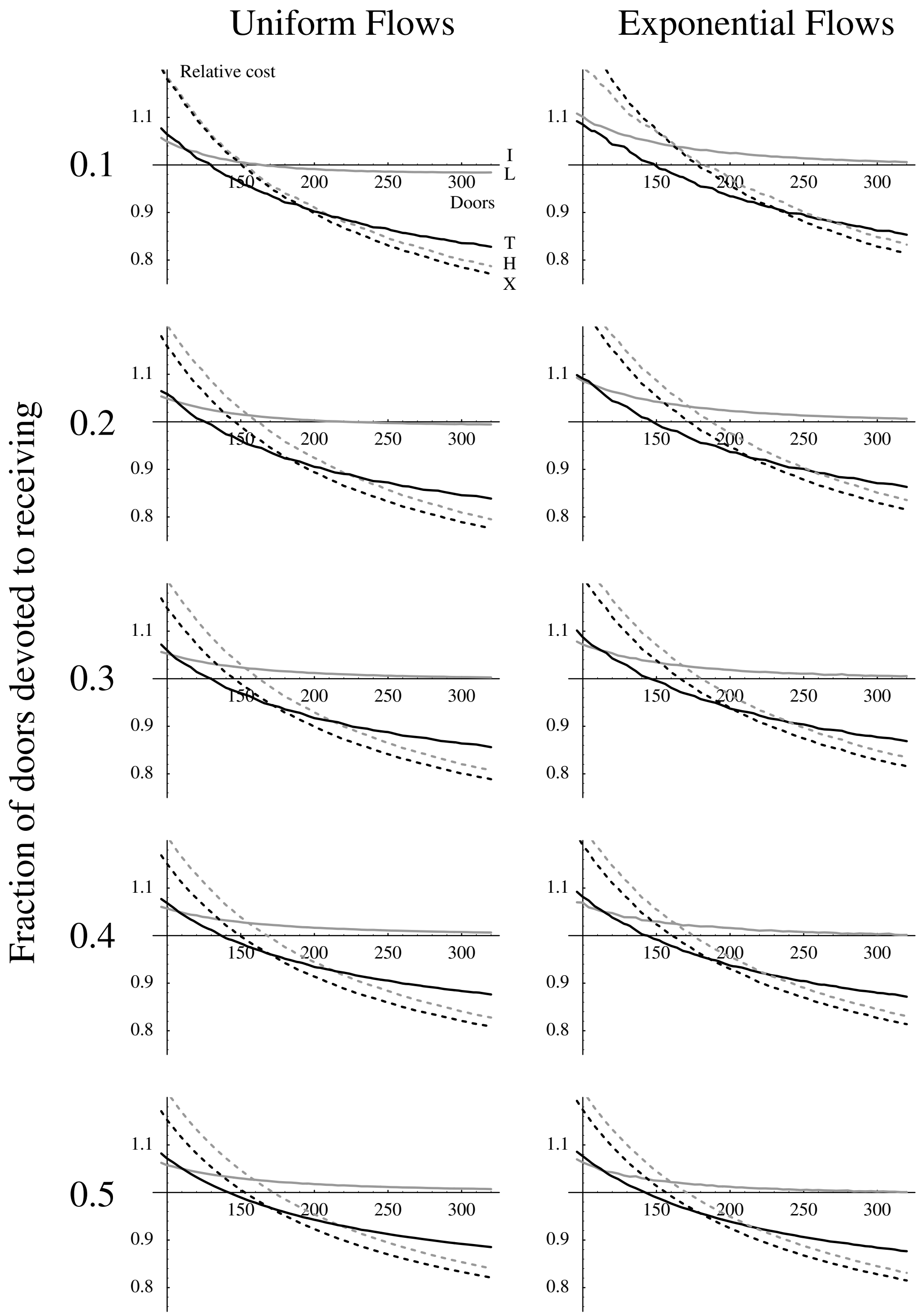


Figure 8: Results of the experiment. Curves represent the cost of each shape *relative to* the I. Thus the x-axis represents the cost of the I; the solid black curve represents the cost of the T; the dashed black curve represents the X; the solid gray curve represents the L; and the dashed gray curve represents the H, as indicated in the upper left-hand plot.