XIV. AN EXPERIMENTAL STUDY OF THE IMPACT OF WAREHOUSE PARAMETERS ON THE DESIGN OF A CASE-PICKING WAREHOUSE

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Abstract

The best design for a warehouse is based on its ability to meet the demands placed on the warehouse, which are typically characterized by warehouse parameters like the order profile, inventory requirements, etc. Consequently, these parameters should be considered in the design process. In this paper we characterize the design of a case-picking warehouse with five design variables and identify the warehouse parameters that have the greatest impact in setting the values of these variables. With our analysis, the search for the optimal design can be reduced by limiting the design space considered.

1. Introduction

One challenging aspect of warehouse design is that the demands placed on warehouses vary. For example, some warehouse are expected to accommodate a highly skewed demand profile (a very small percentage of the products account for a very high percentage of demand) and others a demand profile that is not highly skewed, or accommodating very little inventory of each product in one warehouse and a lot of inventory in another. These varying warehouse demands, which we refer to as warehouse parameters, ultimately lead to different designs. And as a warehouse design is the combination of a set of warehouse design variables, it is possible to measure the impact of the warehouse parameter values on the warehouse design values. Thus, the purpose of this paper is to first identify the parameters that have the greatest impact on the best warehouse design and then to illustrate how these parameters can be used to limit the solution space for the best warehouse design.

We focus on a manual, case-picking warehouse that entails picking from pallet rack, where the bottom level of pallet rack serves as a forward area for picking fast-moving cases, and the upper levels are comprised of reserve storage locations. We assume that any items that do not have a forward location are picked from reserve storage. The design variables that we consider include the number of levels of pallet rack, the shape of the pallet area, the dock door configuration, as well as the size and layout of the forward area, if a forward area is warranted. We consider random storage in the forward area, as well as two class-based storage layouts. In order to evaluate design performance, we use a pallet-area sizing algorithm and analytical models for putaway, order picking and replenishment operations based on our previous research [8, 11].

The warehouse parameters that we consider include the number of SKUs and pallet locations, the number of cases per pallet, the number of picks per line, the number of lines per batch, and demand skewness. We evaluate these parameters over a wide range of design variables and use complete enumeration to determine the best design.

2. Literature Review

A forward picking area generally includes smaller quantities of fast-moving products in order to improve picking productivity, as picking occurs over a smaller area. The tradeoff is that picking from a forward area results in an added cost of replenishment from reserve storage. In addition, as more items are placed in the forward area, productivity decreases. Thus, the forward-reserve problem entails determining the number and quantity of items that should be placed in the forward area to minimize the overall picking and replenishment time. Bozer [3] considered a configuration with a co-located forward area, where the bottom level of pallet rack serves as the forward area, and the upper levels include the reserve storage locations. This configuration is conducive to a case-picking operation where cases are received in pallet quantities, as no additional storage space is needed for the forward area.

Frazelle et al. [5] developed a procedure for determining the best size of the forward area, as well as the quantity of items to include based on input data including the activity profile, pick and replenishment productivity, and occupancy index. In the procedure, clusters of SKUs that are typically ordered together are considered. This methodology resulted in a 40% decrease in annual operating costs in a case study, as compared to the current policy of including all SKUs (in equal quantities) in a forward area with bin shelving and flow rack.

van den Berg et al. [12] consider a forward area where order picking is performed during a busy period, and replenishments occur during a preceding idle period. In this paper, replenishments are deferred until after the busy picking period by placing more than one unit load in the forward area. The authors present heuristics to determine the items that should have more than one unit load in the forward area in order to minimize extra replenishment labor during picking, so as to increase throughput.

Bartholdi and Hackman [1] consider storage units in less-than-pallet quantities as in a distribution center that stocks small parts. The authors showed that storing the same amount of space for each SKU is equivalent to storing an equal time supply for each SKU. In addition, the authors showed that a three to six percent reduction in restocks can be achieved by changing from equal space-time allocations to optimal allocations that use the mean lead-time demand and safety stock information to reallocate space in the forward area.

Bartholdi and Hackman [2] developed a model for case picking from a forward area within bottom-level pallet locations. The model determines the number of locations to allocate to each SKU such that the maximum benefit is achieved from the forward area. In this model, the labor savings per pick in the forward area is fixed and independent of the size of the forward area.

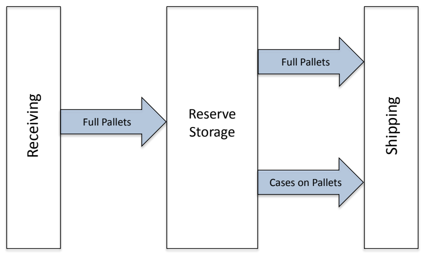
Another decision variable is the number of pallet rack levels; higher levels of pallet rack minimize the footprint of the pallet area, but higher levels also entail more vertical travel that is generally slower than horizontal travel. Parikh and Meller [9] considered the optimal height of a single-deep pallet rack storage system that employs order-picking trucks with both Tchebychev and rectilinear travel. They presented a model to determine the number, length and height of storage aisles needed to meet storage and throughput requirements. The authors concluded that the optimal storage height decreases for a system with a high throughput requirement, but increases as the cost of storage space increases.

Pallet area shape is another design decision that involves determining the optimal width-to-depth ratio of the pallet rack area. Francis [4] modeled the expected travel in a random storage warehouse for unit-load retrievals with a single pickup and deposit (P&D) point. For this configuration, the optimal width-to-depth ratio of the storage area is two-to-one. Thomas and Meller [11] show that for multiple pickup and deposit points (i.e., a uniform distribution of dock doors), a three-to-two shape ratio is optimal for single stops. Hall [6] developed models for order picking in a random storage warehouse and determined that the optimal shape of the pallet area increases (with more aisles that are less deep) as the number of pick lines per tour increases.

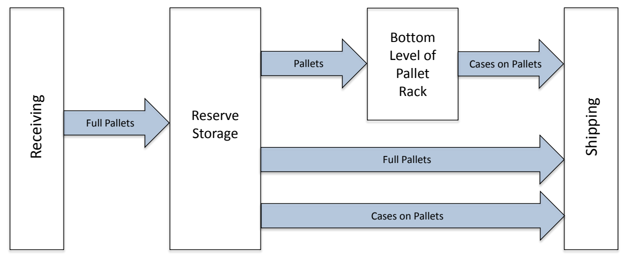
3. Methodology

To conceptualize designs, we utilize the Functional Flow Network (FFN) as first introduced by McGinnis et al. [7]. A FFN is a series of nodes and arcs, where nodes represent the functional areas of the warehouse, and arcs denote the flow of product from one functional area to another. For a case-picking warehouse, we consider the two FFNs illustrated in Figure 1, where the Figure 1(a) denotes pallet rack for picking cases with no forward area, and Figure 1(b) includes a co-located forward area on the bottom level of pallet rack for picking fast-moving cases.

In our analysis, we assume that cases are received in pallet quantities, and we use an average number of cases per pallet to estimate the number of pallet put aways. Cases are picked and loaded onto pallets, such that the case quantity per order-picking tour is 80 percent of the number of cases on incoming pallets. The number of lines



(a)



(b)

Figure 1: Functional Flow Networks: (a) Basic FFN with all picks from reserve storage; (b) FFN including a co-located forward area with case picks from the forward area (bottom level), pallet and case picks from the reserve area, and with replenishments in pallet quantities from the reserve area to the forward area.

per order-picking tour is calculated by diving the pallet capacity (in cases) by the average number of picks per line.

To assess design performance, we use a pallet-area sizing algorithm [8] along with analytical models [11] to quantify the space and labor requirements for a given design. We consider a large range of designs, with every possible combination of design variables: forward area layout and size, pallet area shape and pallet rack levels. The exact values considered for these variables are listed in Table 1.

Table 1: Designs Considered

Design Variable	Values Considered
Random Forward-Area SKUs	0%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70&, 80%, 90%, 100%
1-Sided Class-Based Forward Area SKUs	20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%
2-Sided Class-Based Forward Area SKUs	20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%
Pallet Area Shapes	0.5, 1.0, 1,5, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0
Level of Pallet Rack	4, 5, 6

Using the 20 data sets in Table 2, we calculate correlation coefficients between the warehouse parameters and the design variable of forward area size that results in the least labor hours. We focus first on the forward area size, as this variable can have a significant impact on design performance [10]. (The variable for pallet area height was set at 6 levels because, as we show later, designs with higher levels of pallet rack result in lower labor hours than lower levels of pallet rack in most cases.) Table 3 lists the correlation coefficients for each warehouse parameter with the optimal forward area size for each layout.

Table 2: Data Sets Based on Order Data

Data Set	Pallet locns	SKUs	Incoming cases per pallet	Case picks per day	Avg picks per line	Skewness	
						A	%Lines/%SKUs
DS1	60,000	5,286	96.0	389,396	11.65	0.097	65/20
DS2	24,000	10,831	12.7	4,293	1.50	0.071	77/20
DS3	23,600	10,612	10.6	3,384	1.28	0.079	75/20
DS4	14,000	5,493	11.8	2,401	1.19	0.053	81/20
DS5	8,650	5,574	12.5	1,251	1.29	0.122	68/20
DS6	35,000	8,539	48	44,097	3.69	0.024	92/20
DS7	50,000	8,000	25	60,000	4.00	0.079	75/20
DS8	45,000	6,000	30	45,000	1.50	0.071	77/20
DS9	30,000	7,000	35	40,000	2.25	0.053	81/20
DS10	10,000	4,000	20	11,000	4.50	0.122	68/20
DS11	50,000	8,333	70	126,000	3.00	0.068	80/20
DS12	40,000	6,700	100	160,000	8.00	0.253	55/20
DS13	30,000	5,000	30	32,400	1.00	0.146	66/20
DS14	10,000	6,000	15	6,600	3.00	0.096	74/20
DS15	40,000	26,000	100	96,000	8.00	0.253	55/20
DS16	30,000	25,000	80	76,800	1.00	0.107	72/20
DS17	10,000	5,000	8	2,880	2.00	0.079	75/20
DS18	20,000	6,000	30	21,600	1.50	0.097	65/20
DS19	45,000	4,500	20	36,500	3.50	0.024	92/20
DS20	5,000	500	15	2,400	1.00	0.117	71/20

Table 3: Correlation Coefficients of Warehouse Parameters with Forward Area Size

Warehouse Parameter	Forward Area Layout 1-Sided	2-Sided	Random
Pallets	-0.138	-0.176	-0.062
Cases per pallet	0.216	0.218	0.010
SKUs	-0.436	-0.428	-0.237
Picks per line	-0.140	-0.145	0.266
Skewness	-0.357	-0.306	-0.069
SKUs-to-bottom-level-pallets	-0.562	-0.546	-0.292
Lines per batch	0.295	0.308	-0.094

From Table 3 we see that the most important factor in determining the size of the forward area is SKUs-to-bottom-level-pallets, as this factor has the highest absolute correlation with the size of the forward area. This ratio represents a comparison of the number of SKUs to bottom-level pallet locations and can be calculated from the second and third columns in Table 2, while considering the number of levels of pallet rack. A ratio of less than one indicates that there are enough bottom-level locations to allocate all SKUs a bottom-level, forward area location (if warranted). For values greater than 1.0, the footprint of the pallet area would have to grow in order to accommodate designs with all SKUs on the bottom level. This ratio has a negative correlation with the size of the forward area. It is more advantageous to have a smaller forward area with fewer SKUs than to have a larger footprint that can accommodate more SKUs.

The number of SKUs is also a significant factor. As the number of SKUs increases, the size of the forward area should decrease in order to achieve the maximum benefit from the forward area. The skewness factor has a slight negative correlation, especially for the class-based storage layouts. As the skewness of the ABC curve increases, less SKUs should be placed in the forward area. The lines per batch has a slight positive correlation with the size of the forward area for class-based storage.

Next, we consider the correlation of the optimal shape of the pallet area with the type of layout (i.e., 1-sided class-based layout, 2-sided class-based layout and random forward area layout). The shape factor represents the width-to-depth ratio of the warehouse, where higher ratios indicate more elongated warehouses with aisles that are less deep. A correlation coefficient of 0.381 was calculated for pallet area shape and layout type, indicating a slight correlation between these two factors. From our previous investigation of warehouse shape (see [11]), the 1-sided class-based layout performs best for lower shapes as compared to the 2-sided class-based layout and random storage layout. However, in our previous research we assumed that the class-based layouts comprised the entire pallet area. When the class-based forward area includes only a portion of the pallet rack aisles, two shapes are involved: the shape of the entire pallet area (that includes picks from reserve storage) and the shape of the smaller forward area (that includes picks from the centermost, bottom-level pallet locations). Thus, the (smaller) shape of the forward area depends on how many SKUs are assigned to the forward area. Further, previous research shows that the optimal shape of the picking area varies by operation (when considering pallet put-aways, order picking, and replenishment operations). Consequently, determining the optimal shape is not straightforward.

In our next analysis, we consider each data set from Table 2 and the performance of each data set for each design (by enumerating over all possible values for the design variables). Hence, we evaluate the data sets to determine any trends in design performance associated with the parameters of the warehouse. In other words, if certain designs perform well for a given range of warehouse parameters, then generalizations can be made about the preferred design for the range of (fixed) warehouse parameters. In order to be thorough in our analysis, we also vary the warehouse parameters for each of the 20 data sets to determine their impact on design performance.

3.1 Forward Area Layout and Pallet Area Shape

Of the design variables considered, the forward area size and layout, as well as the shape of the pallet area have the greatest impact on travel times (see [11] and [10]). First we consider these variables for each of the data sets listed in Table 2. Tables 4–5 list pallet area shapes ranging from 0.5 to 7.0 for data sets 1 and 2, as well as the percent of SKUs in the forward area *that results in the least labor hours* for four layouts: no forward area, a forward area with random storage, a forward area with the 1-sided class-based layout, and a forward area with the 2-sided class-based layout. The daily hours listed in the tables total the travel times for put away, order picking and replenishment that meet the throughput requirements for each data set. The results for data sets 3–20 are listed in A.

Table 4: DS1 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	3223	30%	2411	100%	1662	50%	2329
1.0	2554	20%	1942	100%	1342	50%	1906
1.5	2403	30%	1806	100%	1272	50%	1726
2.0	2271	30%	1680	100%	1214	40%	1601
3.0	2212	40%	1580	100%	1208	50%	1487
4.0	2180*	40%	1511	70%	1203*	70%	1432
5.0	3205	40%	1493	70%	1211	50%	1398
6.0	2196	50%	1459*	70%	1212	50%	1369*
7.0	2268	40%	1475	70%	1251	50%	1382

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 5: DS2 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	175	5%	145	40%	112	20%	152
1.0	142	5%	120	30%	94	20%	115
1.5	136	10%	113	30%	91	20%	109
2.0	126	10%	106	20%	86	20%	100
3.0	120*	10%	98	20%	83*	20%	93
4.0	126	10%	100	20%	86	20%	95
5.0	122	10%	97*	20%	86	20%	93
6.0	126	10%	98	20%	87	20%	93
7.0	125	10%	97*	20%	88	20%	92*

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

From Tables 4–5 and Tables 18–35 in A we observe that, in general, the 1-sided layout outperforms the other layouts (lower total hours), followed by the 2-sided layout. Also, we observe that the percent of SKUs included in the forward area varies by the type of forward area as well.

Table 6 provides a summary for all twenty data sets, listing the best shape and forward area size for each of the three layouts. From this set of twenty examples and their associated skewness levels, a forward area is warranted in all the data sets. That is, the savings in order picking from the forward area outweighs the extra labor in replenishment, even for data sets 2–5, 14, 17 and 20, where the number of cases per pallet is relatively low (approximately 8–15). In addition, the impact of pallet-area shape is the greatest for shapes of 0.5–2.0, but shapes higher than 2.0 yield more similar results in terms of required labor hours. In general, pallet-area shapes of 3.0 or higher result in the least labor. The examples also reveal that the one-sided, class-based storage layouts perform best with more SKUs in the forward area as compared to the random-storage forward area layout. As more SKUs are included in the class-based layouts, they are generally assigned to less favorable locations (i.e., class-C locations). Consequently, although the total area increases, the location of the fastest-moving SKUs does not change. Thus, the performance of class-based storage layouts do not deteriorate by adding additional SKUs, except in those cases where adding more SKUs necessitates an increase in the footprint of the pallet area.

In comparing the results presented in Tables 4–5 and Tables 18–35 in A, most of the data sets result in the least labor with ∼10% of the SKUs in the random storage forward area, ∼20-30% of the SKUs in the one-sided, class-based layout, and ∼10-20% in the two-sided, class based layout. However, the data sets with a low SKUs-to-bottom-level-pallets ratio ($<= 1.0$) performs best with a higher percentages of SKUs in the forward area compared to the others. Thus, further investigation is necessary in order to determine the impact of this parameter on the best design.

Table 6: Summary of Best Shape and Forward Area Size[1]

Warehouse	Random		1-Sided		2-Sided	
	Best Shape	SKUs	Best Shape	SKUs	Best Shape	SKUs
DS1	6.0	50%	4.0	70%	6.0	50%
DS2	3.0	10%	3.0	20%	3.0	20%
DS3	3.0	10%	3.0	20%	3.0	20%
DS4	3.0	10%	3.0	20%	3.0	20%
DS5	3.0	10%	3.0	20%	3.0	20%
DS6	3.0	10%	3.0	30%	6.0	20%
DS7	6.0	20%	3.0	30%	6.0	20%
DS8	6.0	30%	3.0	90%	6.0	40%
DS9	6.0	20%	4.0	30%	6.0	20%
DS10	4.0	10%	3.0	20%	3.0	20%
DS11	6.0	20%	6.0	50%	6.0	20%
DS12	6.0	30%	6.0	50%	6.0	40%
DS13	6.0	30%	6.0	60%	6.0	50%
DS14	4.0	5%	2.0	20%	4.0	20%
DS15	5.0	10%	5.0	20%	6.0	10%
DS16	6.0	10%	6.0	20%	6.0	20%
DS17	4.0	10%	2.0	10%	5.0	10%
DS18	6.0	30%	4.0	40%	6.0	20%
DS19	4.0	10%	3.0	40%	6.0	20%
DS20	4.0	40%	3.0	70%	3.0	90%

[1] Results assume 6 pallet levels and $\alpha = 0.4$.

3.2 SKUs to Bottom-Level Pallets

In considering the impact of the SKUs-to-bottom-level-pallets ratio, data sets 1, 8 and 19–20 have SKUs-to-bottom-level-pallets ratios of less than 1.0, and data sets 7 and 11–13 have ratios of 1.0. The remaining data sets have ratios higher than 1.0. To determine if this ratio affects the optimal number of SKUs in the forward area, this ratio is adjusted (by varying the number of pallet locations). Table 7 lists the optimal percentage of SKUs in the random-storage forward area, and Tables 8 and 9 list the optimal percentage of SKUs in the forward areas for the 1-sided and 2-sided class-based storage layouts for a range of SKUs-to-bottom-level-pallets ratios. (Again, we fix the number of pallet levels to 6 and the pallet area shape to 3.0, as these values generally perform well as compared to other values for these variables.)

Table 7: Optimal SKUs in Random Forward Area[1]

Example	SKUs-to-bottom-pallets					
	0.3	0.5	1.0	2.0	3.0	4.0
DS1	50%	40%	30%	20%	20%	20%
DS2	20-40%	20-30%	20%	10-20%	10%	5-10%
DS3	20%	20%	10-20%	10%	10%	10%
DS4	20%	10-20%	10-20%	10-20%	10%	5-10%
DS5	20-40%	20-50%	20-40%	10-20%	5-20%	10%
DS6	10%	10%	10%	5%	5%	5%
DS7	10%	10%	10%	10%	5%	5%
DS8	30%	30%	20%	20%	20%	20%
DS9	20%	20%	20%	20%	10%	10%
DS10	30%	20%	20%	20%	20%	20%
DS11	20%	20%	20%	20%	20%	20%
DS12	40%	40%	30%	20%	20%	20%
DS13	30%	30%	30%	20%	20%	20%
DS14	30%	20-30%	10-20%	10%	10%	50%
DS15	30%	30%	20%	20%	10%	10%
DS16	30%	20%	20%	20%	10%	10%
DS17	20-30%	20-30%	10-20%	10%	5-10%	5-10%
DS18	30%	30%	40%	30%	20%	20%
DS19	10%	10%	10%	10%	10%	10%
DS20	40%	30%	40%	30%	30%	30%

[1] Results assume 6 pallet levels and a pallet area shape of 3.0.

Table 8: Optimal SKUs in 1-Sided, Class-Based Forward Area[1]

Example	SKUs-to-bottom-pallets					
	0.3	0.5	1.0	2.0	3.0	4.0
DS1	100%	100%	70%	40%	20%	20%
DS2	80-100%	70-80%	40-50%	20-30%	20%	10-20%
DS3	90-100%	70%	40-50%	20%	20%	10-20%
DS4	80-100%	50-80%	30-60%	20-30%	20%	20%
DS5	80-100%	60-100%	40-70%	20-40%	20%	20%
DS6	50%	50%	40%	30%	30%	10%
DS7	90%	70%	30%	20%	20%	20%
DS8	100%	90%	70%	40%	30%	20%
DS9	90%	80%	50%	30%	20%	20%
DS10	70%	60%	20%	20%	20%	20%
DS11	100%	100%	60%	40%	20%	20%
DS12	90%	90%	60%	40%	30%	20%
DS13	100%	100%	90-100%	50%	30%	30%
DS14	60-100%	50-70%	30-40%	20%	20%	10%
DS15	90%	90%	60%	30%	30%	20%
DS16	100%	100%	100%	50%	30%	20%
DS17	60-90%	50-60%	30-40%	20%	10-20%	10%
DS18	100%	100%	70%	40%	40%	20%
DS19	60%	60%	30%	20%	20%	10%
DS20	100%	100%	60%	40%	40%	40%

[1] Results assume 6 pallet levels and a pallet area shape of 3.0.

Table 9: Optimal SKUs in 2-Sided, Class-Based Forward Area[1]

Example	SKUs-to-bottom-pallets					
	0.3	0.5	1.0	2.0	3.0	4.0
DS1	70%	50%	20%	20%	20%	20%
DS2	20%	50%	20-40%	20%	10-20%	10-20%
DS3	20%	30%	20-30%	20%	10-20%	10-20%
DS4	40%	20-30%	20-30%	20%	20%	20%
DS5	60%	50-60%	20%	20%	20%	20%
DS6	20%	30%	30%	20%	20%	20%
DS7	40%	30%	20%	20%	20%	20%
DS8	60%	50%	40%	30%	20%	20%
DS9	40%	30%	30%	20%	20%	20%
DS10	30%	20%	20%	20%	20%	20%
DS11	40%	20%	20%	20%	20%	20%
DS12	60%	60%	30%	30%	20%	20%
DS13	90%	50%	40%	40%	30%	20%
DS14	40%	20-30%	20%	20%	20%	20%
DS15	60%	50%	30%	20%	20%	10%
DS16	50%	30%	20%	20%	20%	20%
DS17	30%	20%	20%	20%	20%	20%
DS18	80%	50%	20%	20%	20%	20%
DS19	30%	20%	20%	20%	20%	10%
DS20	100%	70%	60%	40%	30%	30%

[1] Results assume 6 pallet levels and a pallet area shape of 3.0.

Again, a SKUs-to-bottom-level-pallets ratio of 1.0 or less implies that all of the SKUs can be located in bottom-level pallet positions, and values greater than 1.0 indicate that the footprint of the pallet area would have to grow in order to accommodate all SKUs on the bottom level. Thus, in moving from left to right in Tables 7–9, it is not surprising that the optimal number of forward SKUs decreases as the number of available bottom-level locations decreases. When there are few SKUs compared to bottom-level pallets, intuitively, more SKUs should be placed in the forward area to minimize travel. Also, note that the 1-sided forward area layout performs best with significantly more SKUs in the forward area for SKUs-to-bottom-level-pallets ratios of 1.0 or less as compared to the random storage and 2-sided forward area layouts.

3.3 Demand Skewness

Next, we consider the effect of demand skewness on the optimal size of the forward area. We evaluate the example data sets using three levels of demand skewness as depicted in Figure 2: average skewness (80/20, such that 20% of the items represent 80% of the demand), moderately skewed (60%/20%), and hardly skewed (40%/20%).

In comparing the percent of SKUs in the forward area across all data sets, we assume that the number of pallet positions is such that all SKUs can have a bottom-level location (with the number of bottom-level locations approximately equal to the number of SKUs).

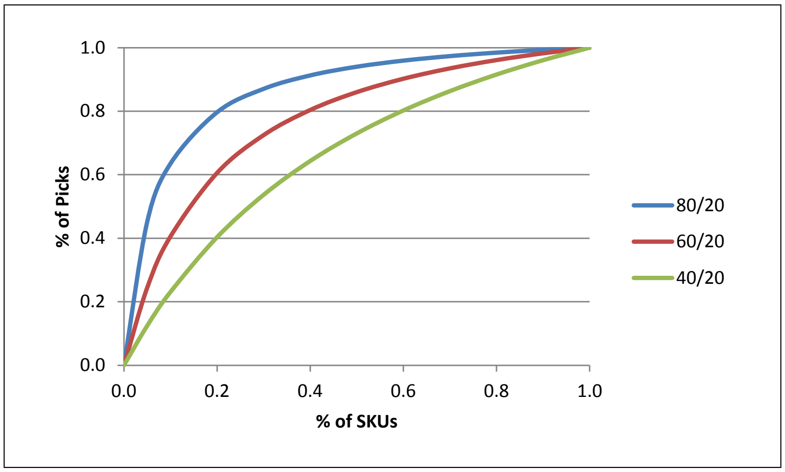


Figure 2: Demand skewness levels.

The results for the example data sets are listed in Tables 10–12, with the forward area size that results in the least amount of travel for each layout.

In general, the optimal forward area size increases as the skewness decreases, as indicated in Tables 10–12. For an ABC curve with average skewness, the optimal percentage of SKUs in the random storage forward area is approximately 20%; a moderately skewed curve prefers 20–40% of the SKUs, and the hardly skewed curve performs well with 40–70% of the SKUs in the forward area.

Again, the 1-sided layout in Table 11 outperforms the other layouts. The curve with an average skewness results in the least travel for approximately 40–50% of the SKUs in the forward area; the moderately skewed curve performs well with about 60% of the SKUs, and the hardly skewed curve performs best with 60% or more of the SKUs in the forward area.

For the 2-sided forward area layout, the curve with an average skewness performs well with 20% of the SKUs; the moderately skewed curve prefers about 40-60% of the SKUs, and the hardly skewed curve performs the best with around 40–80% of the SKUs in the forward area. Note that for a hardly skewed curve, the random storage forward area and 2-sided forward area have similar performance, especially for the data sets with a lower throughput requirement. Thus, for lower demand skewness, the random storage forward layout may be preferred for a doors-on-two-sides configuration, as random storage is generally easier to maintain than class-based storage.

Table 10: Random Forward Area Sizes for Different Skewness Levels[1]

Example	No Forward Area	Random Forward Area					
		80/20		60/20		40/20	
		% SKUs	Hours	% SKUs	Hours	% SKUs	Hours
DS1	1695	20%	1164	20-30%	1309	40-50%	1406
DS2	182	20%	138	30%	155	50-60%	169
DS3	169	20%	127	30%	139	30-50%	150
DS4	93	20%	63	20-30%	70	40%	75
DS5	45	20%	31	20-30%	35	40-70%	38
DS6	473	10%	332	20%	373	30%	400
DS7	961	20%	731	20%	786	30%	832
DS8	1178	20%	659	40%	782	70%	859
DS9	686	20%	520	40%	607	80%	660
DS10	104	20%	87	20%	96	20%	105
DS11	1554	20%	858	20%	1025	40%	1146
DS12	886	10%	575	30%	652	40%	708
DS13	971	20%	477	30%	575	50-60%	650
DS14	103	10%	87	20%	92	20%	96
DS15	921	10%	675	20%	746	30%	796
DS16	3510	20%	1745	20%	2168	40%	2512
DS17	98	20%	78	20-30%	83	30-40%	87
DS18	544	20%	323	30%	374	40-50%	409
DS19	699	20%	492	30%	537	40%	575
DS20	48	20%	21	40%	24	70%	26

[1] Results assume 6 pallet levels, a pallet area shape of 3.0, and a SKUs-to-bottom-level-pallets ratio of 1.0.

Table 11: 1-Sided Forward Area Sizes for Different Skewness Levels[1]

Example	No Forward Area	1-Sided Forward Area					
		80/20		60/20		40/20	
		% SKUs	Hours	% SKUs	Hours	% SKUs	Hours
DS1	1695	40%	931	60%	1124	50%	1295
DS2	182	50%	105	60%	127	60-90%	149
DS3	169	40-50%	98	60%	117	60-70%	136
DS4	93	40-50%	50	60%	59	60-90%	69
DS5	45	40-50%	24	60-70%	29	60-100%	34
DS6	473	40%	269	40%	325	40%	375
DS7	961	40%	545	60%	637	60%	720
DS8	1178	50%	507	100%	602	100%	704
DS9	686	50%	391	90%	479	100%	558
DS10	104	20%	74	20%	88	20%	110
DS11	1554	60%	713	100%	877	100%	1049
DS12	886	50%	442	60%	535	70%	624
DS13	971	60%	390	100%	480	100%	576
DS14	103	20%	72	40%	81	40%	89
DS15	921	50%	496	60%	603	60%	703
DS16	3510	100%	1405	100%	1819	100%	2320
DS17	98	40%	62	40%	71	40-50%	79
DS18	544	50%	252	70%	312	80%	369
DS19	699	40%	388	60%	461	60%	526
DS20	48	40%	18	60%	21	100%	23

[1] Results assume 6 pallet levels, a pallet area shape of 3.0, and a SKUs-to-bottom-level-pallets ratio of 1.0.

Table 12: 2-Sided Forward Area Sizes for Different Skewness Levels[1]

Example	No Forward Area	2-Sided Forward Area					
		80/20		60/20		40/20	
		% SKUs	Hours	% SKUs	Hours	% SKUs	Hours
DS1	1695	20%	1084	40%	1256	50%	1382
DS2	182	20%	130	40%	149	50-80%	164
DS3	169	20%	119	40%	135	40-50%	148
DS4	93	20%	58	30-60%	68	40-60%	74
DS5	45	20%	29	30-70%	34	50-80%	37
DS6	473	20%	306	30%	361	30%	396
DS7	961	20%	678	30%	768	40%	824
DS8	1178	40%	601	60%	738	100%	821
DS9	686	20%	477	60%	574	80%	636
DS10	104	20%	83	20%	95	20%	105
DS11	1554	30%	768	40%	977	40%	1128
DS12	886	20%	529	40%	630	40%	698
DS13	971	40%	429	40%	540	60%	634
DS14	103	20%	84	20%	91	20%	95
DS15	921	20%	629	20%	732	40%	788
DS16	3510	20%	1600	40%	2121	40%	2482
DS17	98	20%	74	40%	78	20-30%	86
DS18	544	20%	292	40%	356	50%	402
DS19	699	20%	461	40%	517	40%	567
DS20	48	40%	18	60%	22	70%	25

[1] Results assume 6 pallet levels, a pallet area shape of 3.0, and a SKUs-to-bottom-level-pallets ratio of 1.0.

3.4 Cases Per Pallet

The number of cases per pallet, along with the number of picks per line, affect the number of replenishments. Next, we evaluate various combinations of cases-per-pallet and picks-per-line (average values) to determine if there are any situations where a forward area is not preferred. The number of cases per pallet for order picking is assumed to be approximately 80 percent of the number of cases on incoming pallets.

Table 13 lists the labor hours for an ABC curve with average skewness, and Table 14 lists results for a hardly skewed ABC curve for DS2 for various cases-per-pallet and picks-per-line combinations. (The travel-time model for the 2-sided, class-based layout requires at least three pick lines per tour, so travel times are blank for pick lines of less than three.)

As expected, the benefit of having a forward area is diminished as the number of picks per line is high relative to the capacity of the pallet, especially for a low ABC

Table 13: DS2 Labor Hours for an ABC Curve with Average Skewness

Incoming cases/pallet	Picks/ Line	Avg Lines	No Forward	Random Forward	1-Sided Forward	2-Sided Forward
10	1	8	241	167	128	153
10	5	1.6	99	87	72	–
10	10	0.8	69	68	59	–
20	1	16	202	130	101	117
20	5	3.2	88	73	61	68
20	10	1.6	66	59	51	–
50	1	40	165	92	78	83
50	5	8	74	59	48	54
50	10	4	58	50	42	47

Table 14: DS2 Labor Hours for an ABC Curve with Low Skewness

Incoming cases/pallet	Picks/ Line	Avg Lines	No Forward	Random Forward	1-Sided Forward	2-Sided Forward
10	1	8	241	198	176	196
10	5	1.6	99	94	88	–
10	10	0.8	69	69	66	–
20	1	16	202	160	143	157
20	5	3.2	88	80	75	79
20	10	1.6	66	63	60	–
50	1	40	165	120	110	117
50	5	8	74	65	60	64
50	10	4	58	54	49	53

curve skewness. Also, in situations where the savings of having a forward area is low, failure to choose the optimal percentage of SKUs in the forward area may actually result in higher labor for the forward area layouts as compared to a random storage layout with no forward area. However, if the number of bottom-level pallets is much greater than the number of bottom level SKUs, a forward area may be justified, even for a high number of picks per line. Note also that even though we only consider one pallet for each SKU in the forward area, including all of the reserve locations in the forward area for fast-moving SKUs that have a very high number of picks per line may be beneficial.

3.5 Pallet Rack Height

Finally, we investigate the variable for pallet rack height by evaluating the labor required for pallet rack levels of 4, 5, and 6. A pallet area shape of 3.0 is considered for the example data sets. The results for DS1 and DS2 are listed in Tables 15 and 16, and the remaining 18 examples are included in B.

For DS1 all of the SKUs can be accommodated on the bottom level of pallet rack for the three levels of pallet rack considered. Table 15 lists the labor required for the different levels of pallet rack for various percentages of SKUs in the forward area (note that the random storage layout with no forward area is included as 0% of the SKUs with the random storage forward area). For each layout in Table 15, the travel times decrease as the number of pallet levels increase. For this example data set, the decrease in the footprint of the pallet area results in labor savings that are more than the labor increases associated with the extra vertical travel for higher levels of pallet rack.

Table 15: DS1: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	2388	2300	2212	–	–	–	–	–	–
20	1785	1700	1647	1667	1591	1536	1677	1601	1540
40	1724	1654	1580	1462	1405	1346	1627	1563	1519
60	1766	1704	1619	1352	1312	1256	1625	1586	1507
80	1854	1765	1706	1287	1239	1217	1641	1587	1521
100	1936	1858	1792	1254	1225	1208	1659	1611	1541

For DS2 listed in Table 16, the labor hours decrease as the pallet rack height increases for forward areas that have 20% or less SKUs in the forward area. However, with 10,831 SKUs and at most 6,000 bottom-level locations (for 4 levels of pallet rack), not all SKUs can receive a bottom-level location without increasing the footprint of the warehouse. Thus, for more than 40% of the SKUs in the forward area, the travel

Table 16: DS2: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	127	127	120	–	–	–	–	–	–
20	107	107	101	86	86	83	99	99	93
40	120	119	118	90	91	92	106	105	105
60	138	139	141	100	102	104	118	120	122
80	160	161	163	111	113	114	134	136	137
100	177	178	180	119	121	122	145	146	148

times increase for higher levels of pallet rack due to the larger footprint of the pallet area.

From this analysis, a smaller pallet rack footprint (with higher levels of pallet rack) is preferred if all SKUs can be accommodated on the bottom level. Further, we observe that having less SKUs in the forward area is preferred to increasing the footprint of the warehouse in order to make room for more bottom-level SKUs.

4. Results

For our final analysis we generate 520 test data sets and determine the best design for each by enumerating over all possible designs. From the correlation coefficients for the optimal forward area size, three parameters that should be considered in sizing the forward area include: the SKUs-to-bottom-level pallets ratio, the ABC curve skewness, and the number of lines per batch. Recall also that the number of SKUs also resulted in a significant correlation; however, this parameter is embedded in the SKUs-to-bottom-level ratio parameter (that has a slightly higher correlation). In order to determine the range of parameters that are suitable for a given design, we classify the parameters into three ranges (high, medium and low) as shown in Table 17. The breakpoints for the classifications in Table 17 allow a categorization of data sets. The breakpoints were determined by first considering a more finite range for each parameter (using the 520 data sets) and then consolidating them in such a way that the consolidation did not result in an overlap of designs (as characterized by the best layout and forward area size). Nonetheless, in a few cases, even the more finite ranges considered included multiple designs. For example, the data sets with SKUs-to-bottom-pallets ratios ranging between 2.6 and 3.0, skewness levels of 50/20–55/20, and with lines per batch of 16–20, included two design types: a 1-sided layout with 30% of the SKUs (for three of the five data sets in this category) and a random storage forward area with 10% of the SKUs (for 2 of the data sets).

A three-letter sequence is used to categorize each of the 520 data sets, where the

Table 17: Parameter Levels

Parameter	High Range	Medium Range	Low Range
SKUs-to-bottom-level ratio	2.6–4.0	1.1–2.5	≤ 1.0
ABC Skewness	90–95	70–85	50–65
Lines per batch	> 40	11–40	3–10

letter in the sequence denotes the level for the parameter (H–high, M–medium, and L–low) and the position of the letter indicates the parameter (position 1 = the SKUs-to-bottom-level ratio, position 2 = ABC skewness, and position 3 = number of Pick lines). For example, a sequence of “LHM” would indicate that the data set has a low SKUs-to-bottom-level-pallets ratio, a high ABC curve skewness, and a medium number of lines per batch.

For the 1-sided door configuration, 492 of the 520 data sets (95%) resulted in four dominant designs: a 1-sided forward area layout with 20% of the SKUs (11%), a 1-sided forward area layout with 30% of the SKUs (49%), a 1-sided forward area layout with 80% of the SKUs (13%), and a random storage layout with 10% of the SKUs (22%). The remaining 5% resulted in designs with a 1-sided layout with 40%, 50% and 60% of the SKUs in the forward area. Also worth noting, the 1-sided layout generally outperforms the 2-sided layout, as only six of the 520 data sets prefer the 2-sided layout when considering all of the forward area layouts. For each of the 27 ($3 \times 3 \times 3$) categories, we determine the distribution of data sets over each type of design (as characterized by the layout and forward area size). Figure 3 illustrates the distribution of these four designs for a 1-sided door configuration.

Notice that each of the faces of the cube represents a particular parameter sequence. For example, the designs that have a high SKUs-to-bottom-level-pallets ratio (three-letter sequence begins with “H”) are represented on the right face of the cube. All 27 sequences are represented with a sequence at each of the following locations along or within the cube:

- 8 corners,
- 12 edge midpoints,
- 6 face midpoints,
- 1 cube centerpoint (represented by sequence MMM).

The dominant designs for the parameter sequences are color coded, where 1S, 2S and R represent the 1-sided class-based layout, 2-sided class-based layout and random storage layout, and the percentage indicates the percent of SKUs that should be picked from the forward area within the bottom-level, centermost aisles. Based on the distribution of the designs in the cubes, particular parameter-range combinations yield

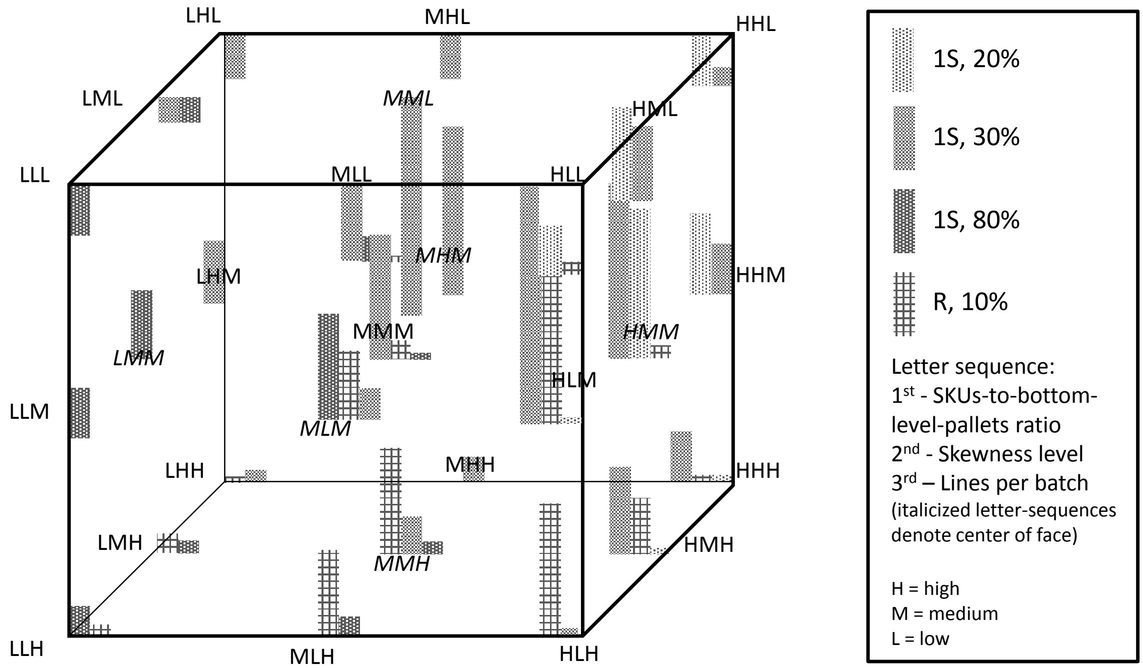


Figure 3: Parameter Levels and Optimal Designs for a 1-Sided Door Configuration

similar designs, as seen from the clustering of designs. Accordingly, generalizations can be used to arrive at an initial solution based on the value of the parameters.

From Figure 3, data sets that have a high SKUs-to-bottom-level-pallets ratio with at least a medium skewness level (HM- or HH-) perform best with a 1-sided layout with 20% of the SKUs in the forward area. Data sets with a high SKUs-to-bottom-level-pallets ratio (H–) or a medium SKUs-to-bottom-level-pallets ratio and medium–high skewness level (MM- or MH-) prefer the 1-sided layout with 20% of the SKUs in the forward area, whereas data sets with a low SKUs-to-bottom-level-pallets ratio and low–medium skewness level (LL- and LM-) perform well with 80% of the SKUs in the 1-sided forward area. Random storage with 10% of the SKUs in the forward area performs well with a medium–high ratio, a low–medium skewness level and a high number of lines per batch (MLH, MMH, HLM, and HMH).

For a 2-sided door configuration, 507 of the 520 data sets (98%) resulted in the following dominant designs: a 2-sided forward area layout with 20% of the SKUs (17%), a 2-sided forward area layout with 30% of the SKUs (16%), a 2-sided forward area layout with 80% of the SKUs (2%), a random storage forward area with 5% of the SKUs (7%), and a random storage forward area with 10% of the SKUs (56%). The remaining 2% of the solutions were 2-sided layouts with 40%, 50% and 60% of the SKUs in the forward area. Figure 4 depicts the distribution of these designs for the 2-sided door configuration for the 507 data sets.

The left face of the cube includes designs with a low SKUs-to-bottom-level-pallets

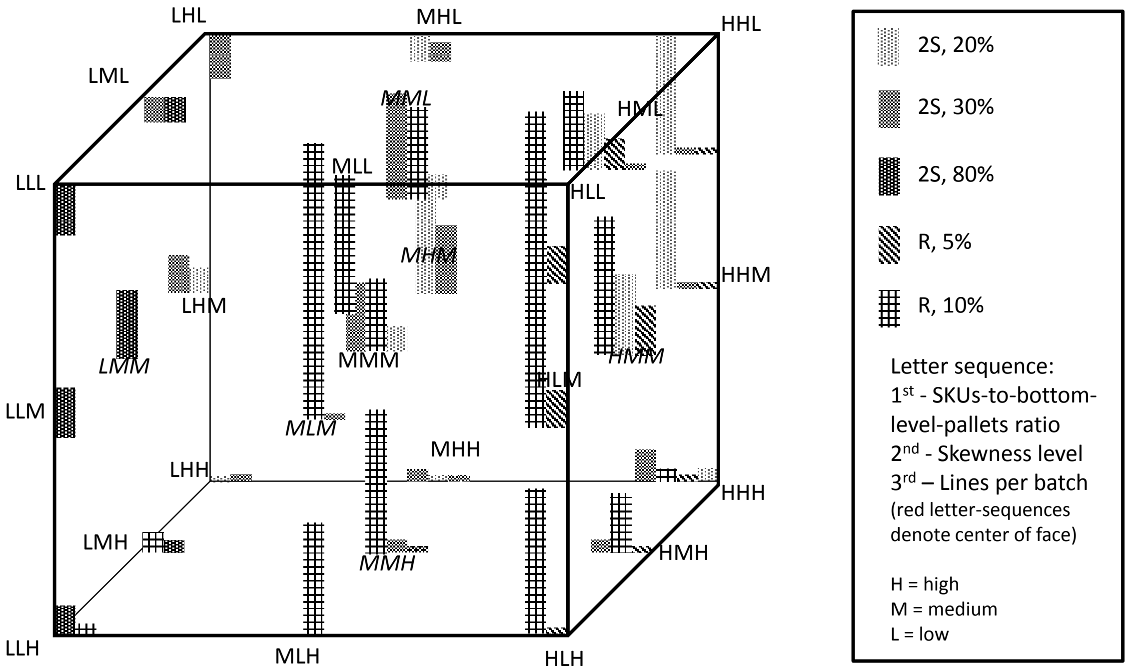


Figure 4: Parameter Levels and Optimal Designs fir a 2-Sided Door Configuration

ratio. In general, unless the skewness level is high, data sets with low SKUs-to-bottom-level-pallets ratios and low–medium skewness levels (LL-, LML, and LMM) perform best with the 2-sided layout with 80% of the SKUs in the forward area. However, if the skewness is not low, a smaller 2-sided forward area layout is preferred with 30% of the SKUs. A 2-sided layout with 20% of the SKUs is desirable when both the SKUs-to-bottom-level-pallets ratio and skewness level are high, as long as the number of lines per batch is not high (HHL, HHM, MHM). When SKUs-to-bottom-level-pallets ratio is medium–high and the skewness level is medium to low (MM-, ML-, HM-, HL-), the random storage layout with 10% of the SKUs performs well. Also worth noting, even though the random forward area layout with 5% of the SKUs appears in the solution space for these data sets, the random forward area layout with 10% of the SKUs dominated the layouts with just 5% of the SKUs for the 507 data sets.

Our results indicate that warehouse parameters can be useful in predicting a design that will result in the best operational performance in terms of labor required for putaway, order picking and replenishment operations. Given the vast solution space associated with warehouse design, we feel that this research can benefit practitioners in pointing to an initial design that can then be further analyzed and optimized. In addition, our analysis can be used to gain insight into the impact of warehouse parameters on design performance.

A. Labor for Varying Shapes and Layouts (Data Sets 3–20)

Table 18: DS3 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	162	5%	130	40%	106	20%	136
1.0	132	5%	108	30%	88	20%	107
1.5	126	5%	104	30%	84	20%	101
2.0	118	5%	97	30%	81	20%	92
3.0	112*	10%	90	20%	78*	20%	87
4.0	112*	10%	89*	20%	78*	20%	86
5.0	114	10%	89*	20%	80	20%	85*
6.0	117	10%	90	20%	81	20%	86
7.0	117	10%	89*	10%	82	20%	86

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 19: DS4 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	99	10%	70	60%	53	30%	64
1.0	76	5%	52	30%	44	20%	52
1.5	69	5%	49	20%	41	20%	46
2.0	73	5%	51	20%	42	20%	47
3.0	66*	10%	46	20%	39*	20%	43
4.0	68	10%	46	20%	40	20%	43
5.0	67	10%	46	20%	40	20%	43
6.0	67	10%	45*	20%	40	20%	42*
7.0	70	10%	47	20%	42	20%	44

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 20: DS5 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	40	10%	32	40%	27	20%	30
1.0	32	10%	26	20%	23	20%	25
1.5	30	10%	24	20%	21	20%	23
2.0	30	10%	24	20%	21	20%	23
3.0	28*	10%	22*	20%	20*	20%	21*
4.0	29	10%	23	20%	21	20%	22
5.0	29	10%	23	20%	21	20%	22
6.0	28*	10%	22*	20%	21	20%	21*
7.0	30	10%	23	20%	22	20%	22

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 21: DS6 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	687	10%	366	70%	277	20%	369
1.0	593	10%	322	50%	243	30%	309
1.5	540	10%	301	40%	227	20%	286
2.0	491	5%	278	40%	215	20%	253
3.0	473	10%	268	30%	214*	20%	249
4.0	475	10%	269	30%	214*	20%	244
5.0	468*	10%	266*	30%	216	20%	243
6.0	469	10%	266*	30%	218	20%	238*
7.0	474	10%	269	30%	225	20%	238*

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 22: DS7 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	1314	5%	1083	100%	674	30%	1036
1.0	1083	5%	865	70%	601	20%	830
1.5	1045	5%	818	70%	584	30%	799
2.0	1004	10%	797	50%	569	20%	757
3.0	961*	10%	743	30%	556*	20%	688
4.0	969	20%	730	30%	563	30%	683
5.0	998	20%	729	30%	572	30%	675
6.0	1006	20%	719*	30%	583	20%	668*
7.0	1023	20%	724	30%	595	20%	670

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 23: DS8 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	1791	30%	1069	100%	745	70%	956
1.0	1483	20%	913	100%	619	30%	806
1.5	1045*	20%	825	90%	569	40%	729
2.0	1263	20%	794	90%	549	50%	692
3.0	1178	20%	750	90%	538*	40%	645
4.0	1158	20%	730	70%	545	40%	643
5.0	1164	20%	728	70%	554	30%	632
6.0	1117	30%	690*	60%	539	40%	610*
7.0	1148	30%	700	60%	552	40%	614

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 24: DS9 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	912	10%	622	70%	449	20%	573
1.0	825	10%	569	80%	395	20%	496
1.5	766	10%	512	50%	375	30%	456
2.0	702	10%	476	50%	358	20%	431
3.0	686	20%	459	30%	355	20%	407
4.0	667	20%	440	30%	347*	30%	396
5.0	665*	20%	434	30%	350	20%	391
6.0	673	20%	431*	30%	350	20%	387*
7.0	684	20%	436	30%	361	20%	397

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 25: DS10 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	134	5%	123	40%	96	20%	121
1.0	108	5%	94	20%	77	20%	91
1.5	102	5%	89	20%	73	20%	86
2.0	101*	10%	85	20%	72*	20%	83
3.0	104	10%	85	20%	73	20%	82
4.0	102	10%	82*	20%	73	20%	80
5.0	103	10%	82*	20%	74	20%	79*
6.0	105	10%	83	20%	75	20%	80
7.0	108	10%	84	20%	78	20%	81

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 26: DS11 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	2208	20%	1158	100%	970	20%	1224
1.0	1865	20%	1011	100%	817	20%	919
1.5	1790	20%	967	100%	782	20%	893
2.0	1688	20%	918	100%	755	20%	855
3.0	1554	20%	858	60%	713	20%	768
4.0	1510	20%	846	50%	698	20%	776
5.0	1503	20%	836	50%	696	20%	758
6.0	1473	20%	830*	50%	693*	20%	749*
7.0	1461*	20%	830*	40%	702	20%	754

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 27: DS12 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	1231	20%	929	90%	744	30%	922
1.0	1054	20%	815	90%	636	40%	809
1.5	960	20%	738	90%	588	30%	721
2.0	928	30%	709	90%	572	30%	686
3.0	886	30%	667	60%	557	30%	647
4.0	887	30%	656	50%	557	30%	635
5.0	876*	30%	644	50%	558	40%	619
6.0	878	30%	635*	50%	556*	40%	612*
7.0	888	30%	638	50%	568	40%	615

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 28: DS13 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	1224	40%	688	100%	621	40%	639
1.0	1164	30%	624	100%	542	30%	597
1.5	1091	30%	604	100%	498	40%	574
2.0	1001	20%	564	100%	467	40%	534
3.0	971	30%	550	90%	455	40%	508
4.0	934	30%	530	80%	447	40%	497
5.0	921	30%	533	70%	449	40%	497
6.0	919*	30%	520*	60%	443*	50%	485*
7.0	925	30%	526	60%	451	40%	490

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 29: DS14 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	85	5%	82	30%	69	20%	88
1.0	69	5%	65	20%	57	20%	68
1.5	65	5%	61	20%	55*	20%	64
2.0	64*	5%	60	20%	55*	20%	62
3.0	67	10%	60	10%	56	20%	62
4.0	66	5%	59*	10%	55*	20%	61*
5.0	67	10%	59*	10%	56	20%	62
6.0	69	10%	60	10%	57	20%	63
7.0	71	10%	61	10%	58	20%	65

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 30: DS15 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	738	5%	671	20%	632	20%	692
1.0	632	10%	571	20%	531	20%	580
1.5	576	10%	519	20%	483	10%	517
2.0	557	10%	499	20%	463	10%	497
3.0	532	10%	473	20%	443	10%	470
4.0	532	10%	468	20%	442	10%	466
5.0	525*	10%	460*	20%	439*	10%	458
6.0	527	10%	460*	20%	443	10%	457*
7.0	533	10%	464	20%	450	10%	461

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 31: DS16 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	1979	10%	1325	10%	1445	20%	1422
1.0	2015	10%	1331	10%	1423	10%	1323
1.5	1948	10%	1299	20%	1327	10%	1280
2.0	1814	10%	1224	20%	1221	10%	1212
3.0	1787	10%	1199	20%	1166	20%	1182
4.0	1727	10%	1168	20%	1117	20%	1148
5.0	1702	10%	1161	20%	1097	20%	1132
6.0	1695*	10%	1146*	20%	1077*	20%	1115*
7.0	1697	10%	1153	20%	1081	20%	1122

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 32: DS17 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	86	5%	79	30%	61	20%	80
1.0	69	5%	62	20%	51	10%	61
1.5	65	5%	57	20%	48*	10%	56
2.0	64*	5%	55	10%	48*	10%	53
3.0	67	5%	56	10%	49	10%	53
4.0	66	10%	54*	10%	49	10%	53
5.0	67	10%	54*	10%	49	10%	52*
6.0	68	5%	55	10%	50	10%	53
7.0	70	5%	56	10%	52	10%	54

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 33: DS18 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	580	20%	406	60%	323	20%	374
1.0	507	20%	368	50%	320	20%	335
1.5	496	20%	353	60%	299	20%	323
2.0	464	20%	327	60%	284	20%	298
3.0	441	30%	309	40%	274	20%	284
4.0	438	30%	303	40%	272*	20%	279
5.0	442	30%	302	40%	274	20%	279
6.0	434*	30%	297*	40%	273	20%	274*
7.0	446	30%	303	40%	278	20%	280

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 34: DS19 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	1228	5%	791	90%	468	50%	720
1.0	1009	10%	624	60%	411	40%	569
1.5	913	10%	595	60%	379	30%	510
2.0	883	10%	553	60%	372	20%	501
3.0	851*	10%	530	40%	368*	20%	455
4.0	861	10%	512	30%	370	30%	449
5.0	889	20%	524	30%	383	40%	463
6.0	869	20%	491*	30%	374	20%	438*
7.0	913	20%	505	30%	389	30%	445

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

Table 35: DS20 Labor for Varying Shapes and Layouts[1]

Shape	No Forward Area	Forward Area Layouts					
		Random		1-sided		2-sided	
		SKUs	Hours	SKUs	Hours	SKUs	Hours
0.5	69	50%	31	80%	26	–	–
1.0	61	30%	28	90%	22	90%	25
1.5	60	30%	26	90%	21	90%	23
2.0	54	30%	25	60%	20*	80%	21
3.0	52*	30%	25	70%	20*	90%	21
4.0	53	40%	24*	70%	20*	50%	21
5.0	53	50%	24*	50%	21	50%	21
6.0	55	50%	24*	50%	21	50%	21
7.0	56	50%	25	50%	22	60%	22

[1] Results assume 6 pallet levels and $\alpha = 0.4$.
* Denotes the best solution for the layout considered.

B. Daily Travel for Different Levels of Pallet Rack

Table 36: DS3: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	119	119	112	–	–	–	–	–	–
20	100	98	93	81	80	78	92	92	87
40	112	111	109	85	86	86	100	99	98
60	128	129	131	94	96	97	110	112	113
80	146	147	148	104	105	107	123	124	126
100	165	166	167	112	114	115	136	138	139

Table 37: DS4: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	71	66	66	–	–	–	–	–	–
20	52	49	48	42	40	39	46	44	43
40	59	55	55	43	42	42	50	48	48
60	65	65	66	46	46	47	54	54	54
80	73	74	75	50	51	52	59	60	61
100	82	83	84	53	54	55	65	66	67

Table 38: DS5: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	28	28	28	–	–	–	–	–	–
20	23	23	23	20	20	20	21	21	21
40	26	27	27	21	22	23	24	24	25
60	31	32	32	24	25	25	27	28	28
80	36	36	37	26	27	27	31	31	32
100	40	41	41	28	29	29	34	34	35

Table 39: DS6: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	511	492	473	–	–	–	–	–	–
20	315	300	289	253	241	233	263	251	249
40	372	353	337	226	219	215	283	278	263
60	421	402	388	239	236	237	315	298	290
80	438	424	420	255	257	261	326	316	311
100	456	452	456	269	273	277	339	334	337

Table 40: DS7: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	1056	1008	961	–	–	–	–	–	–
20	819	782	744	629	605	580	763	726	688
40	859	824	788	589	574	558	783	748	712
60	911	874	843	592	580	573	806	777	744
80	962	937	912	609	611	613	837	813	786
100	1021	996	976	641	644	654	869	842	817

Table 41: DS8: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	1256	1217	1178	–	–	–	–	–	–
20	784	773	750	700	680	657	720	722	700
40	826	790	764	629	603	583	710	673	645
60	880	843	802	594	573	551	705	699	661
80	940	894	860	582	562	551	748	707	692
100	998	953	913	567	554	546	764	744	706

Table 42: DS9: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	713	682	686	–	–	–	–	–	–
20	486	462	459	385	368	368	434	409	407
40	530	502	497	368	355	356	448	422	427
60	577	549	540	370	362	363	471	454	444
80	619	597	602	382	383	388	494	477	482
100	665	670	675	408	412	417	519	523	528

Table 43: DS10: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	107	105	104	–	–	–	–	–	–
20	91	88	87	74	73	72	85	83	83
40	100	98	98	80	79	81	92	90	90
60	111	110	113	87	88	91	100	98	101
80	125	127	130	97	99	101	109	112	114
100	138	140	142	105	107	110	118	120	123

Table 44: DS11: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	1638	1596	1554	–	–	–	–	–	–
20	931	882	858	842	800	773	845	803	768
40	1067	1013	975	793	758	729	888	840	803
60	1183	1130	1084	764	736	713	924	878	861
80	1282	1227	1177	761	740	723	945	927	903
100	1366	1311	1259	763	748	738	986	964	937

Table 45: DS12: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	961	923	886	–	–	–	–	–	–
20	732	704	674	698	670	640	722	696	–
40	736	706	673	627	602	577	705	680	648
60	766	737	704	595	576	557	719	687	660
80	805	777	747	587	575	563	735	712	684
100	846	821	795	600	594	588	768	745	719

Table 46: DS13: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	982	952	971	–	–	–	–	–	–
20	561	548	560	572	554	562	548	538	551
40	582	566	562	516	496	492	534	515	508
60	638	616	603	489	470	462	538	531	521
80	693	667	654	477	462	457	569	542	543
100	742	714	696	473	462	455	585	571	555

Table 47: DS14: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	70	68	67	–	–	–	–	–	–
20	66	65	64	57	56	56	64	63	62
40	77	76	78	63	64	66	71	71	73
60	92	94	96	72	74	76	83	85	86
80	105	107	109	80	82	84	93	95	96
100	116	117	119	87	89	91	100	102	104

Table 48: DS15: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	576	554	532	–	–	–	–	–	–
20	520	501	481	476	459	443	512	493	474
40	580	589	598	488	497	506	556	565	574
60	712	718	725	558	565	571	668	675	681
80	824	829	834	613	618	623	760	765	770
100	918	922	926	664	668	671	841	845	849

Table 49: DS16: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	1749	1721	1787	–	–	–	–	–	–
20	1273	1247	1246	1207	1168	1166	1203	1182	1182
40	1666	1689	1712	1300	1324	1347	1459	1482	1505
60	2066	2079	2093	1392	1405	1419	1698	1711	1724
80	2455	2463	2470	1461	1468	1476	1897	1905	1912
100	2815	2819	2823	1561	1565	1569	2134	2138	2142

Table 50: DS17: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	70	68	67	–	–	–	–	–	–
20	61	60	58	52	49	49	57	56	55
40	69	68	70	54	55	56	63	62	64
60	80	82	83	62	63	65	71	73	74
80	90	92	93	69	70	72	78	80	81
100	101	102	104	74	76	77	86	88	89

Table 51: DS18: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	457	436	441						
20	326	313	311	311	297	295	296	283	284
40	337	323	315	291	280	274	319	307	300
60	365	350	354	286	278	282	333	320	324
80	398	400	403	286	289	292	347	350	353
100	439	442	445	295	298	301	364	367	370

Table 52: DS19: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	937	894	851	–	–	–	–	–	–
20	602	563	539	435	411	396	513	481	455
40	651	618	584	394	381	368	519	492	491
60	693	656	627	389	379	374	543	513	506
80	730	699	666	402	398	395	570	558	528
100	764	738	711	423	426	428	598	584	555

Table 53: DS20: Daily Travel Time for Different Levels of Pallet Rack

% Forward SKUs	Random Layout			1-Sided Layout			2-Sided Layout		
	Levels			Levels			Levels		
	4	5	6	4	5	6	4	5	6
0	52	52	52	–	–	–	–	–	–
20	26	26	27	26	26	27	–	–	–
40	25	24	25	23	22	22	–	–	23
60	25	25	25	21	21	21	–	22	21
80	28	27	26	20	20	20	21	22	22
100	28	28	27	20	20	20	22	22	21

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