

The Application of New Aisle Designs for Unit-Load Warehouses

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Abstract: In a traditional unit-load warehouse, racks are arranged to create parallel picking aisles, perhaps with one or more orthogonal cross aisles to reduce travel distances for order pickers. We have argued that these designs are based on a number of unspoken assumptions, and that by relaxing them we can create warehouses with significantly improved performance. To illustrate, we have introduced warehouse designs with two innovations: diagonal cross aisles and picking aisles having different orientations. One of our designs promises to improve productivity by approximately 20 percent for warehouses of reasonable size. In this paper we also present details associated with the application of these new aisle designs and our on-going work on this topic.

1. The Traditional Unit-Load Warehouse: Unit-load warehouses receive, store and ship product in unit-load quantities (typically pallets). Such warehouses are sometimes referred to as a “simple warehouse” [1] in juxtaposition to “order fulfillment centers” that receive and store product in unit-load quantities, but also break down the unit-load quantities so that fulfilling demand for orders in less-than-unit-load quantities can also be achieved. A unit-load warehouse is a component of order fulfillment centers as well, because such facilities typically have the need for a reserve storage area. Thus, of the 597,000 warehouses in the United States [12], most will contain an area that shares some characteristics of a unit-load warehouse. Figure 1 illustrates a typical unit-load area of a warehouse.

Unit-load warehouses are ubiquitous in industry, and many are also very large. There are approximately 4,000 warehouses between 200,000–500,000 square feet and 3,000 over 500,000 square feet. Some of these, especially import distribution centers that support international supply chains, are up to 2,000,000 square feet [12]. In fact, within a 5-hour drive of Savannah, GA, the 4th-largest port in the U.S., there are seven distribution centers larger



Figure 1: A Traditional Unit-Load Warehouse

than 1,000,000 square feet [7]. And given that supply chains are not likely to decrease in complexity, these types of facilities are likely to become even more common [2].

Unit-load warehouses in industry are typically comprised of single- or double-deep pallet rack arranged in parallel picking aisles, as in Figure 2. This structure generally affords good storage density and so makes the storage area smaller than it otherwise would be, which confers two advantages: (1) construction costs are held to a minimum, and (2) smaller storage areas are believed to reduce travel distances for workers.

Unfortunately, designing a storage area exclusively to maximize storage density ignores the operational cost of retrieving items from the space. For example, sacrificing a bit of storage density may allow a design that reduces the cost of retrieving items. This insight has led warehouse designers to insert *cross aisles*, which are intended

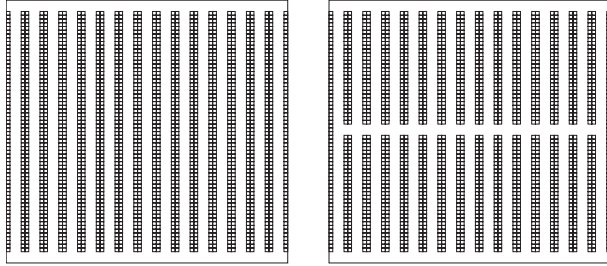


Figure 2: Typical Unit-Load Warehouse Layouts in Industry

to facilitate more efficient picking tours in less-than-unit-load picking operations (e.g., picking cases off pallets).

For unit-load operations, where each pick visits a single location, cross aisle confers no advantage because travel from the pickup-and-deposit (P&D) point to any item is still the rectilinear distance between them. In fact, the cross aisle in this case confers a *dis*-advantage because approximately half the storage locations are farther from the I/O point than they otherwise would be [11].

As we have presented in prior work [3, 4, 5], we believe that all unit-load warehouses (save now the two we discuss below) conform to at least two design assumptions:

1. Cross aisles are straight, and they meet picking aisles only at right angles.
2. Picking aisles are straight, and are oriented in the same direction.

Neither of these assumptions is necessary from a construction point of view, and, as has been shown in our prior work, both tend to constrain productivity.

In this paper, we illustrate the new aisle designs that we have introduced, along with general statements on their expected impact on productivity (Section 2). We then discuss two implementations of these aisle designs at facilities in the past two years (Section 3). We conclude the paper with a discussion of our on-going work (Section 4).

2. Our New Aisle Designs: The overall design problem we faced when developing new aisle designs was:

Problem statement: How should picking aisles and cross aisles be arranged to minimize the expected travel distance to a single pick?

In developing our new aisle designs, we made the following assumptions:

- As discussed previously, we are considering a unit-load warehouse (e.g., pallet in, pallet out; no picking tours like that found in a case-retrieval system).

- The travel of the unit-load starts and ends at a single picking and deposit (P&D) point. We further assume that the P&D point is located at the bottom, center of the warehouse.
- We assume uniform storage density, which means that regardless of the unit load’s characteristics (either physical or demand-related), it will be stored anywhere in the warehouse with equal probability.
- We ignore vertical travel, handling time, and acceleration/deceleration effects associated with the material handling device.

As we will discuss later, all of these assumptions affect the numerical results we present later in this section.

2.1. Flying-V Design: In the first of our designs we challenge the first design assumption presented above, namely, that “cross aisles are straight, and they meet picking aisles only at right angles.” For this design, which we name the “Flying-V” design due to its shape, we insert a cross aisle into the storage space and do not constrain it to meet the picking aisles only at right angles. That is, we formulate an optimization model that selects the intersection of the inserted cross aisle with the picking aisles — allowing for the intersection to occur at a different point for each picking aisle.

Figure 3 shows the result for a warehouse with 21 aisles and 100 picking locations per picking aisle. Notice that the optimal cross aisle is slightly “curved” (it is actually piecewise linear). The design in Figure 3 has an expected travel distance 10.0 percent lower than a traditional warehouse (see Figure 2, left side) with the same total length of picking aisles. Note that this comparison accounts for the additional space needed in the Flying-V warehouse to insert a cross aisle. A full range of comparisons is presented in Figure 4.

The main insight behind the Flying-V design is that a cross aisle that cuts diagonally across the picking aisles affords a sort of “Euclidean advantage,” which allows

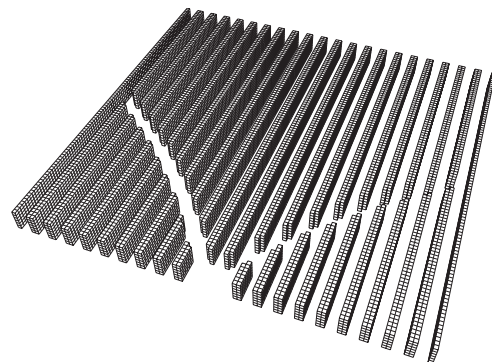


Figure 3: Optimal Design for a Flying-V Warehouse

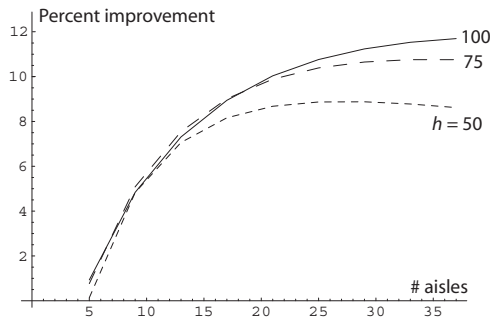


Figure 4: The Percent Improvement in Expected Travel Distance for Flying-V Warehouses of Three Heights (h in number of pallets)

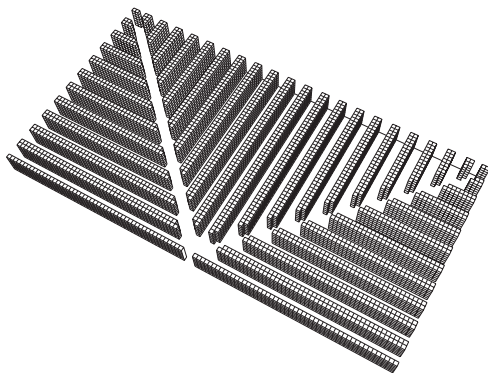


Figure 5: Optimal Design for a Fishbone Warehouse

workers to get to most locations more quickly. Workers would still travel in a strict rectilinear fashion (across the bottom of the warehouse and then “up” into the picking aisle) only for locations near the bottom of the warehouse.

It is that final observation that led us to consider the next aisle design in the hopes of constructing an aisle design where every location would be closer to the P&D point than in a comparable traditional warehouse.

2.2. Fishbone Aisles: Our second design relaxes the second unspoken assumption—that picking aisles must be parallel to one another. Notice that picks along the bottom of the Flying-V design still require rectilinear travel. The “Fishbone” aisle design (Figure 5) overcomes this disadvantage by rotating picking aisles in this region by 90 degrees. Figure 5 shows the result of our optimization model for the equivalent of 21 vertical picking aisles, each having length of 50 pallet locations. In this case, it is optimal for the inserted cross aisle to run to the corner of the warehouse. This design has expected travel distance 20.4 percent lower than an equivalent traditional warehouse. Again, this comparison accounts for the additional space needed in inserting a cross aisle. A full range of comparisons is presented in Figure 6.

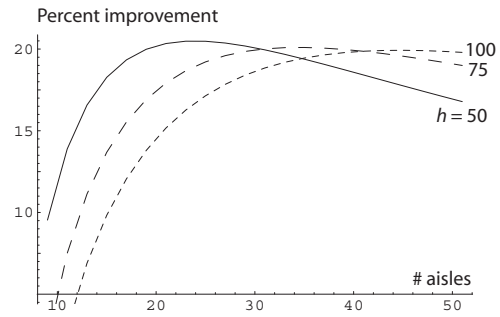


Figure 6: The Percent Improvement in Expected Travel Distance for Fishbone Warehouses

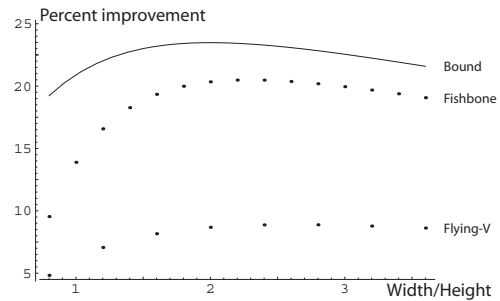


Figure 7: Comparisons Between Aisle Designs and an Unachievable Bound for Different Width-to-Height Ratios

To compare these designs, we can calculate a limit for improvement by assuming straight-line travel is possible between the P&D point and every location in the warehouse. Although not achievable in practice, it does give us a measure of how close our designs are to an (unachievable) best case. Figure 7 shows that the Fishbone design is quite close to a theoretical best design.

2.3. Chevron Aisles: One drawback of the fishbone design is limited access to the storage space due to the single, central P&D point. Our third design, which we call “Chevron aisles” is an attempt to address this concern. An example is illustrated in Figure 8.

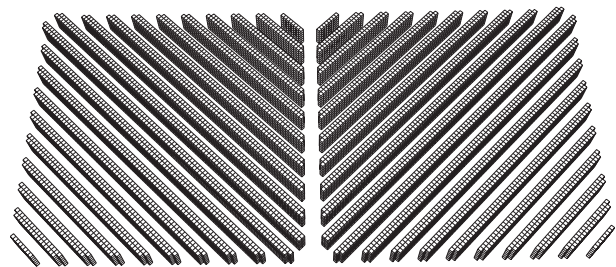


Figure 8: A Warehouse with Chevron Aisles

With comparable assumptions about aisle widths, etc., reductions in travel distance are very close to reductions

for the Fishbone design. This can be seen by considering the same location in either design and noting that travel in the Fishbone is along the diagonal, then horizontal or vertical to the location, whereas travel in a Chevron is vertical or horizontal, then along a diagonal picking aisle to the location. In this sense, Chevron aisles are a sort of “dual” to Fishbone aisles.

2.4. Objections from Industry: As these designs have been presented to Industry, a common list of objections is raised:

1. What effect does the placement of building columns have on these designs?
2. By how much is storage density reduced?
3. What about congestion in the Fishbone layout?
4. What if the warehouse has multiple P&D points?
5. Do these designs work for dedicated storage?
6. How do they perform with task interleaving?

The placement of building columns certainly must be considered when implementing non-traditional aisles. We have two observations on this point: First, the standard 50-foot separation of building columns allows quite a bit of flexibility with respect to diagonal aisles. Both of the implementations we report below have standard building columns. Second, we contend that architects and warehouse planners should be able to design building columns around the storage racks, should this be required (we know of one company that did this in a new facility to allow the potential for a Fishbone design).

The second question we have already addressed—inserting any kind of cross aisle reduces storage density. Therefore, designers must wrestle with the tradeoff of a slightly larger storage space versus a reduction in operating costs.

The question about congestion in a Fishbone design, which we hear frequently, is interesting because it seems to spring from the observation (reinforced by looking at a figure of the layout) that all flow starts and ends at a single point. We have not performed detailed analysis on this issue, but for most unit-load warehouses there simply are not enough workers in the space at one time for this to be a problem.

We are addressing the final three questions (multiple P&D points, dedicated storage, and task interleaving) in our on-going work, which we present in Section 4. But first, we present two implementations where the underlying issues related to these objections were not present.

3. Implementations: The underlying concepts embedded in our aisle designs have been put into practice at two facilities. In this section we provide an overview of the operations of these facilities and share anecdotal accounts of their effectiveness. We note here that in both cases, many other aspects of the facilities, besides a new



Figure 9: Non-Traditional Aisle Design Implemented at the Generac Distribution Center

aisle design, were changed at the same time. Therefore, we are unable to make statements about improvements due to the aisle design itself.

3.1. Generac Power Systems: We believe the first implementation of non-traditional aisle designs occurred in 2007 at a warehouse in Whitewater, WI. This warehouse was built by Generac Power Systems, a manufacturer of generators.

For the most part, this facility is a unit-load warehouse, with all product received on pallets and almost all orders being for a (full) pallet of generators. Thus, pallets of generators, which are shipped from a nearby Generac manufacturing facility, are unloaded with pallet trucks and deposited at a centrally-located “lay-down area,” which serves as the “pickup point” for the warehouse. Pallets are picked up at the lay-down area with lift trucks and put away in a storage area that is configured with a V-shaped aisle (see Figure 9, taken from the “point of the V”). The warehouse area above the aisle is racked; areas below the cross aisle are pallet floor storage. Random storage is used within each area. When a pallet is needed to fulfill a shipment, a lift truck retrieves the pallet from storage and delivers it to the centrally-located staging area. Workers use pallet trucks to retrieve the pallets from the staging area, which are then loaded onto trailers for shipment.

The Generac distribution center was new, replacing storage areas at the manufacturing plant and at other points in the Generac logistics network. The Logistics Manager at Generac learned of the Flying-V and Fishbone aisle design ideas from an article in *Modern Materials Handling* [6]. As the above description implies, this facility complies with many of our models’ assumptions, namely, random storage and a single, centrally-located P&D point. Thus, it should not be a surprise that the operators of the Generac facility have reported positive results associated with the new design [8]. In particular, Generac

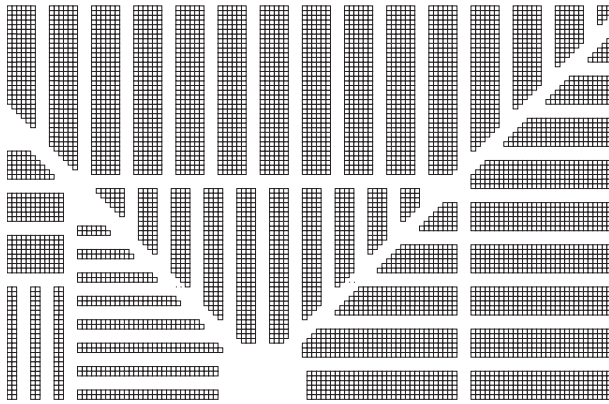


Figure 10: Non-Traditional Aisle Design Implemented at the Facility of a Distributor in Florida

cites improved material flow and reduced travel distances. But the company has realized some unexpected benefits as well. For example, workers no longer make 90-degree turns to enter the picking aisles. The 45-degree turns are easier to make, resulting in increased productivity.

3.2. A Distributor in Florida: To the best of our knowledge, the second implementation of non-traditional aisles occurred in 2008 at a distributor in Florida. (For reasons of confidentiality, we are not at liberty to disclose some details of this implementation, including the company's name.)

Like the Generac facility, for the most part this facility handles unit-loads, with all product received on pallets and most orders being for full pallets (or for a pallet consisting of two items). Unlike in the Generac implementation with a centrally located P&D location, in this facility pallets are received along the top of the layout shown in Figure 10. The pallets are stored in a block-stacking arrangement in single-, double-, or triple-deep configurations. Retrieved pallets are taken to a shrink-wrapping station, located at the bottom, center of the layout. After this step, pallets are then taken to the shipping doors located at the bottom of the layout.

As with Generac, the facility was new, replacing an older warehouse. The staff at the company worked directly with us on a new design (which they learned about through a presentation of our designs at a professional society meeting). As the above description implied, this facility conforms less with our models' assumptions, namely with respect to the single, centrally-located P&D point. In this facility, there are many P&D points for receiving, but a single P&D point for shipping. A careful look at Figure 10 reveals that put-away moves in receiving are the same or slightly less than in a warehouse with

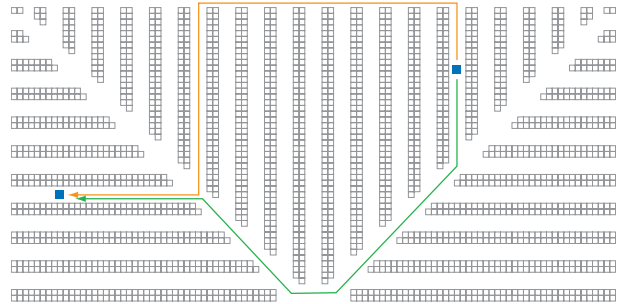


Figure 11: Interleaved Operations Illustration: Two Possible Paths Between Two Locations

traditional aisles. And for the retrieval operations, a great number of locations benefit from the diagonal cross aisle. Like the Generac facility, the management of this facility is pleased at the increases in performance that have been achieved to date; e.g., they report the same production levels with fewer workers. Workers also praised the new layout.

4. On-Going Work: Our on-going work is focused on examining some of the assumptions made in evaluating the designs above. Namely, we are in the process of examining the impact on the savings that can be realized in warehouses in which:

1. storage and retrieval operations are interleaved;
2. the number of P&D points is greater than one; and
3. the storage density is not uniform.

4.1. Interleaved Operations: With the implementation of a warehouse management system (WMS) it is often possible to "interleave" the storage and retrieval operations (these are typically called "dual-command cycles"). In traditional warehouses, interleaving operations typically decreases the travel distance per operation by 33% [9]. However, it is unclear as to the benefit of interleaving operations in, say, a Fishbone layout because the cross aisle does not necessarily facilitate the efficient movement between all storage locations (e.g., examine the two possible paths between two locations in Figure 11).

Therefore, one question of interest is what performance we should expect to see in a warehouse when operations are fully interleaved with fishbone aisles as compared to a warehouse with no cross aisle or a warehouse with a traditional cross aisle. To do so, we developed a travel-distance model for a fishbone warehouse under the interleaving operation strategy [10]. The results presented in Figure 12 illustrate that the improvement is approximately 15% (or more) when compared to a facility with no cross aisle and approximately 8% when compared to a facility with a traditional cross aisle.

Because most facilities use both single-command and dual-command operations, the final improvement is also

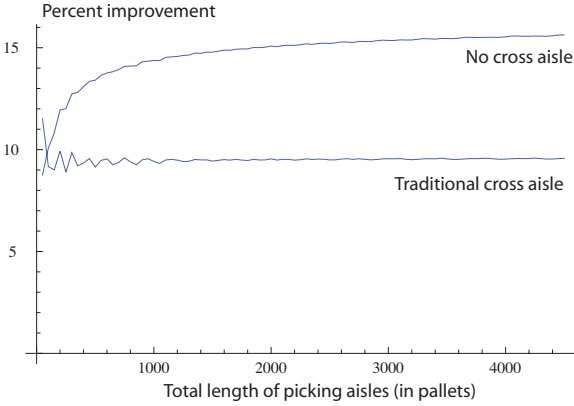


Figure 12: Interleaved Operations Performance in a Fishbone Warehouse

a combination of the improvement results. Namely, for a facility in which 2/3 of its operations are performed under dual-command (and 1/3 under single-command), the expected improvement with a fishbone layout is approximately 17% and 13% when compared to a facility with no cross aisle and a facility with a traditional cross aisle, respectively. Note that the latter facility would be approximately the same size as the fishbone facility, whereas the facility with no cross aisle would be approximately 5% smaller [10].

4.2. More than One P&D Point: As the implementations in Section 3 suggest, the single P&D location may be appropriate due to the need to transfer material handling equipment (Generac) or the need to shrink-wrap the unit-load (distributor in Florida). But in many facilities the assumption of a single P&D point is not appropriate. In the most extreme case, each receiving/shipping door may act as a P&D point, as illustrated in Figure 13.

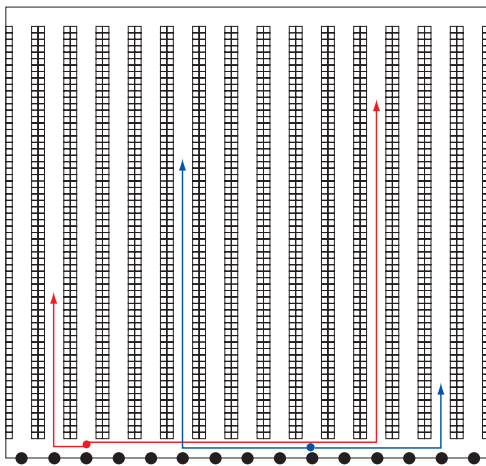


Figure 13: Warehouse with Multiple P&D Points and Illustrated Paths

In comparing the Flying-V layout with a traditional aisle layout with multiple P&D points, note that there are fewer travel paths that use the inserted cross aisle to reduce travel distances. Thus, we would expect the improvement afforded by the Flying-V layout to be less under this assumption than under the assumption of a single P&D point. This relationship is shown in Figure 14, where we allow the percentage of the bottom wall used as a P&D points varies from 1 to n .

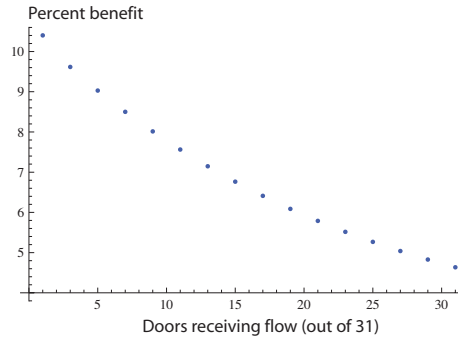


Figure 14: Expected Savings with Multiple P&D Points

4.3. Non-Randomized Storage Policies: In the reserve area of a warehouse, it is typical to use random storage (or more precisely, not to consider the relative product activity levels in assigning incoming pallets to storage locations). The main advantage is that random storage makes more efficient use of space [1].

However, there are some cases where the relative activity levels of some items are so much higher that there are significant benefits to be achieved by dedicating some number of “good” openings to high-activity items. Thus, we have investigated the performance of the Flying-V and Fishbone layouts under (fully) dedicated storage. Storage patterns in this case look very different for different designs (see Figure 15, where the darkness of the storage location is inversely proportional to the distance from the P&D point — i.e., darker locations are better). By connecting locations of the same level of activity, we can form contour lines. The contour lines of the traditional warehouse (Figure 15, top) form a triangular shape, reflecting rectilinear travel, whereas the contour lines of the fishbone warehouse (Figure 15, bottom) form an almost semi-circular shape, indicating near-Euclidean travel. The contour lines in the Flying-V warehouse (Figure 15, middle) are more difficult to characterize due to two travel paths in this type of warehouse. That is, in a Flying-V warehouse some points are accessed from the bottom cross aisle and the remaining points are accessed from the inserted cross aisle.

The performance comparisons under single-command operations for a variety of relative item activity (e.g., 20/80 indicates that 20% of the items are responsible for

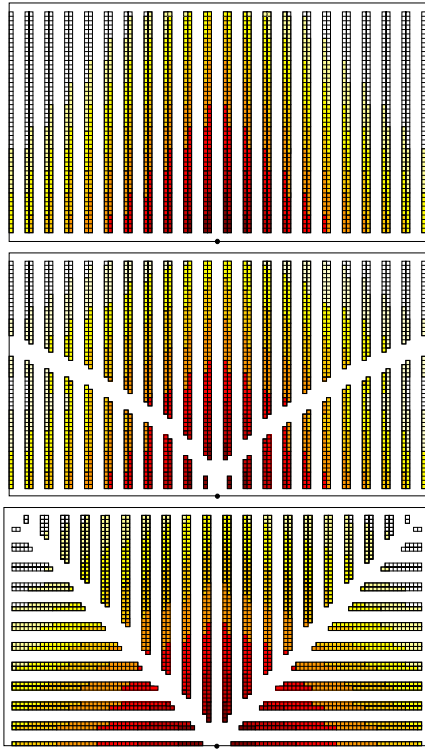
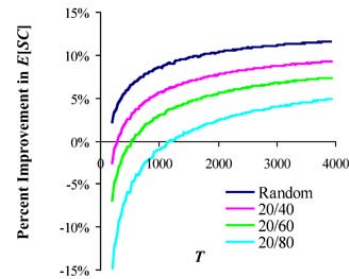


Figure 15: Dedicated Storage in Warehouse Designs

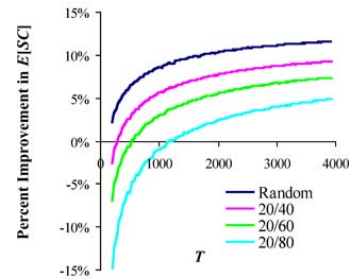
80% of the demand) are presented in Figure 16 for the Flying-V and Fishbone layouts. In general, as expected, as the item demand profile more closely resembles random storage, the new layouts perform the best. However, even with the relatively steep 20/80 curve, a fishbone layout can achieve more than a 10% improvement over a traditional design for most facility sizes.

5. Conclusions: We believe that the aisle design problem is a fundamental, but curiously overlooked problem in warehouse design. Through our research we have relaxed only two of several common presuppositions of previous research and practice, and have found that there is much to be gained by considering new designs. Our theoretical results (and two recent implementations) suggest that for unit-load warehouses, new designs could lead to higher throughput, or to significantly reduced costs of picking. Our future will consider both the assumptions of our models and the limitations assumed in practice about what is possible.

6. Acknowledgments: This study was supported in part by the National Science Foundation under Grant DMI-0600374 and 0600671. Much of this work has been submitted for publication.



(a)



(b)

Figure 16: (a) Dedicated Storage Comparison for Flying-V Layout; (b) Dedicated Storage Comparison for Fishbone Layout

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