Fulfillment Center Storage Optimization

by

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Submitted to the Department of Mechanical Engineering and the MIT Sloan School of Management in partial fulfillment of the requirements for the degrees of

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Abstract

Warehouses and fulfillment centers have traditionally been designed to handle bulk orders of pallet and cases. The growth in e-commerce is demanding operational improvements for efficient storage of large selections and the ability to quickly pick, fill, pack and ship single items and small orders. Online grocery fulfillment presents a new gamut of challenges due to the unique storage and handling requirements of grocery products. As demand increases, storage space can quickly become a performance-limiting constraint. Operations managers must find creative ways to fit more products into the same amount of space, while maintaining or increasing throughput to meet the increased demand and efficiency targets.

This thesis proposes that an optimum fulfillment center storage system can be achieved by strategically balancing trade-offs between labor productivity and space utilization and by minimizing the impacts of variation. This document evaluates the relationships between these trade-offs and highlights five guiding principles of great storage systems for high-rate fulfillment centers.

Amazon Fresh will serve as a case-study to provide a real-world complex application for testing the claims presented in this thesis. Research findings and the five guiding principles are are used to develop data-supported recommendations to address storage-related challenges at Amazon Fresh fulfillment centers. The insights from this research can be used to improve storage capacity and efficiency with a well-balanced storage system.

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Introduction

1.1 General Problem Statement

High-rate fulfillment centers operate in an environment with many competing priorities that require constant oversight and management to prevent imbalance. Constant trade-offs have to be made. Most of these trade-offs are due to the interrelationships between space utilization, labor productivity and flexibility for the future.

Many challenges with complex systems are not due to simple cause-and-effect relationships, but rather are the result of unknown interconnections and relationships between elements of the system. Changes made to one part of the system can have unexpected impacts that degrade overall performance and create additional problems. Achieving operational effectiveness and efficiency in a system with multiple competing demands and many sources of variation requires a more systematic approach[1].

1.2 Hypothesis

This thesis proposes that an optimum fulfillment center storage system can be achieved by strategically balancing trade-offs between labor productivity and space utilization, and by designing a system that minimizes the impact of variations. Significant increases in storage capacity can be realized with a balanced system—often with minimal capital investment.

1.3 Purpose & Goals

Substantial research has been conducted on the design of specific aspects of warehouse systems but a comprehensive study of storage systems and the complex interactions between the competing demands of labor productivity, space utilization, flexibility, and the impact from uncontrolled variables does not exist. An understanding of the dynamics at play can prevent sub-optimization and lead to better results from a well-balanced storage system.

This thesis will highlight five principles of great storage systems discovered through academic research. It will analyze the relationships between elements of storage systems and offer data-supported recommendations to address current storage challenges at Amazon Fresh fulfillment centers. These insights can help fulfillment centers achieve achieve new levels of operational excellence.

1.4 Case-Study Structure

This work is based on a research project that was conducted at Amazon Fresh. The objective of the project was to identify storage solutions that can improve Fresh fulfillment center storage space utilization by 25% without sacrificing labor productivity.

This would enable Fresh to meet increases in demand with existing fulfillment centers, and postpone the capital investment required to build additional fulfillment centers.

The concepts presented in this thesis can be applied to other high-rate fulfillment centers. In order to avoid broad, vague assertions unsupported by data, this thesis will utilize the Amazon Fresh project as a case-study. Amazon Fresh will provide a real-world complex application for testing the claims presented in this thesis.

1.5 Thesis Overview

Chapter 2 provides insight into the financial and strategic motivations for improving fulfillment center storage systems. It provides background information on Amazon.com, Amazon Fresh and the Online-Grocery Industry and it summarizes the approach that was used to address the problem statement. Chapter 3 highlights key features of storage systems from a literature review. Chapter 4 provides an analysis of the current state of Amazon Fresh's storage system, including a review of facility layout, storage equipment, storage and retrieval processes, and over-arching storage policies. Chapter 5 identifies overarching goals and challenges of high-rate fulfillment centers, and it defines a vision for the ideal storage system. This vision, combined with findings from research and bench-marking, is leveraged to identify five guiding principles that can be applied to improve storage systems. Chapter 6 dives deeper into complex relationships between conflicting priorities and sources of fluctuations that cause storage challenges at Fresh. The guiding principles from Chapter 5 are leveraged to identify data-supported recommendations for specific storage challenges. Chapter 7 summarizes the key findings of this research and suggests opportunities for future expansion of this work.

1.6 Data Confidentiality

Data presented in this document has been disguised to protect Amazon's proprietary information. Process rates, volumes and costs were normalized or presented as percentages. Mathematical formulas describing the relationships between Amazon's processes were adjusted to communicate concepts notionally.

Chapter 2

Motivation, Background & Approach

This chapter provides insight into the financial and strategic motivations for improving storage systems. It provides background information on Amazon.com, Amazon Fresh, and the online grocery industry. It summarizes the approach that was used to address the problem statement.

2.1 Motivation

There are financial and strategic reasons that underscore the importance of storage systems. The arguments are even stronger for high-rate fulfillment centers focused on operational excellence and efficiency—where every second counts.

Financial Motivation: *Financial Impacts of Storage Systems*

The original research project sought to increase storage capacity or space utilization in order to allow Fresh to meet increasing demand with existing fulfillment centers. Postponing the capital investment required to build additional fulfillment centers represents a significant cost savings from the cost of capital, the opportunity cost, and the strategic advantages from delaying the decision on where to build the next fulfillment center. But this is only part of the financial motivation to improve storage. Another, perhaps even more significant financial benefit from extending the capacity of a fulfillment center is explained by the Square Root Law of Inventory Management expressed in Equation 2.1. This law describes how costs increase as the number of warehouse locations increase[2]. As additional warehouse are added to the network, overhead costs increase due to additional expenses such as utilities, maintenance and administrative staff. In a fulfillment center with large product selection, a significant increase in inventory safety stock is also required.

$$X_2 = X_1 * \sqrt{\frac{N_2}{N_1}} \tag{2.1}$$

Where X_1 is existing inventory, X_2 is future inventory, N_1 is the number of existing warehouses, and N_2 is the number of future warehouses.

For example, if one Fresh fulfillment center does not have the capacity to meet demand and an additional facility had to be built to serve the same market, Equation 2.1 estimates that Fresh will need to increase inventory by 41.2% just to hold sufficient safety stock in two fulfillment centers instead of one—without an increase in demand. An increase in inventory represents a significant financial cost well beyond the capital cost of owning additional inventory. Much of Fresh's inventory requires strict temperature control in refrigerated or frozen storage areas with high operating costs. Additionally, much of Fresh's inventory has a short-shelf life. An additional fulfillment center could double the cost associated with product spoilage.

This thesis will also explore the relationship between a storage design and labor productivity. At many high-rate fulfillment centers, direct stowing and picking labor account for majority of operating costs. There are strong financial arguments for storage system improvements.

Strategic Motivation: *Storage as a Competitive Advantage*

Many high-rate fulfillment centers have sought to use operational effectiveness and efficiency to achieve a competitive advantage with a low cost-structure. Lean initiatives and productivity improvements are common activities, but these initiatives typically target one small aspect of a company's operations. Often such advantages are easy for competitors to replicate. Improvements in individual areas lead to temporary improvements at best. A company can only continue to outperform rivals if it can preserve the advantage. Sustaining improvements requires a systematic approach[1].

A long-term sustainable competitive advantage can be extremely difficult to replicate if the advantage is in the way individual activities fit together and reinforce one another—as a system. The Toyota Production System is a great example of a system that has been extremely challenging for competitors to replicate, even though Toyota willingly shared the philosophy and tactics behind it's secret to success.

Much of the research in this document underscores the importance of taking a systematic approach to storage improvements. Leveraging the interconnections between individual elements of a system can lead to significant and sustainable competitive advantages[3]. The following quote reiterates the importance of a strategic systematic approach:

> "Merely cutting costs or investing heavily in expansion has proven insufficient for ensuring long-term success or even survival for retailers. Instead they need to clearly identify and develop capabilities that create distinct competitive advantage, and build an operating model that continuously delivers improved performance. By systematically and rigorously extracting more efficiency and effectiveness out of targeted functions, retailers will find themselves well positioned to ride the next wave of growth and mitigate their risk when the next tide of turbulence strikes." —Booze & Co[1]

2.2 Company and Industry Background

Amazon.com

Amazon.com is a Fortune 500 company based in Seattle, Washington. In 1994, it started as an online bookstore and quickly diversified by adding video downloads, DVDs, music, and many other goods. Today, Amazon.com is well known as an online retailer, a manufacturer of electronic book readers, and a web service provider. Amazon is the iconic example of success in electronic commerce[4].

Business Overview & Growth

The company has implemented its highly criticized "Get Big Fast" strategy to become the largest internet retailer in the world by revenue and market capitalization, employing more than 566,000 people[5]. However, even with decades of significant growth and expansion into other markets, Amazon has never lost the focus of its first leadership principle, Customer Obsession[6]. This customer-centric ideal permeates into every level of the company, keeping the customer's interests at the forefront of business decisions and daily operations. The Amazon Flywheel in Figure 2-1 shows the levers in Amazon's growth model, clearly illustrating the importance of customer experience in Amazon's operations[7]. This concept will reappear throughout this document as an integral part of fulfillment operations at Amazon.

Amazon has proven that it's not afraid to try new things. It has invested in start-ups, acquired companies and launched new businesses in many different industries from consumer electronics to media production.

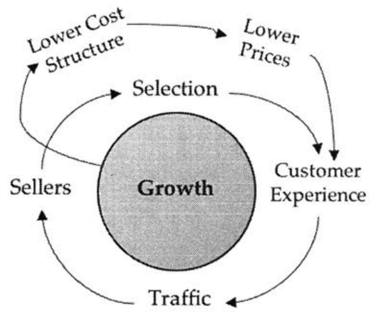


Figure 2-1: Amazon's Flywheel

Amazon Fresh

Amazon Fresh was launched in 2007, providing same-day grocery delivery to customers in several major metropolitan areas. Amazon Fresh offers a huge selection including everything from fresh produce to household electronics[8]. While Amazon Fresh's primary value proposition is centered around providing convenience, Fresh is also focused on ensuring customer satisfaction by carefully hand-picking, packing and delivering groceries with 100% satisfaction guaranteed—a confirmation of Amazon's commitment to Customer Obsession.

The Online Grocery Industry

The grocery industry is infamous for thin profit margins. To remain profitable, stores depend on a high volume of sales and efficient inventory management. Traditional grocery stores are facing increased competition from warehouse clubs, super-centers and online retailers. Online grocery delivery is still in its infancy. The earliest online grocers, Webvan and HomeGrocer, emerged in the late 1990s. Few companies in this industry survived the collapse of the internet bubble. The CEO of Relay Foods summarized the challenges of the industry as "the Bermuda Triangle of e-commerce- a place where investment dollars go but never return"[9]. Success in this highly competitive industry requires operational excellence and competitive pricing; two areas where Amazon.com has excelled[10].

Unique Aspects of Fresh Fulfillment

It should be noted that Amazon Fresh fulfillment centers differ significantly from Amazon.com fulfillment centers. Fresh fulfillment centers handle primarily perishable goods—many of which have strict temperature control requirements. A lot of the most popular grocery products, such as produce, dairy products, and bread, have very short shelf-lives. Fresh must find a balance between having sufficient inventory to prevent stock-outs, while also minimizing waste from product spoilage. Many Amazon.com fulfillment centers have a significant amount of automation, but all picking and stowing at Fresh are 100% manual tasks. Delivery schedules and order profiles are also quite different at Fresh. Fresh customers typically prefer grocery delivery during times when they are home, in the early morning or in the evening creating large swings in order-picking labor and large staging areas for filled totes awaiting delivery. Unlike Amazon.com orders which can be fulfilled from from multiple warehouses across long distances, Fresh orders must be combined into one shipment for each customer. Fresh serves customers within a two-hour delivery radius, requiring relatively small warehouses in relatively expensive, urban neighborhoods. These are just a few examples of the additional requirements that Fresh is facing. More details will be provided in Chapter 4.

2.3 Approach

The insights and recommendations in this document were informed by a number of key investigative activities: research, data analysis of a Fresh fulfillment center, and design and testing of proposed hardware solutions.

Phase 1: Research

External and internal research, interviews with associates and operations managers, and hands-on experience during Associate Experience Week provided the foundation for the recommendations. External benchmarking highlighted several best practices for a variety of storage policies. Several internal Amazon.com and Amazon Fresh studies have been conducted on similar topics with discoveries that provided valuable insight into unique storage-related challenges and previous improvement initiatives at Amazon.

Phase 2: Data Analysis

For this evaluation, one Fresh fulfillment center was selected as a representative of the network and used as a test case for a detailed analysis.

Quantitative Analysis: Traditional methods of inventory analysis employ velocity profiling to identify the best-selling SKUs. But if the goal is to optimize space utilization, additional factors should be considered. For example, expanding a frozen or chilled storage zone is more expensive than expanding an ambient zone due to capital investment in chillers and other challenges associated with expanding climate-controlled areas. Therefore, an improvement in space utilization in a frozen or chilled zone may be more valuable than a similar improvement in an ambient zone. To integrate multiple factors, a weighted sum model was created.

$$Score_i = T_i \cdot w_{temp} + S_i \cdot w_{space} + V_i \cdot w_{velocity} \tag{2.2}$$

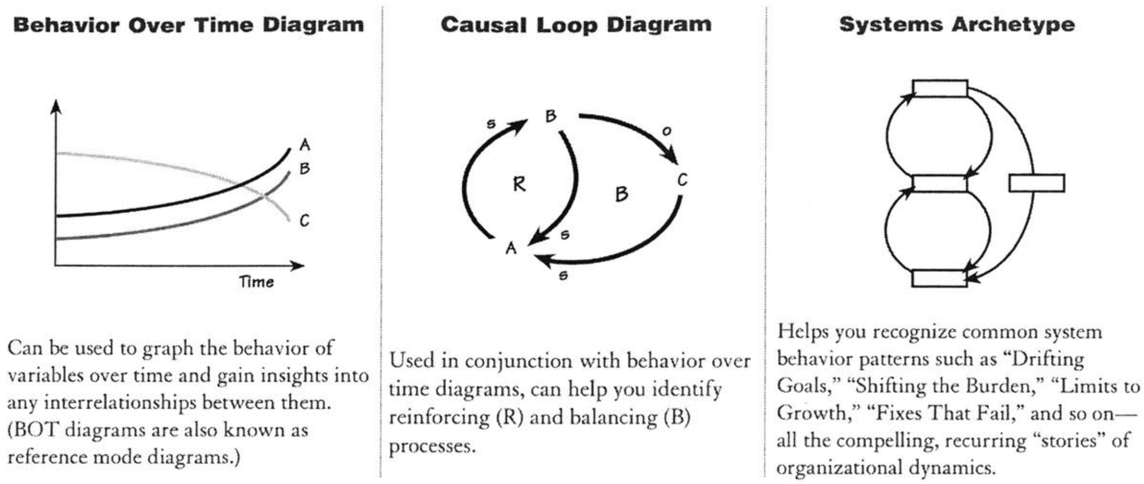
where:

i represents a particular product or product family
$Score_i$ is the resulting score for product i
T_i is the value assigned to the temperature zone of i; normalized from 0 to 1
S_i is the inventory cube of i; normalized from 0 to 1
V_i is the velocity of i; normalized from 0 to 1
w_{temp} is weighting assigned to temperature zone
w_{space} is weighting assigned to space
$w_{velocity}$ is weighting assigned to velocity
$w_{temp} + w_{space} + w_{velocity} = 1$

The model serves as a multi-criterion decision tool to build a prioritized list of product families and indicate the top opportunities for storage improvements—areas which should be addressed first. Weightings can be adjusted to prioritize space or productivity. For this analysis, more weight was applied to W_{space} than $W_{velocity}$ and W_{temp}, in order to apply a preference to saving space without ignoring velocity *(productivity)* or the relative value of each temperature zone.

The model supported the Data Analysis phase of this study by narrowing the focus to the high-leverage opportunities and challenges. Three product families that rose to the top of the prioritized list include Beverages, Produce, and Paper Products. A sensitivity analysis was conducted by varying the weightings. The same three products were near the top of the list in all scenarios tested, with Snack-Foods and Meat Products also showing up in the top 10 in several scenarios. To keep the analysis simple, detailed inventory analysis focused primarily on the three product families: Beverages, Produce and Paper Products. The storage and handling requirements and challenges of these product families were then studied in further detail. Other quantitative analysis included an evaluation of pick and stow records, inventory storage locations and order profiles—each studied in detail in order to evaluate the current state.

Qualitative Analysis: One reason large systems are not easily understood is due to the behavior of stochastic systems with queues, variability, non-linear behavior, limited information, and delayed feedback that prevent us from seeing impact of decisions on the larger system. For this research, systems thinking tools were employed as part of a qualitative analysis to help model the dynamics of complex systems, identify root causes of problems, and visualize unintended consequences. Three such tools were used to capture dynamic relationships of Fresh's storage system: behavior-over-time graphs, causal loop diagrams, and structural archetypes[11, 12], summarized in Figure 2-2[11, 12]. Systems thinking tools can act as free-standing solutions to help understand complex issues or as an aid to quantitative modeling[13].



Source: The Systems Thinker; Diagnosing Systemic Issues and Designing High-Leverage Interventions

Figure 2-2: Dynamic Thinking Tools

Phase 3: Design & Test

Storage hardware solutions were designed to address key challenges discovered from the research and analysis phases. Calculations were conducted to estimate the expected increase in storage capacity and space utilization, but to verify assumptions, pilot tests of the proposed hardware configuration are underway at a Fresh fulfillment center in Washington State. The tests will evaluate the benefits of the new hardware and highlight any unexpected challenges prior to large-scale implementation.

Chapter Summary

This chapter provided insights into the financial and strategic motivation for improving storage systems. It provided background information on Amazon.com, Amazon Fresh and the online grocery industry. It also summarized three phases of the approach that was used to address the problem statement. The next chapter will provide additional background with insights from a literature review of fulfillment center storage systems.

Chapter 3

Literature Review

This chapter provides insights from a literature review of warehouse design concepts and important elements of fulfillment center storage systems.

3.1 Product Requirements

Warehouse design decisions are dependent on the characteristics of the products that will be stored and processed in a warehouse, such as product type, quantities, and SKU variety. To minimize spoilage rates, storage systems for perishable goods generally require strict inventory control protocols, such as first-in-first-out (FIFO). The storage policy must enable operations to meet these requirements by using flow-racks or specialty racking to rotate inventory, additional labor to check expiration dates, or electronic inventory management systems that monitor expiration dates. It is imperative to have a good understanding of the product characteristics over the lifespan of the warehouse before storage system elements are defined.

Product Velocity: *Velocity* refers to the quantity and frequency that a SKU is sold over a designated length of time, e.g. 100 units per month. Velocity profiling is a common method used to prioritize inventory, and can be very helpful when optimizing for labor productivity. Velocity may drive the need for different storage hardware for high velocity and low velocity SKUs.

Product Packaging: Packaging can have a large influence on space utilization. The type of storage hardware used for boxes may not be optimal for non-stackable goods such as bags or bottles.

Product Cube: *Cube* refers to the three-dimensional volume of a SKU.
*Cube = height * width * length (Units: cubic inches or cubic feet)*

The total inventory cube for all units in stock of each SKU can provide insight into the space required to store the typical quantities in inventory. The dimensions and cubic volume of one unit can help identify the appropriate storage hardware.

Special Handling: Storage systems can be designed to protect fragile inventory. Products may require special storage hardware, processes, environmental and temperature controls, or other special handling requirements.

3.2 Facility Layout

Warehouse storage areas are often designed to enable smooth flow of goods and people and reduce time required to travel through the warehouse. The layout of aisles can have a significant impact on labor cost and productivity. Frazelle (1996) estimated that 55% of labor used for order-picking is spent traveling between picks[14]. Aisles need to be wide enough to enable smooth flow of goods and people, but aisle space should also be minimized to maximize storage space. Many layouts have been studied to maximize accessibility while minimizing travel time. Designs range from traditional parallel pick to unique fish-bone aisle configurations. Aisle length and proximity to the inbound and outbound areas are important factors in warehouse design. Some warehouses use mezzanines to create multi-level storage zones. Expanding vertically in high-bay warehouses can be a quick way to add more storage space, but this can create the need for a sorting process if orders are fulfilled from multiple levels and then combined for shipping.[1]

Warehouse size is also an important design consideration. More products require more storage space and additional aisles for accessibility and material flow, but all of these changes can increase travel time[15]. Most picking improvement initiatives target reductions in travel time between picks by increasing *pick density*[2]. Bartholdi and Hackman (2016) conducted a benchmarking study which concluded that a large facility can be more efficient than a small facility, but only if processes are adapted for size[15]. Size and scale can improve operational efficiency when processes are designed appropriately. For example, It requires much less labor to stow full pallets directly in pallet locations instead of breaking pallets apart and storing individual units on shelves. Some warehouses use replenishment processes to keep the pick area relatively small, and replenish items from excess supply from a storage location outside of the pick area. This helps reduce travel time, but at the cost of additional labor to replenish the pick area.

3.3 Storage Hardware

A wide variety of specialized storage hardware is available. Hardware is typically selected for space efficiency, organization and accessibility. For example, spring-loaded shelf organizers can be used to keep small items organized and easy to pick. Soup can dispensers can ensure first-in-first-out inventory management policies are followed. Pallet racks can multiply the number of pallet locations for a given amount

[1]Mezzanines and pick towers are not included in this research due to scope constraints and order consolidation limitations at Fresh, but these solutions should not be overlooked when seeking to expand storage cube without growing a building's footprint.

[2]*pick density* describes the number of picks for a given area or travel distance[16].

of floor space by adding multiple levels. Hardware selection decisions between standardized and customized storage solutions should consider the appropriate balance space-saving benefits, capital investment and risk of obsolescence if the product mix or demand changes in the future.

3.4 Storage & Retrieval Processes

Inventory Management Systems: Warehouses use inventory management systems to manage the location, quantity, and condition of inventory. Some warehouses use a simple pen and paper method to manage inventory, and some warehouses have complex electronic inventory management systems that use radio-frequency identification (RFID) to keep accurate inventory records updated in real-time as products move throughout the warehouse. The type of system has a big impact on the operational processes required to store and retrieve inventory.

Stowing Processes: *Stowing* is the process in which products are physically stored in preparation for retrieval in the downstream picking process[17]. Specifics of stowing processes are dependent on the type of storage policy used.

Picking Processes: *Picking* is the process in which products are physically collected from the storage area to fulfill an order. Manual picking, or "picker-to-part" is the most common method where pickers navigate a pick zone where products are stored. Advancements to this system include "pick-to-light" or "voice picking" to guide pickers to the appropriate locations to increase pick speed and accuracy. Automated picking systems move totes to stationary pickers who then pick the appropriate item to fill an order. More advanced systems eliminate the need for a picker to collect the items and use conveyors and sorting devices to sort items for each order. Hybrid systems employ a combination of these processes. The picking system is dependent on the product characteristics, order size and material handling needs[18].

Picking processes can be broken down into three distinct tasks[15]: 1.) Traveling to the storage location. 2.) Searching to find the correct item. 3.) Extracting the item—the most challenging task to automate.

Picking processes are often the primary target of warehouse productivity improvement initiatives for the following primary reasons:

- *Operating Costs:* Picking processes are often the most labor-intensive operation in fulfillment centers and can account for as much as 55% of the total warehouse operating cost[18].
- *Throughput and Delivery Impact:* When demand fluctuates, picking can quickly become the bottleneck process. For quick turn time and same-day fulfillment, there is only a small buffer between picking and delivery. Picking rates can limit throughput and impact delivery commitments.
- *Quality Impact:* Customers expect pickers to handle products with care. Pickers must be given enough time to carefully pick and pack products to prevent damage. Product quality can have a large impact on customer satisfaction.

3.5 Storage Policies

Hubner and Schaal (2016) referred to shelf space as "a retailer's scarcest resource"[19]. Traditional brick and mortar retailers of consumables organize inventory around four objectives:

1. Make it easy for customers to locate products.
2. Provide shelf space to display and advertise a wide selection.
3. Enable inventory management protocols such as last-in-first-out (LIFO) or first-in-first-out (FIFO).
4. Provide signals to initiate restocking and reordering.

Most brick and mortar retailers strategically allocate shelf space. The horizontal shelf space allocated to a particular product to a known as the *pick face*. Supply in excess of the allocated pick face is stored in a stockroom. This control of space allows retailers to expose customers to a large number of different products in each aisle, but an under-sized pick face can require excessive replenishment activities, resulting in higher operations costs. Many e-commerce retailers have freedom from most of these constraints by using electronic scanners direct pickers to the correct location.

Warehouses and fulfillment centers employ a variety of storage policies for inventory placement, but most can be categorized into two basic philosophies: directed storage and random storage[20]:

Directed Storage Schemes: In directed storage schemes (also known as *fixed* storage schemes), each SKU is assigned to a specific location. This method allows pickers to learn where products are located and storage hardware can be designed to perfectly fit the product. However, directed storage often makes inefficient use of storage space. Figure 3-1 illustrates how inventory levels in one location result in an average space utilization around 50%. Chapter 6 will provide more information about this challenge.

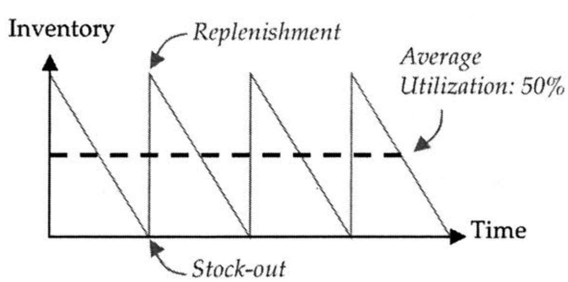


Figure 3-1: Space Utilization in One Storage Location Over Time
Adapted from Warehouse & Distribution Science[15]

Random Storage Schemes: Unlike directed storage schemes, random storage schemes (also known as *shared* storage schemes), do not allocate storage space to a particular product. Instead, products are stored wherever there is vacant space.

This approach requires stowers to record the location of a product in an electronic inventory management system so pickers know where to find the product. Current academic research suggests that random storage uses space more efficiently than directed storage[17, 21]. If a warehouse carries a large number of SKUs, SKU selection changes often, demand frequently fluctuates, or storage space is limited, a random storage policy may be the best option.

Random storage policies do not have to stop at assignment of individual storage bins or shelves; further subdivision of space can be leveraged for better space utilization. Different products can be stowed together in a bin to utilize vacant space by assigning it to other products instead of waiting until the bin is picked empty. However, with random storage policies, products are often stored in hardware that is not ideal for the product shape and size, resulting in an inefficient use of space. This problem can become even worse when a wide variety of products with different shapes and sizes are stored together.

Random storage policies can provide benefits beyond minimizing the need for reconfiguration, or efficient space utilization. Random storage schemes reduce picking errors, because employees don't have to search through bins of similar products (i.e. different flavors of the same SKU in similar packaging). When products are perishable, random storage can be an easy way to implement FIFO by directing picks to bins holding units with the closest expiration date. In grocery stores, a lot of stowing labor is spent rearranging products, placing older products towards the front of the shelf to be picked first. Milk flow racks are an example of automating FIFO by using specialized hardware, but with random storage schemes, specialized storage hardware is not required for FIFO management.

Hybrid Storage Schemes: Several companies have merged aspects of directed and random storage to create hybrid storage policies by directing products to zones based on characteristics or categories while also using random storage within each storage zone.

- *Indexed storage schemes* group products by predetermined characteristics, such as product size or product family.
- *Class-based storage schemes* divide products into classes, each with a separate storage zone.
- *Volume-based storage schemes* divide storage into velocity zones. For example, high-velocity products that are hot sellers may be placed in a fast-pick area conveniently located near the drop-off area to reduce picker travel time.
- *Cloud-based storage schemes* distribute units of one product to multiple locations across a pick area. Distributing inventory can attempt to create multiple miniature pick zones within a pick zone, each theoretically holding a majority of the inventory necessary to fulfill an order[17]. This product placement strategy focuses on improving picking productivity by reducing travel time between picks and reducing congestion in areas where high-velocity products are stored.

3.6 Labor Productivity

Other factors can influence the time required for stowing and picking activities in addition to product considerations, layout, equipment, and storage policies previously mentioned. Other such factors include physical, cognitive and motivational factors.

Physical Factors: Examples include the quantity to be picked, warehouse fullness/congestion, bin fullness, bin height/accessibility, product size, and environmental factors—such as the temperature of the pick zone and available lighting. Twisting, bending and reaching can put additional physical strain on stowers and pickers and result in occupational injuries and reduced productivity. Statistics reported by The Occupational Safety and Health Association (OSHA) show that musculoskeletal injuries from reaching and bending in a packaging warehouse operation are a significant cause of lost workdays and workers compensation costs. In one case, workers redesigned packaging processes to use gravity-fed roller systems, reducing twisting by 30%. The result was 100% reduction in lost workdays and a 25% increase in productivity[22].

Cognitive Factors: Examples include the number of unique SKUs in a bin, the organization of the bin, the picker's familiarity with the product, the picker's experience and skill.

15% to 20% of a picker's time is spent searching for the right product once they reach bin[14]. When picking an item from a bin holding a variety of items, each additional item can require more time for pickers to find and identify the correct item. In 1952, William Edmund Hick and Ray Hyman studied cognitive information capacity in choice-reaction experiments. Their findings are described in the Hick-Hyman Law, which describes how increasing the number of choices can increase reaction time logrithmically[23].

Hick's Law:

$$\mathrm{R} = (\mathrm{M}) + (\mathrm{P}) * log_2(n) \tag{3.1}$$

where:

R is the Reaction Time
M is the Movement Time
P is the Processing Speed
n is number of choices

Cognitive experimental psychology studies evaluated reaction time in more detail. Reaction time can be broken down into three phases: perception (seeing, hearing or feeling a stimulus with certainty), processing (understanding the information, making sense of the stimulus) and action (motor agility necessary to respond to the stimulus). Reaction time can vary depending on the following factors[24]:

- *Complexity of the stimulus:* the amount of information that has to be processed. Adding additional unique products to a bin increases this complexity.
- *Familiarity, preparation and expectations:* If a picker sees the name of a familiar product on the hand-held scanner, reaction time will likely be lower because the picker has a general idea of the products size, shape and color.
- *State of the organism:* fatigue, age, and health can influence a person's ability to detect the stimulus.
- *Stimulated sensory modality:* reaction time is shorter when the stimulus is auditory than if it visual because auditory stimuli require less cognitive processing.

In a highly manual fulfillment center where the average pick time includes more than 30 seconds of travel time between picks, improvements that shave milliseconds off of cognitive processing time may not seem like the best investment. However, lessons learned form this research could potentially be leveraged to reduce erroneous picks.

Motivational Factors: Examples include performance metrics, engagement and training. Well-designed performance metrics can align associate behavior with the company's goals. But frequently, metrics drive behaviors that negatively impact overall fulfillment center performance. The pressure to meet expected pick or stow rates may drive performance that meets metrics at the detriment of product quality or efficient use of storage space. Rate metrics may cause associates to take short-cuts. Deming (2000) warned that performance quotas and management-by-numbers work against quality[25].

3.7 Warehouse-Level Performance Metrics

Performance metrics provide measurements on the operational performance of a warehouse. In general, most metrics can be split into three categories: Order metrics, inventory management metrics, and productivity metrics. Order fulfillment metrics track the timeliness and accuracy of order fulfillment, and are closely tied to customer satisfaction. Inventory management metrics provide insight into inventory accuracy, damaged inventory, days-on-hand (average inventory vs. average sales), inventory turns, and capacity metrics (e.g., fullness and utilization). Many productivity metrics are a measure of input vs. output. Examples include orders-per-hour, items-per-hour and cost-per-order[26].

Chapter Summary

This chapter provided insights from a literature review of fulfillment center storage systems, including fulfillment center facility layout, storage hardware, storage and retrieval processes, and overarching storage policies. Chapter 4 will review the storage systems elements at Fresh fulfillment centers.

Chapter 4

Current State Analysis:

Storage at Amazon Fresh

One Fresh fulfillment center was selected as a representative of the network and used as a test case for a detailed analysis. This fulfillment center will herein be referred to as *"Fulfillment Center X"* or *"FCX"*. This chapter summarizes characteristics of storage at Amazon Fresh fulfillment centers.

> ***Note:*** *This chapter includes several note sections that describe observations on the limitations of traditional analysis techniques and how new approaches are needed when storage improvement is the objective. These notes are provided to caution readers and provide guidance for those who wish to replicate this analysis.*

4.1 Product Requirements

A typical Fresh fulfillment center offers between 10,000 and 20,000 unique products and holds about 450,000 units in inventory. Many products require refrigeration and special handling.

Product Velocity: An analysis of inventory and sales over a 30-day period at FCX showed that 18% of the SKUs accounted for 80% of the units sold. 38 SKUs sold over 1000 units per month. 80% of all of the SKUS sold less than 30 units and 10% of the SKUs in inventory had not sold any units in that month. This variation in demand is significant, yet in the grocery industry this is quite common. There is a high number of ultra-low velocity SKUs taking up a significant amount of storage space for products that are not selling.

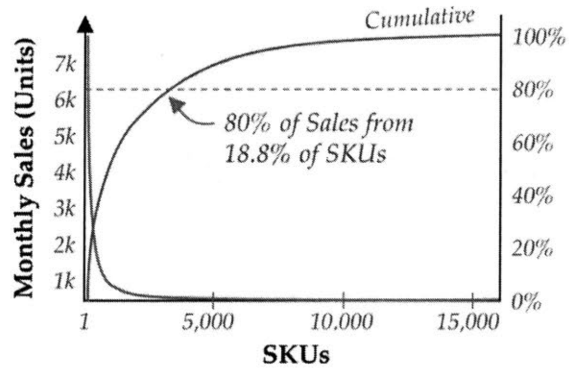


Figure 4-1: Fresh SKU Velocity—*Notional*

> ***Note:*** *Velocity is commonly used to prioritize inventory; an approach that can be very helpful when optimizing for productivity. However, when the goal is to optimize storage space, prioritizing by velocity can lead to sub-optimal results. Fresh's monthly velocity reports provided a list of SKUs sorted by velocity, but velocity only provides the productivity piece of the puzzle and doesn't tell you how much storage space or what type of storage hardware is needed. Looking at velocity alone provided too narrow of a focus for storage design.*

As Figure 4-1 shows, high velocity SKUs account for a large portion of the total outbound units, and therefore a large portion of the touch labor required for stowing and picking. But, Fresh typically receives multiple shipments per month of the high velocity SKUs, so these SKUs are not taking up space very long before they are sold. Velocity is not the best indicator of storage space requirements. For example, consider a specific produce item, which will be referred to as "SKU X".[1] In July 2017, FCX sold 4,442 units of SKU X, making it the 6th best-selling SKU that month. Using velocity data alone, SKU X would have been identified as a high priority SKU. However, if the list of SKUs were instead sorted by total inventory cube[2], SKU X, which takes up only $2.9ft^3$ of storage space for all the units in stock, would be ranked 1,725 on the prioritized list. 1,724 other SKUs take up more storage space than this high velocity SKU. Table 4.1 shows how the list of the top 10 SKUs changes significantly when all SKUs are sorted by velocity, quantity, and total inventory cube.

	Sorted by Monthly Velocity	Sorted by Quantity In Stock	Sorted by Total Inventory Cube
1	Bananas, 1 bunch (min. 5 ct.)	Amazon Dash Wand With Alexa	Bounty Paper Towels, White, 6 Big Rolls
2	Hass Avocado, Large, Ready to Eat	Simply Orange, Pulp Free, 59 fl oz	Scott Paper Towels Choose-A-Sheet, 6 Mega Rolls
3	Lime, One Medium	Bounty Paper Towels, White, 6 Big Rolls	Diet Pepsi, 12 ct, 12 oz Cans
4	Lemon, One Medium	Hershey's Cookies 'n' Cream Candy Bar, 1.55 Ounce	Diet Mountain Dew, 12 ct, 12 oz Cans
5	Strawberries, 1 lb	Lemon, One Medium	Angel Soft Toilet Paper, Bath Tissue, 12 Double Rolls
6	Blueberries, 6 oz	Airhead Bars, Blue Raspberry, 0.55 oz	Nestle Pure Life Purified Water, 16.9-Oz (Pack Of 24)
7	Cucumber, Medium	Ro-Tel Tomato & Green Chilies, Diced, 10 oz	Cottonelle Ultra Comfort Care Double Roll 12 Count
8	Organic Strawberries, 1 lb	Hass Avocado, Large, Ready to Eat	Purina Beneful Original, 15.5 lb
9	Organic Bananas, 1 bunch (min. 5 ct.)	Medium Garlic, One Bulb	Mountain Dew Throwback, 12ct, 12oz Cans
10	Gala Apple, One Large	Tyson, Boneless Skinless Chicken Breasts, 2 lb (Frozen)	Frito-Lay Chips Classic mix Multipack, 20 Count

Table 4.1: Top 10 SKUs Sorted by Velocity, Quantity, and Inventory Cube

Velocity analysis provides valuable information, but alone it is insufficient for this project. The analysis was expanded to include alternate ways to analyze the inventory profile, grouping by product family, packaging type, product cube and special handling characteristics.

Product Family: The weighted model described in Equation 2.2 on page 23 was applied inventory at FCX. Three product families rose to the top of the prioritized list obtained from the model: Beverages, Produce, and Paper Products. Together these product families include over 1,600 SKUs, more than 64,000 units, and 35% of

[1]Specific product name is not identified in an effort to protect proprietary information.
[2]Inventory cube is the storage space required to hold all units in inventory.

the monthly outbound units at FCX. 196 SKUs of paper products were subdivided by product type into ten product groups. The largest paper product groups: paper towels, toilet paper and diapers; represent 91.15% of the inventory cube of all paper products. Grouping by family and product type simplified the problem by reducing the scope from 196 different products to three product types—solving the storage challenges for paper towels, toilet paper and diapers will address nearly all off storage cube required for paper products.

> ***Note:*** *One SKU may not be identified as a high velocity or high cube SKU, but if Fresh products are grouped into product families (e.g., milk, yogurt, bread), the analysis may provide different conclusions. Grouping by product family combines different brands, flavors and sizes of similar products. A storage solution should be identical for different flavors of the same product, but if inventory was only analyzed at the individual SKU level, insights about the whole product family may be missed. After grouping by product family, it's important to evaluate number of unique SKUs in each family. This will impact the storage equipment solution required to ensure pickers find the right product from a group of similar products.*

Product Packaging: Random stowing, without consideration of variations in product packaging, results poor stack-ablity and wasted space. Fresh uses a Cubiscan system to capture the length, width, height and weight of every SKU. This information is used in the calculation of inventory cube and bin utilization. Cubiscan is designed to measure dimensions in cube-like packages, not bags, cans, jars or odd-shaped packages. Package type is not recorded in the system.

After grouping products by family, it was easy to see that Beverages was the largest product family with monthly sales over 50,000 units. Table 4.2 shows how further subdividing the Beverage product family by packaging type provided a clearer picture of the inventory profile by highlighting the proportion of sales for different packages (e.g. 6-packs, 12-packs, 24-packs, half-gallon and gallon containers). Cases and packs represent almost 50% of the beverage inventory cube. The 60-84oz size beverage containers (e.g. 2-liters and half-gallons) represent 22% of the beverage inventory cube.

Package Groups	% of Family Cube	Unique SKUs
Pack/Case: 10-12 units	37%	103
D: Large/Half Gallon/2-Liter (60-84 oz)	17%	183
Pack/Case: 6-8 units	12%	163
Pack/Case: 24 units	11%	21
F: XXL/Gallon (~128 oz)	5%	17
B: Medium (24-36 oz)	5%	159
A: Individual Serving (8-20 oz)	5%	189
E: Extra Large (84-100 oz)	4%	21
G: Drink Mix/Other	2%	177
C: Medium/Large (40-60 oz)	1%	35
Pack/Case: 3-5 units	1%	31
Grand Total	*100%*	*1099*

Table 4.2: Beverage Products at FCX, Grouped by Packaging

Product Cube: The total inventory cube for all units in stock of each SKU or product family provides insight into the space required to store the typical quantities held in inventory. In addition, the dimensions and cubic volume of one unit of a SKU can help identify the appropriate storage equipment to maximize storage/product fit. Beverages, produce, and paper products account for 33.5% of the total inventory cube at Fulfillment Center X.

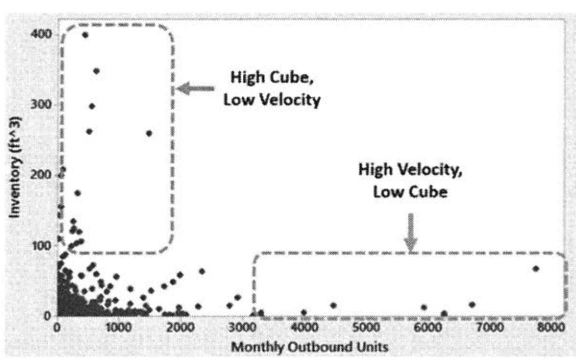


Figure 4-2: Velocity vs. Inventory Cube
The storage solution for high cube/low velocity products may differ significantly from high velocity/high cube products. Analysis should include multiple product characteristics.

Special Handling: Many of Fresh's products require temperature control and special handling. FDA approved food-safe materials and handling processes must be used to ensure the safety and quality of the food. Produce is very important to Fresh's business, but storing and processing produce presents many challenges. Fulfillment Center X has over 20,000 units of produce (342 SKUs) with short shelf lives and environmental sensitivity (temperature, humidity, and air flow). Many produce SKUs use space inefficiently because they are nearly impossible to stack. Produce can be easily damaged during handling and limited air flow can cause condensation and mold. Produce is also sensitive to ethylene gas, a gas which is as it ripens. Ethylene can expedite ripening of other produce, shortening shelf-life. Different types of produce vary in both ethylene emission and sensitivity. For example, apples, avocados and bananas are high ethylene emitters and are highly sensitive to ethylene, where asparagus, citrus fruits and broccoli are sensitive to ethylene, but are low ethylene emitters. Segregating storage of these two groups of produce or filtering the air with ethylene scrubbers could extend shelf-life.

4.2 Facility Layout

Fresh fulfillment centers are divided up into pick areas by temperature. The main pick zones include ambient, chilled, tropical, meat product and frozen zones. These zones are further subdivided into aisles for specific products. For example, the ambient zone has dedicated aisles for beverages, non-food products such as cleaning supplies, fragile items such as chips and bread, and produce. The purpose of this subdivision is to enable the pickers to pick heavy products first and fragile products last, preventing a customer's bread from being damaged by a 6-pack of soda and reducing the need for pickers to rearrange products in a bag. With this layout, the pick path algorithm can direct pickers from one side of the pick zone to the other with continuous flow through the pick zone. When Fresh fulfillment centers are designed, the typical allocation of total storage space is as follows: 75% Ambient, 9% Frozen, 13% Chilled, and 3% Produce. Allocations are based on historical storage capacity needs.

4.3 Storage Hardware

Most Fresh fulfillment centers use Riveter library-style shelving referred to as *library bays*, and single-level pallet storage. Pallet storage areas are typically configured in double-deep pallet configurations with 72" wide aisles. 48" wide aisles are used between library-style shelving. Shelf dividers divide library shelving into bins, creating more than 8,500 unique storage locations. Each bin and pallet location are labeled with a barcode and bin identification code, or "bin ID". At FCX, the inventory was distributed by volume as follows: 74.3% in library-deep bins, 20.3% on pallets, and 4.0% in produce bins, and 1.4% in drawer or vertical storage bins. See Appendix B for photos of storage hardware used at Fresh.

4.4 Storage & Retrieval Processes

Inventory Management System: Fresh utilizes hand-held barcode scanners for stowing and picking processes. The scanners are used for inventory management by updating the quantity, location, and expiration of every unit in inventory. This information can be used to ensure expired, or soon-to-expire products are removed to free up space. Fresh FCs currently use 100% manual stowing and picking with no automation.

Stowing: Fresh fulfillment centers are fairly small, serving customers within a two-hour delivery route. Most of the pallets Fresh receives are mixed-pallets, containing a variety of products on a pallet. A stower breaks-down a pallet by filling a stow cart with cases from the pallet. Then the stower travels to the appropriate area of the pick zone to find vacant bin space, where the cases are then broken down into individual units. The stower uses an electronic hand-held scanner to scan the bin's barcode and the product's barcode. This process is repeated for each additional unit.[3] Next, the stower enters the product expiration date into the scanner, completing the stow transaction. The scanners transmit the information over a wireless connection, updating the electronic inventory management system.

At Fresh fulfillment centers, inventory is typically taken from the loading dock and stowed directly in the appropriate pick zone. Fresh rarely uses the grocery store approach of storing excess units in a stockroom. This eliminates the labor to replenish the pick zone from the stockroom, but this approach requires a larger pick zone.

Picking: Picking is the first part of the order-fulfillment outbound process. Most Fresh orders have between 10 and 50 items. After orders for a particular delivery window[4] are received, a pick algorithm creates a pick path, directing pickers to the products that will expire first (first-in-first-out, FIFO). This algorithm starts every pick path at the same end of the pick zone–enabling Fresh's strategic pick area layout that ensures heavy and bulky items are picked before fragile items, as mentioned previously in Section 3.2. Above all else, the algorithm prioritizes expiration date to minimize spoilage. When multiple bins hold units of a SKU with identical expiration dates, the algorithm will select the bin that minimizes travel distance between picks.

Pick carts are filled with 10 bags, each with a barcode label to associate it to a customer's order. Each bag may be part of a larger order which will be grouped together in downstream processes, prior to delivery. A picker could have multiple bags for the same customer on their pick cart, and multiple pickers could each be filling different bags that belong to the same order. The algorithm sends instructions

[3] Some Fresh fulfillment centers have chosen to enable a feature on the hand-held scanner called *quantity-stow*, which allows associates to input the quantity of units they are stowing, instead of scanning each unit individually.

[4] Amazon promises customers will receive delivery within one and two-hour time periods. Delivery windows are used to group orders so picks are completed in time for the promised delivery timeframe.

to the picker's electronic hand-held scanner. The scanner provides the bin ID, the name of the product to pick, the quantity of units to be picked,[5] and which bag the unit(s) should be placed.

Multiple picking quality checks have been designed to ensure customer satisfaction:

- The bin barcode scan verifies the pick is from the correct bin was scanned.
- Visual inspection of product condition and expiration date to ensure only quality products are sold.
- The item barcode scan verifies the correct product was picked.
- The bag barcode scan verifies the product was placed in the correct bag.

4.5 Storage Policies

Random Stowing: Due to the large product selection and fluctuating demand, Fresh employs a random stowing storage policy for efficient use of space and ease of stowing. As previously mentioned, Fresh's pick zones are laid out with the pick path in mind (e.g. beverages and bread aisles). The stowing policy has limited constraints beyond the aisle designation for certain products. Sophisticated algorithms could be designed to optimize space utilization by directing stowers to the perfectly sized bin for the item they are stowing, but this could significantly over-constrain stowers. Part of the benefit of random storage is the ability to leverage a human's ability make *Tetris-like* decisions that efficiently use space. Highly directed stowing would require more labor.

[5]In an analysis of 150,000 pick records, only 5% were picks of more than two units of a SKU.

Bin Etiquette Stow Rules: In order to maintain organized bins, reduce erroneous picks, and to facilitate ease of picking, stowers must comply with bin etiquette rules, referred to as B.O.A.T.S.:

- B - Blocking: SKUs must not be blocked by other SKUs; all SKUs in a bin should be visible without rearranging the bin.
- O - Overhang/Overstuffed: Products should not overhang into the aisles and overstuffed bins not allowed.
- A - Above Bin Divider: A product should never be placed so that more than half of the item is above the bin divider or safety rope. This mitigates the risk that a product will fall out of a bin or into an adjacent bin.
- T - Type of Bin: Always utilize the smallest bin possible for the product.
- S - Similar SKUs: The Checkerboard Rule; Prevents stowing similar products in the same bin, or adjacent bins.

In addition to the B.O.A.T.S. rules, each fulfillment center can apply additional constraints on stowing. For example, several fulfillment centers limit the unique number of products in a bin. Fulfillment centers often set the limit at three or four unique products per bin in an effort to mitigate quality and productivity issues that can arise when pickers have to search through many products in a bin.

4.6 Labor Productivity

Productivity metrics are used to track labor productivity of every associate. Pickers and stowers are required to meet a minimum rate, measured in units-per-hour (UPH). There are no incentives to encourage associates to exceed the minimum rate. As mentioned the Literature Review, the pressure to meet rates can influence associate's stow and pick decisions—sometimes at the detriment of space utilization and product quality. For example, stow rate metrics can pressure associates to stow products as quickly as possible, without rearranging and organizing products for ease-of picking and good space utilization. Pick rate metrics can pressure pickers to rush, accidentally selecting the wrong product or damaging delicate products through rough handling.

Chapter Summary

This chapter summarized the current state of Fresh Storage Systems, including an overview of fulfillment center facility layout, storage equipment, storage and retrieval processes, and over-arching storage policies. The next chapter will build off of this foundation to explore common storage-related challenges, competing priorities of space utilization and labor productivity, and establish a vision describing the ideal storage system.

Chapter 5

The Ideal Storage System

What does the ideal storage system look like? This chapter will attempt to answer that question by identifying overarching goals and challenges of high-rate fulfillment centers and defining what the ideal storage system should provide. This definition will be combined with findings from research and benchmarking to identify characteristics of the ideal storage system—guiding principles that can be applied to improve storage systems.

5.1 Overarching Goals of Fulfillment Centers

Benchmarking has highlighted three common goals high-rate fulfillment centers:

- **Speed & Reliability**–provide fast, reliable service
- **Operational Agility**–adapt and remain competitive as needs change
- **Competitive Cost Structure**–deliver value to customers and shareholders by minimizing operational costs

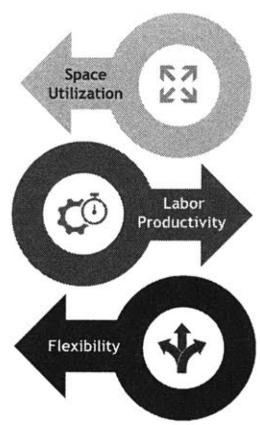
5.2 Primary Challenges at Fulfillment Centers

There are a lot of challenges at high-rate fulfillment centers, but most can be grouped two main categories: competing priorities and fluctuations.

Competing Priorities

As previously discussed, storage systems are complex, with many unknown interconnections and relationships between elements of the system. Changes to one part of the system can have unexpected impacts to other parts of the system. An understanding of these dynamics can prevent sub-optimization and lead to better business performance.

At Fresh fulfillment centers, juggling competing priorities requires constant oversight and management to prevent imbalance. Most of the resulting challenges are due to the relationships between space utilization, labor productivity and flexibility for the future. The relationships will be discussed in detail in the next chapter in the context of specific storage challenges at Fresh.



Fluctuations

The effective capacity[1] of a facility changes over time, even without significant redesigns or equipment modifications. Employee learning curves, process and policy changes, and product selection changes influence effective capacity, even if the total

[1]Effective capacity: the maximum storage capacity that is actually achievable given constraints of the system, such as inventory characteristics, facility layout, storage hardware, product characteristics, and operational processes.

amount of product flowing through the fulfillment center remains constant. Variations in supplier deliveries, demand surges, inventory organization, and even employee morale can influence effective capacity.

Figure 5-1 illustrates the concept of how even small fluctuations from variations in inputs, delays or imperfect information can create huge oscillations in performance and the condition of the storage system. Surges in input can cause fluctuations that oscillate out of control. For example reallocation of resources to address a surge in demand requires neglecting needs in another area. Without a flexible workforce or the ability to reduce surges in inputs, it can be a constant challenge to maintain the delicate balance in a complex system like a fulfillment center. A well designed storage system can mitigate the impacts of variations.

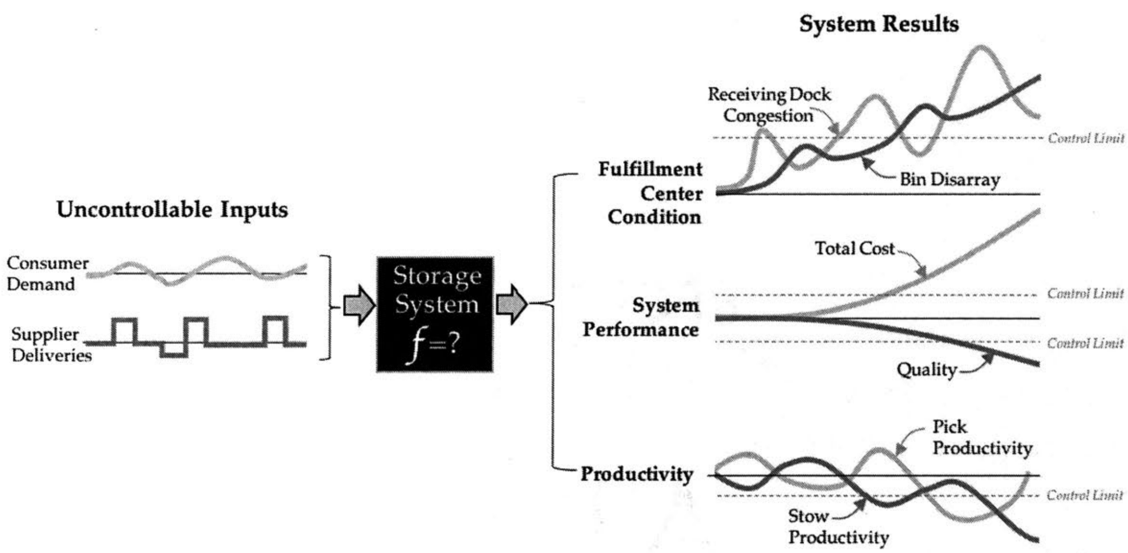


Figure 5-1: Small Variations in Inputs Can Produce Large Oscillations

Common Sources of Variation:

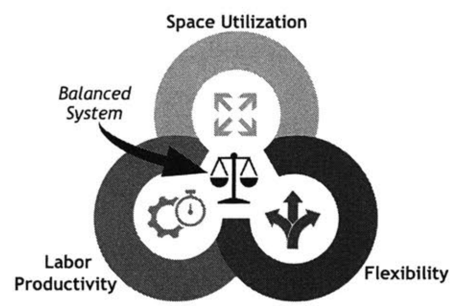
- **Unpredictable Demand:** Fresh doesn't want to stock out of an item, and suppliers have minimum order quantities and typically the price per unit decreases as the quantity ordered increases. Over-buying fills up the fulfillment center's capacity with slow moving items.
- **Delays:** Delays are often a cause of fluctuation. If pallets of product are received, but not stowed immediately, Fresh's inventory management system does not know the product is in the fulfillment center. This can cause additional orders to be placed for the same product.
- **Quantity Received:** Fresh is a small player with limited buyer power. On average, only 80-85% of the units ordered on a purchase order are actually received due to vendor shortages and other supply chain challenges. To make the problem worse, one of Fresh's most popular product families, produce, is a huge source of variation. Most of Fresh's produce SKUs are received in case quantities. Produce cases are guaranteed to be within a certain weight range, but do not always include the same quantity. For example, when Fresh orders a case of 24 apples, but given the characteristics of produce and the contracts with suppliers, the case that Fresh receives must contain 24 +/-2 apples (it could contain as few as 22 or as many as 26 apples). But Fresh's customers order produce in specific quantities. This disconnect makes inventory management of produce extremely challenging.
- **Delivery Frequency:** Fresh's supply chain is complex. The variation in delivery times cause huge swings in the workload at Fresh's receiving docks. Inventory needs to be stowed quickly or the receiving dock quickly becomes congested, slowing down the whole system.
- **Spoilage:** Perishable goods have a limited shelf life and are easily damaged. Combine this challenge with unpredictable consumer demand, and the result

is excess waste from spoiled goods. Labor must be used to pick the expired inventory to remove it from the pick area. If a good is not able to be sold, all of the handling costs to stow, store and pick the item are wasted.

5.3 The Vision: *The Ideal Storage System*

Given the goals and challenges of fulfillment centers and the insights gained from research, this thesis will use the following definition for the ideal storage system:

The ideal storage system balances conflicting priorities of labor productivity and space utilization, it provides flexibility for the future, and it minimizes impacts of variations, operating with speed, agility and a competitive cost structure.



5.4 Finding the Right Balance in Practice

The previous section defined a vision, but realizing that vision in practice requires requires finding the right balance. To guide the design and improvement of storage systems in alignment to that vision, the following list of guiding principles was created. The list can be used as a checklist to ensure a good balance is achieved. Every change to the system should be evaluated against this list to ensure an improvement doesn't offer gains in one area at the expense of negative impacts to other areas, throwing the system out of balance.

Guiding Principles

- ✓ **Good Product/Storage Fit:** Use the best storage hardware for the product. Storage hardware should match a product's characteristics (e.g. size, durability, weight, and velocity).
- ✓ **Eliminate Waste:** Storage processes should minimize wasted space and non-value-added activities such as travel time, extra touches, bin counting, blocked stows, erroneous picks and spoilage.
- ✓ **Enable Smooth Flow:** The storage system and processes facilitate efficient flow of people and materials and avoid unnecessary congestion or overcrowding in the fulfillment center.
- ✓ **Maintain Flexibility to Adapt:** Demand, product mix, and velocity will change over time. Fulfillment centers should strive for flexibility in hardware and processes to adapt as needs change.
- ✓ **Minimize Impact of Variation:** Efficient operations are extremely difficult when a system is not at steady-state and experiencing large fluctuations in input or output. Work-load should be leveled as much as possible. The supply chain should be managed with a "pull" system to avoid excess inventory and waste.

Chapter Summary

This chapter looked at the overarching goals of fulfillment centers and the primary challenges that cause system imbalance. This information was used to create a vision of the ideal storage system. A set of five guiding principles were developed to serve as a checklist to ensure good balance. The next chapter will apply these principles to address specific storage challenges at Fresh.

Chapter 6

Applying the Principles to Address Storage Challenges at Fresh

This chapter will explore the challenges highlighted in Chapter 5 in more detail to learn how these issues contribute to specific storage problems at Fresh. It will apply the five Guiding Principles to address the storage problems. Each data-supported recommendation employs one or more of the Guiding Principles to optimize Fresh's storage system.

The storage challenges in this chapter include the following:

- **Challenge #1:** Unusable Storage Space
- **Challenge #2:** Poor Product/Storage Fit
- **Challenge #3:** Space vs. Productivity
- **Challenge #4:** Low Pallet Space Utilization
- **Challenge #5:** Managing Fluctuations

6.1 Challenge #1: Unusable Storage Space

Most of FCX's bins are only partially full, but stowers struggle to find sufficient space. Stowers often have to rearrange products within a bin to free up space, but even if a bin has vacant space doesn't mean that space is usable. The stowing rules prevent blocking and stacking of different SKUs; all of the empty space in a bin in front of and above a SKU is unusable for storage of other SKUs. As a result of limited space, stowers must often use multiple bins to stow all of the units from a case.

Data Analysis

Distribution of Inventory at the SKU Level:

An analysis of all the products stored in library and library deep shelving shows for 90% of SKUs fewer than five unique bins were used to hold all the units in stock. Only 10% of SKUs are stored in five or more bins, but at this scale, 10% is not negligible, as 10% is using 1,522 unique bins. Ten different SKUs were each using more than 50 unique bins.

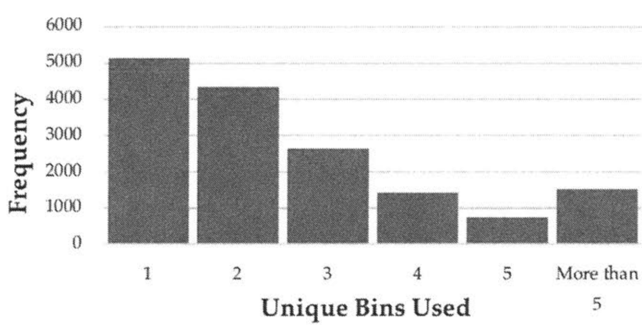


Figure 6-1: Histogram of Bins Used per SKU

A histogram of the top offender, a 150-ounce container of Arm & Hammer laundry detergent, stored in 105 unique bins, can be seen in Figure 6-2. Only 14 of these

105 bins contained more than two units of this SKU—this is most likely due to the fact that this SKU is a large item relative to the average bin dimensions. Other top space-offending SKUs include frozen chicken breasts, 18-count eggs, and gallon jugs of milk, stored in 81, 65, and 56 unique bins, respectively.

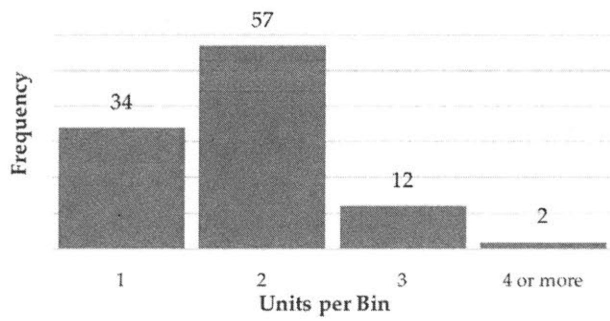


Figure 6-2: Units per Bin of Top 150 ounce A&H Laundry Detergent

Distribution of Inventory at the Bin Level:

Since most bins held more than one unique SKU, the current state was evaluated from a different perspective by adding all the units of every SKU in a bin. Most bins are holding more than 10 total units, but 3,717 bins only held 3 or fewer units.

Fresh's random storage policy and Fresh's pick algorithm are not well aligned. Shared storage is the concept of assigning a product to more than one storage location and when one location is emptied, it is available to be reassigned to another product. This policy can efficiently use space, but this assumes that all picks are from a single location until the inventory in that location is depleted.

Space Utilization with a Random Storage Policy:

Figure 6-3 illustrates the theoretical space utilization when multiple locations are used to hold one product over k inventory periods, each devoted to a particular pick location, assuming that all picks are directed to one location until that location is picked empty, and it is then reassigned to another product.

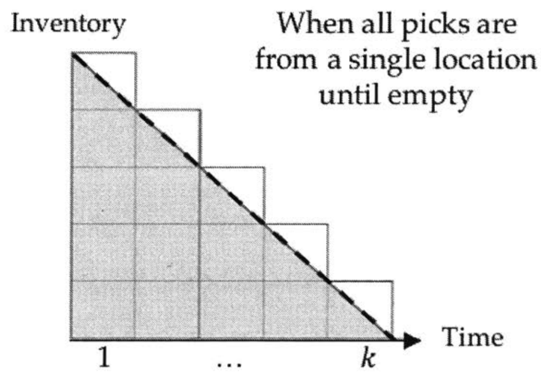


Figure 6-3: Average Inventory Level Over Multiple Locations
Adapted from Warehouse & Distribution Science [15]

The average space utilization in period i is found in Equation 6.1[15].

$$\frac{k - i + \frac{1}{2}}{k - i + 1} \tag{6.1}$$

The average utilization over all k periods is found in Equation 6.2[15].

$$\left(\frac{1}{2}\right) \sum_{i=1}^{k} \frac{k - i + \frac{1}{2}}{k - i + 1} = 1 - \left(\frac{1}{2k}\right) \sum_{i=1}^{k} \frac{1}{i} \tag{6.2}$$

If a product is stored in multiple bins, Fresh's pick algorithm prioritizes picks from the location with the nearest expiration date. Expiration date is prioritized above everything else, regardless of shelf-life. If two units of a product have identical expiration dates and the units are stored in different bins, the algorithm optimizes for the minimum pick path travel distance. The algorithm does not optimize space utilization—picking from multiple bins results in fewer units per bin over time, and lower space utilization.

Even though Fresh utilizes a random storage policy, only part of the policy was implemented—the picking policy was not designed to support the space-saving benefits of a random stowing policy. Chapter 3 explained how directed storage schemes assign each SKU to a specific storage location. Figure 3-1 on page 32 illustrates how inventory levels in one location result in an average space utilization around 50%. In terms of space utilization, this is effectively what is going on at Fresh. Fresh is not achieving the space utilization benefits that random stowing should provide.

Figure 6-4 compares the theoretical space utilization of the current policy (50%), to the potential space utilization if all picks were directed to one location until that location is picked empty (as much as 84%).

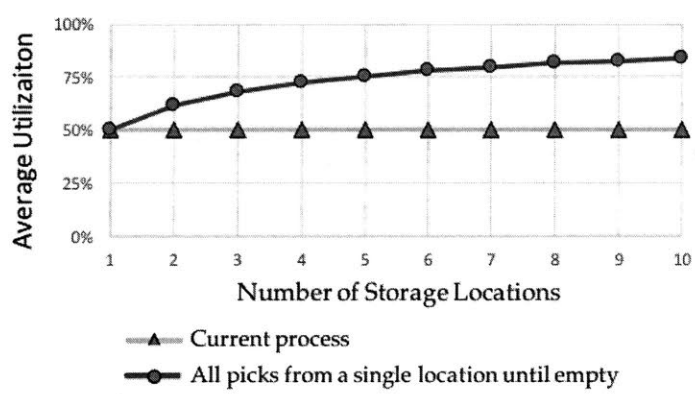


Figure 6-4: Theoretical Space Utilization with a Random Storage Policy
Adapted from Warehouse & Distribution Science [15]

The Trade-offs

Spoilage vs. Pick Productivity vs. Space Utilization: The data illustrates the negative effects of a stow policy that prevents co-location of the same product from different shipments or with different expiration dates for FIFO inventory management purposes. The current algorithm minimizes spoilage cost by picking the closest expiration date and also optimizes pick productivity by reducing travel distance. However, these benefits are often realized only at the detriment of space utilization—the theoretical space-saving benefits of random stowing are not being realized because the algorithm does not direct picks to one bin until the bin is picked empty.

The root cause of this problem is due to the missing link between stowing processes and picking processes, represented in the causal loop diagram in Figure 6-5. Fresh's stowing and picking processes have been designed and revised by separate teams. By not integrating the stowing policy (random stowing) and picking processes (pick algorithm), space utilization is negatively impacted.

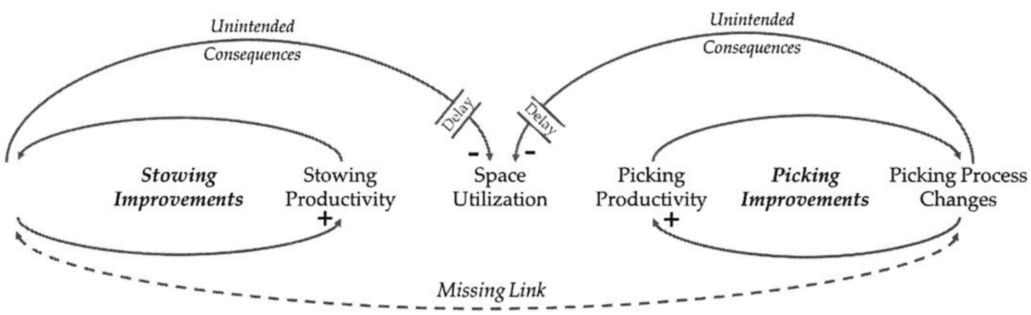


Figure 6-5: Missing Link Between Stowing and Picking Processes

Recommendations

The current algorithm may actually provide the best solution in some situations, specifically for products with high spoilage rates. But Fresh doesn't have to use the same algorithm logic for every SKU. The algorithm can be designed to optimize given multiple criterion, minimizing spoilage for products with short shelve lives and maximizing space utilization for all other products. Fresh should make two modifications to the pick algorithm so it is better aligned with Fresh's random storage policy:

1. **Prioritize the "Use-To-Exhaust" feature** for all SKUs with long shelf-lives. The "Use-To-Exhaust" feature is a pick algorithm feature that prioritizes picks from one bin until that bin is picked empty. This feature currently exists as part of Fresh's pick algorithm, but it is out-prioritized by other logic (e.g. expiration date, travel distance, etc).
2. **Group expiration dates** for products with long shelf lives to allow the pick algorithm to choose a more efficient path.

Expected Benefits

If the recommendations are implemented, the theory indicates Fresh could improve average space utilization from 50% to 84% (See Figure 6-3 on page 60). This assumes there is no wasted space within a bin, which is not realistic given standard bin dimensions and variations in product dimensions.[1] A more conservative estimate assumes only half of the theoretical improvement [insert reference to graph] is realized, results in an average space utilization of 67%—an increase of 34%. This solution does not require an investment in storage hardware.

Given Fresh's network of multiple fulfillment centers, and the large quantity of picks per day, a pilot test at one site or in one pick zone may be a quick way to determine if the solution was viable, but the results should be monitored to detect unexpected consequences. A simulation can be used to evaluate the impact of this change prior to implementation. With actual inventory records, bin location information, and historical order profiles, a simulation can evaluate the impact of the recommendation on spoilage, pick path travel distance, and space utilization.

Potential Risks

For long-shelf life SKUs, the risk of increased spoilage is low. For short-shelf life SKUs with a high probability of spoiling, the algorithm can mitigate the risk of spoilage by

[1] This concept is described in more detail in the next section.

prioritizing expiration date above other factors for products with short shelf-lives.

Summary

Fresh's random storage policy and Fresh's pick algorithm are not well-aligned, resulting in poor space utilization. Two small changes to the pick algorithm could improve space utilization by 34%. The risks may include increased product spoilage and longer travel time for pickers. A simulation using actual inventory records and historical order profiles can verify the risks and benefits.

Principles Applied:

- ✓ Eliminate Waste
- ✓ Minimize Impacts from Variation

6.2 Challenge #2: Poor Product/Storage Fit

When a variety of products of different sizes and shapes are co-located in a bin, the result is high *bin entropy*—the randomness of products in a bin[21]. Fresh offers a huge selection of products, but fulfillment centers use primarily pallet locations and library bay shelving. Standard storage hardware results in poor product/storage fit. If all Fresh's products came in individual boxes, stowers could efficiently pack a variety of products in each bin. It's not uncommon to find small spice jars in the same bin as large cereal boxes. Small SKUs take up valuable space and increase time pickers spend searching through a bin. Products cannot be stacked due to stow etiquette rules, product stackability limitations and product crushability concerns.

The Trade-off: Standard vs. Custom Storage Hardware

Fresh could design the perfect storage solution for every SKU, but customization limits future flexibility as demand fluctuates and popular SKUs change over time. At one time, it may have been a good idea for the to standardize the type of shelving in fulfillment centers to gain economies of scale. But today, nearly all of the library bay shelves are configured to standard dimensions. This configuration provides acceptable product/storage fit to a large number of SKUs, but many small and large products need a better storage solution to improve product/storage fit and reduce wasted space.

Recommendations

Fresh can improve space utilization while also maintaining flexibility for the future with two changes: 1.) Create zones for packaging types. 2.) Use modular storage hardware solutions to improve product/storage fit.

1. **Create new zones for packaging types.** This simple change is a low tech and easy-to-implement solution. Fresh should create zones for boxed goods, bagged goods, canned goods, bottles, small SKUs and crushable items. This solution is only a minor change from the current zones used today to optimize pick path based on product weight (i.e., heavy products first). Aisles should be designated and labeled for various packaging types such as small items, boxed goods, bagged goods, canned goods, bottles, and crushable items. Stowers will be able to easily identify the appropriate aisle without the complexity of sophisticated technical solutions required for highly-directed stowing processes.

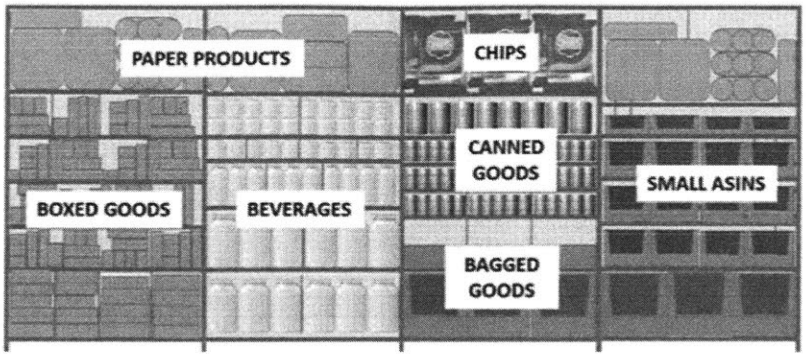


Figure 6-6: Notional Packaging Zones

Grouping products by packaging has been overlooked by past storage improvement initiatives and academic research. But this storage strategy could have a significant influence on space utilization for fulfillment centers with a large variety of products.

2. **Use modular hardware to maintain flexibility and to achieve good product/storage fit.** Modular hardware can be used to customize storage for packaging types. Components include universal base structures and modular shelving inserts.

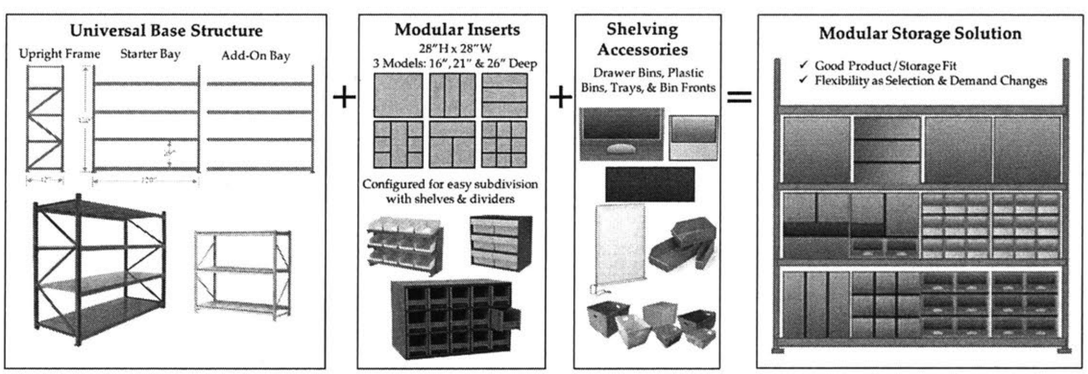


Figure 6-7: Modular Hardware for Flexible Customization

- *Universal Base Structures:* Instead of choosing between library shelves and pallet storage, Fresh should select a universal base structure that can be configured in a variety of ways by adjusting shelf heights and depths.

The hybrid over-pallet racking configuration from the previous section is one example of an adjustable base structure.

- *Modular Inserts and Storage Accessories for Shelf Customization:* Modular inserts and storage accessories can provide the next level of customization for various product characteristics. One Amazon fulfillment center piloted corrugated cardboard drawer bins for small SKUs, a small change which led to a 14% improvement in bin utilization. A cost-effective and food-safe version of these drawer bins could be inexpensively fabricated from corrugated plastic.[27]

Potential Risks

Stowing similar looking products in the same or in an adjacent bin violates the bin etiquette rule aimed at preventing erroneous picks. Stow rules need to be relaxed for the new packaging zones, increasing the risk of picking errors. Fresh's handheld barcode scanners help reduce this risk by alerting an associate of an error. Quality metrics should be monitored closely after relaxing the stow rules to ensure erroneous picks do not increase.

Summary

Mixing a variety of products of different sizes and shapes in a bin uses space inefficiently. Fresh needs to balance hardware standardization and customization to use the right storage hardware for the product while also maintaining flexibility for the future. The recommendations suggest creating zones packaging types and group similar products for better space utilization and using modular storage hardware solutions to improve product/storage fit.

Principles Applied:

✓ Good Product/Storage Fit

✓ Maintain Flexibility to Adapt

6.3 Challenge #3: Space vs. Productivity

This section will study the relationship between space utilization and productivity—specifically how fulfillment center fullness and bin-level fullness impact facility throughput and labor productivity. It will address a specific storage challenge Fresh experiences from the use of ladders for picking, but this ladder challenge is only one small example of a bigger issue that is not well understood: how space and productivity are related.

The Trade-offs

- **Warehouse Fullness vs. Operational Performance** Storage and picking are two separate processes but they are also interdependent, jointly determining the operational performance of the system[28].

  The Myth of 100% Capacity Utilization:

  It's a commonly held belief across multiple industries that efficient operations should be at or near 100% capacity utilization. Many managers believe that if you're not fully utilizing your assets, you're wasting resources. This belief often leads to major operational challenges as soon as one part of the system experiences a delay or a surge. At high utilization, operational costs increase as congestion and wait times increase, and overall flow slows down. At low utilization, excess capacity is not delivering value.

  Consider the following scenario: An airline is loading passengers onto a commercial airplane. When only half of the seats on an airplane have been sold, passengers are able to load and unload quickly with minimal congestion and wait times. However, the airline is not fully utilizing the plane's capacity; there's an opportunity cost associated with idle capacity that is not producing value. If more seats are sold, the flow of passengers slows and the time to load an airplane increases.

This scenario is similar to the flow of people and goods in a warehouse—people and goods flow through at different rates depending on the building fullness. As demand grows, the flow rate of goods must increase. A warehouse reaches maximum capacity when the flow-rate peaks; often long before it runs out of room for additional inventory. After this point, without changing the system, increasing capacity utilization will result in non-linear increases in variable cost.

Figure 6-8 illustrates the cost of idle capacity and the exponentially increasing delay cost experienced at high levels of utilization. There is an optimum utilization level where total cost (cost of idle capacity plus the delay cost) is minimized.

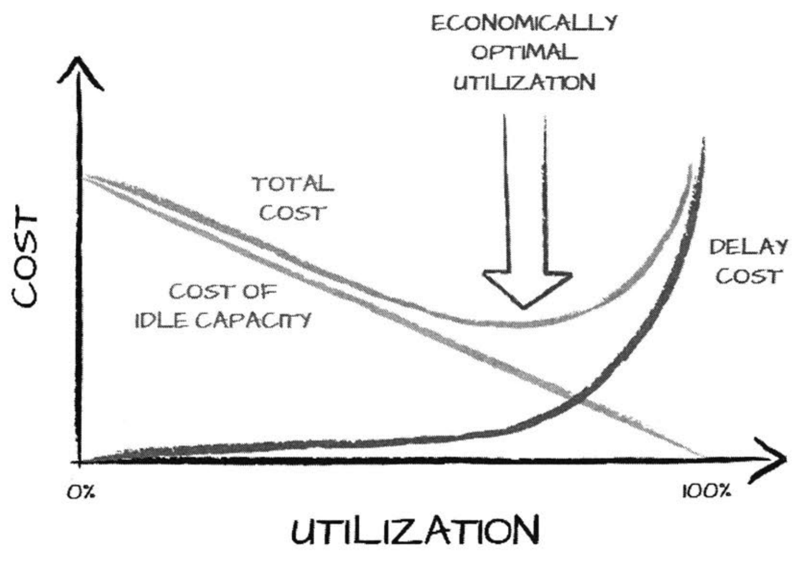


Figure 6-8: Utilization vs. Cost and the Economically Optimal Utilization Level
Source: Brodzinski.com[29]

- **Bin Fullness vs. Picking Productivity:** A similar trade-off occurs at the bin level. As bin fullness increases, it takes more time for pickers to locate the correct product, decreasing picking productivity. This relationship has only been studied between fullness levels of 30% to 90% gross fullness, with detailed studies focused on fullness levels between 43% and 57%. One internal study found a 1% increase in bin fullness resulted in a 0.42% increase in the average time taken to complete a pick. Given the typical pick rates in this fulfillment center, the result is a 12.6% increase in the average pick time from a bin that is 30% full and a bin that is 60% full[30].

  An internal study evaluated bin fullness vs. pick time and identified the relationship in Equation 6.3[30].[2]

$$P_t = 20f + \beta \tag{6.3}$$

where:

P_t is the pick cycle time in seconds
f is fullness expressed as a percentage
β is the base pick cycle time in seconds—representing the average pick cycle time from a bin with only one unit of one SKU (no searching)

A Specific Example: *The Ladder Penalty*

Picking productivity is hindered by a "ladder penalty"—the extra time required to get and return a ladder to pick from high shelves. Fresh fulfillment centers are in high-bay buildings, but only a small portion of the total cubic space is used for storage. The easiest way to add storage cube is to go vertical with higher shelving, but even with current eight-foot-high shelving, associates spend a lot of time getting and returning step-ladders. Step-ladders are stored on the end-caps of every-other aisle in a pick zone. To expedite picking, many fulfillment centers have blocked stowing to the top

[2]The numbers have been adjusted to protect proprietary information. Note that Equation 6.3 represents the linear range of the relationship between fullness and pick cycle time, but does not represent the non-linear relationship at high levels of utilization.

shelf. Fresh is considering eliminating the top shelf from the shelving structure design in all new fulfillment centers.

Data Analysis

A time-study conducted at one Fresh fulfillment center found that when associates had to use a ladder complete a pick, it took an additional 38 seconds to retrieve and return a ladder from the aisle end-cap[31]. Three months of pick records were analyzed to see if this was a common occurrence. The records indicate that 15% of all picks came from high shelves that required associates to use a step-ladder. The data shows that 93% of the time a ladder was needed, it was only used once in that aisle.

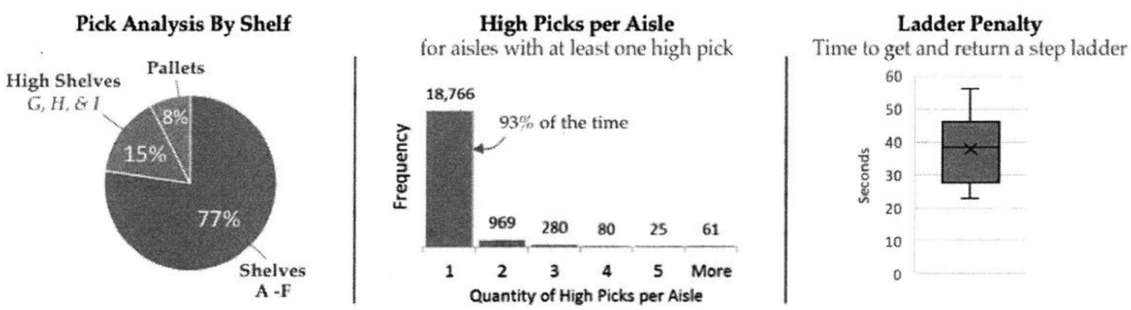


Figure 6-9: The Ladder Penalty

To see the impact that the ladder penalty has on labor costs, the 38 second average ladder penalty was applied to 15% percent of total number of picks per month. When compared to the total labor hours the fulfillment center spent on picking activities in that month, the ladder penalty accounted for 13% of total picking labor. Considering the cost of labor and the fact that picking is Fresh's bottleneck process, eliminating the top shelf sounds like it may be a good idea. But while this change could improve pick-rate, it would also eliminate a significant proportion of the storage cube—reducing the total capacity of the fulfillment center. It would constrain all of the inventory into a smaller space, increasing bin fullness in the remaining shelves. When fullness increases, stowers spend more time searching for vacant space and pickers spend more time searching for the correct product in a bin. There may also be other consequences such as a reduction in inventory accuracy and product quality.

Figure 6-10 is a causal loop diagram that illustrates the short-term intended impact of increased pick rates, along with the unintended consequences from reducing storage capacity.

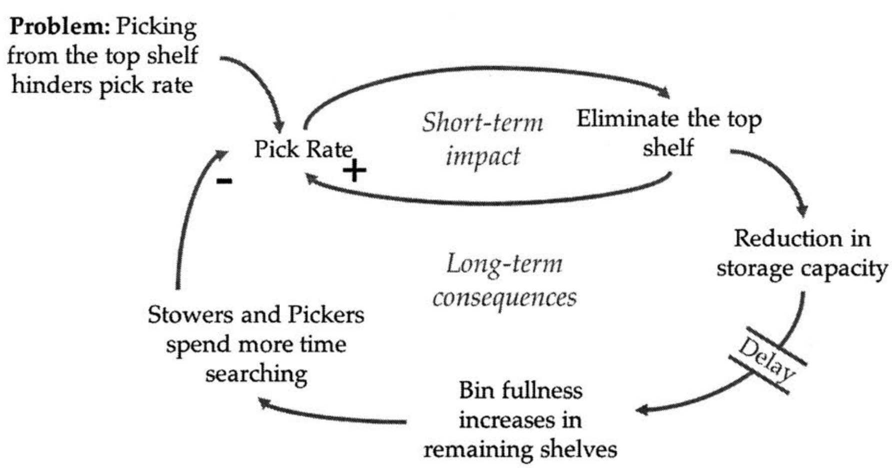


Figure 6-10: Causal Loop Diagram: Impact of Top Shelf Elimination

Equation 6.4 estimates the current picking cost with the ladder penalty applied to 15% of all picks:

$$P_c = C_s\Big((T_pP_t)+(0.15T_pL_p)\Big) \tag{6.4}$$

where:

P_c is the picking cost
C_s is the labor cost per second
T_p is the total number of picks in the given time period
P_t is the picking cycle time from Equation 6.3 in seconds
L_p is the ladder penalty

The Impact

Since the relationship between fullness and pick productivity is known, the impact on picking rate can be estimated. Figure 6-11 is a notional representation of this impact. The expected growth rate of the fulfillment center was plotted to estimate

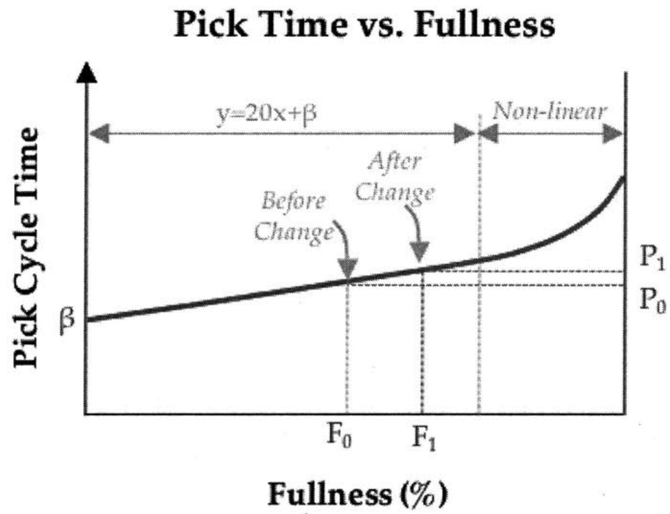


Figure 6-11: Notional Impact on Productivity and Fullness from Elimination of Top Shelf

the impact of fullness and productivity as the fulfillment center grows. Eliminating the top shelf will produce a step-change increase in fullness due to the reduction in storage capacity, and will also result in a corresponding change to pick cycle time. The new pick cycle time at the higher fullness level can be calculated using Equation 6.3.

If pick productivity was the only factor of interest, eliminating the top shelf would be the right decision only when:

$$\Big(T_p\big(20f_2 + \beta\big)\big)\Big) < \Big(T_p\big(20f_1 + \beta\big) + \big(0.15T_pL_p\big)\Big) \tag{6.5}$$

where:

T_p is the total number of picks in the given time period

f_2 is the future fullness level after the top shelves are eliminated
f_1 is the current fullness level before changes are made
β is the base pick cycle time in seconds
L_p is the ladder penalty in seconds

Unintended Consequences

The unintended consequences of this change may outweigh the productivity benefits from eliminating the ladder penalty. If the fulfillment center continues to grow, it will hit maximum capacity sooner than expected, due to the reduction in total storage capacity. This impact is illustrated in Figure 6-11. Although this change may deliver savings in terms of picking labor, it may drive the need for substantial capital investment in additional storage capacity much earlier than currently forecasted.

Recommendations—Part 1:

Strategic Recommendation:

- **Strive for Economically Optimal Utilization:** Fresh should strive to operate at the economically optimal utilization (fullness) level. The optimum may vary by fulfillment center given the relative cost of capacity (e.g. real-estate, labor, etc.) and the layout of the facility (e.g. aisle configuration and width). As Section 6.2 discussed, storage/product fit and product characteristics can have an impact on fullness and space utilization. It may require some experimenting to find the optimum level to achieve the lowest total cost. In general, Fresh should rethink the concept of utilization and fullness. "Operating at 100% capacity" should NOT be seen as synonymous with "operating at maximum efficiency".

Tactical Recommendation #1:

- **Attach Step-Ladders to Pick Carts:** Instead of eliminating storage cube, Fresh should add brackets to attach step-ladders to pick carts. This solution may improve pick productivity without increasing fullness. This wouldn't completely eliminate the ladder penalty, but let's assume it can reduce it by 50%, from 38 to 19 seconds per high pick. The cost savings from this change is expressed in Equation 6.6. There will be an initial investment to modify the pick carts. The net-present-value (NPV) of this option was calculated for one Fresh Fulfillment Center X. A conservative estimate of five-year NPV of modifying 90 pick carts at Fulfillment Center X that assumed a 50% reduction to the ladder penalty, resulted in an NPV of more than $660,000.

$$CostSavings = C_s \cdot T_p \cdot 0.5L_p \tag{6.6}$$

where:

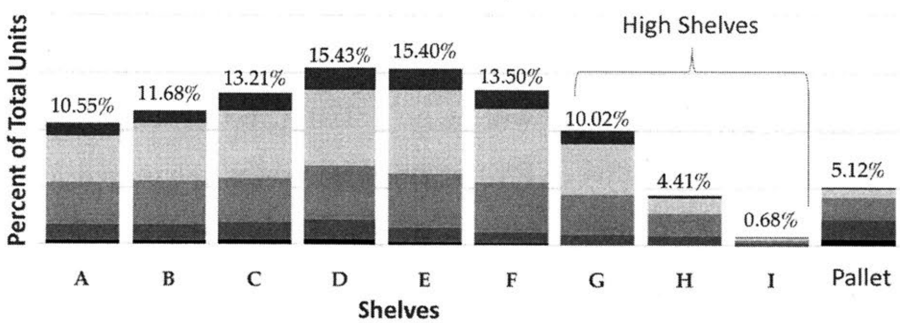
C_s is the labor cost per second
T_p is the total number of picks in the given time period
L_p is the ladder penalty

Fresh is currently conducting a pilot tests on pick carts with integrated ladders.

Taking it Even Further

Shelf Height vs. Picking Productivity: Inventory in a Fresh fulfillment center is distributed across shelf heights, regardless of SKU velocity. A fast-moving SKU that may be picked immediately could be stored on the hard-to-reach top shelf and a slow-moving SKU that might take a month to sell could be located on the easy-to-reach middle shelf. Lieu (2003) evaluated the relationship between productivity and shelf height, specifically the impact of the "power-zone" (also known as "golden zone" or "strike-zone"), the shelves between knee and shoulder level where no bending or reaching is required. Lieu's research estimated that a picker could spend 3 to 10 seconds more if the item being picked is outside of the power zone[21].

Figure 6-12 illustrates how inventory is distributed across shelves without regard to SKU velocity at FCX.



Velocity Categories	Outbound Units per Month	SKU Quantity	Percent of Total Outbound Units
A: Ultra High Velocity	>1000	38	16%
B: High Velocity	100 to 200	343	28%
C: Low Velocity	30 to 100	3087	41%
D: Ultra Low Velocity	1 to 29	11469	16%
E: Deadwood (No Velocity)	0	2701	0%

Figure 6-12: Units per Shelf as a Percent of Total Units in Inventory

A pick time study was conducted at an automated Kiva fulfillment center[32]. Kiva sites employ part-to-picker automation, where bins are brought to the pickers. Leveraging this time study allows us to remove the travel time between bins and examine the portion of the picking process that is done at a bin. The data from this time study found a correlation between pick time and bin height with a correlation of 95%. Picks from the golden zone in the middle of a pod were indeed faster than picks from bins that required the picker to reach or bend. On average, picks outside of the golden zone took an additional 3.2 seconds.

Recommendations—Part 2:

- **Velocity Zoning—by Shelf:** To further expedite picking time, Fresh should consider velocity zoning by shelf. Directing high velocity SKUs to shelves in the power zone and low velocity SKUs to high shelves could result in huge gains in productivity. Providing associates with basic velocity category information (e.g. "high velocity" or "low velocity") may be sufficient to guide stowing by shelf without over-constraining stowing with additional stow rules.

Summary

Warehouse fullness (throughput) and operational performance (productivity) are highly correlated. Fresh should strive to operate at the economically optimal space utilization level. One specific challenge this section addressed was the "ladder penalty"—the extra time required to get and return a step-ladder to pick from high shelves. Eliminating or blocking stowing of the top shelf reduces storage capacity, increases fullness, and negatively impacts pick and stow rates. A better solution that doesn't reduce storage capacity is to modify pick carts by adding brackets to attach step-ladders directly to the carts or by using carts with integrated ladders. Further productivity improvement could be achieved by stowing only low velocity SKUs on hard-to-reach shelves outside of the power zone.

Principles Applied:

✓ Good Product/Storage Fit

✓ Eliminate Waste

✓ Enable Smooth Flow of People and Materials

6.4 Challenge #4: Low Pallet Space Utilization

Space utilization in pallet locations is extremely low. Vertical space above a pallet is unusable. Pallet space is very valuable for high velocity and large cube SKUs. Stowing a whole pallet in a pallet space can be much faster than stowing individual units in library bins. Fresh needs to find a way to use pallet space more efficiently.

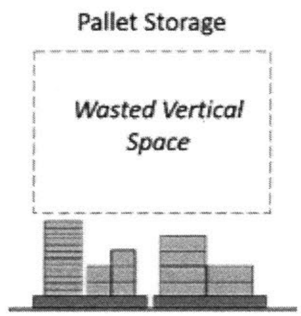


Figure 6-13: Low Space Utilization in Pallet Locations

Improvement Attempts: Some Fresh fulfillment centers use 48" deep over-pallet-racks (OPR) in a double-deep configuration with wide aisles (72") on both sides of the racks. The addition of shelves improving the use of vertical space above pallets, but only 20% of the shelf space is accessible in this configuration. Figure 6-14 illustrates how much of the space is unreachable due to the depth of the shelves in the double-deep configuration.

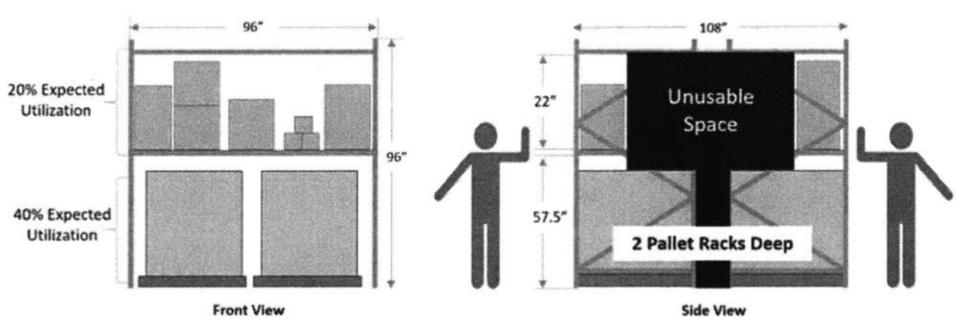


Figure 6-14: Current Over-Pallet-Racking Configuration

Data Analysis

At Fresh Fulfillment Center X, 18.8% of the SKUs account for 80% of the monthly outbound units. However, 97% of the high-velocity SKUs[3] (90.26% of the total units) are stored in library-deep bins—requiring more labor to stow than if pallet quantities were stowed together in one stow transaction. Analysis of pick records revealed only 8% of the units picked during this study period were picked from pallet locations. The average space utilization of pallets at Fulfillment Center X is 28%.[4]

> *A Note About Cube Calculation:* When calculating storage cube for a pallet location, Fresh assumes a 40" W x 48" D x 48" H pallet space. All of the space above 48" is not considered part of the storage cube. However, if a library bay was stored in the floor space currently allocated to a pallet, the storage cube would use 96" height in the storage cube calculation. Pallet utilization is actually much lower if the utilization calculation factored in the potential storage capacity of the space. One way to eliminate this discrepancy is to compare storage types by net-cube-per-square-foot.

Root Causes

There are three primary reasons pallet space utilization is so low.

1. **SKU velocity information is not provided** to associates working in inbound processes. Over time, some associates have learned which SKUs should be stowed on a pallet, but this is only tribal knowledge.
2. **Pallets must be picked empty** (or nearly empty and then consolidated) so the average utilization rarely exceeds 50%. The target utilization[5] for Fresh's frozen and chilled pallets is 40%, and tropical pallets only 30%.

[3]categorized based on total outbound units

[4]The theoretical average space utilization in one location over time should be 50%. (See Figure 3-1 on page 32.)

[5]"Target utilization" is the average expected utilization for a given storage hardware type and temperature zone.

3. **Many products are difficult to stack.** Some products can be easily stacked and are therefore well suited for pallet storage, such as paper towels and toilet paper. At Fresh Fulfillment Center X, the average space utilization of pallets of paper products is high—76.5%. Other products that are often difficult to stack, such as produce, have poor space utilization of 20.2%.

Recommendations

Fresh should implement a new racking configuration—a hybrid between pallet storage and library bin storage. This racking should be configured as single-deep racks, pickable from both sides with alternating 72" wide and 48" wide aisles. Maneuvering pallets requires 60" to 72" wide aisles. Library bay aisles are typically configured with 48" wide aisles. In the proposed configuration pallets can be loaded using every-other aisle. This configuration will increase net cube and eliminate the unreachable dead space in current over-pallet-racks configurations.

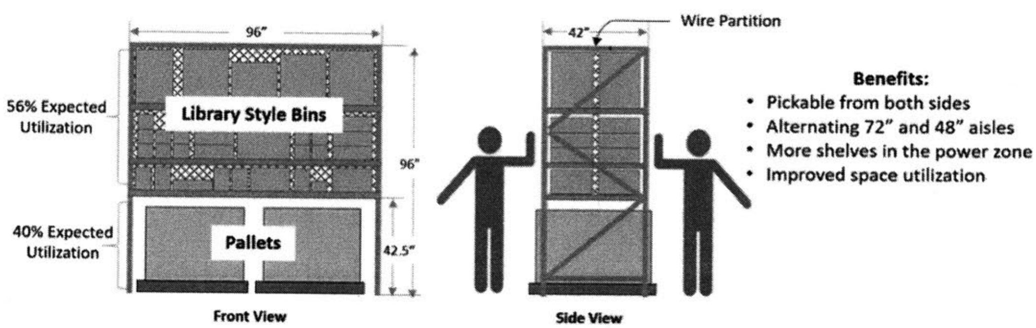


Figure 6-15: Proposed Hybrid Over-Pallet-Racking Configuration

Estimated Benefits

This project evaluated space utilization of various storage structures and layouts. Net-cube-per-square-foot was calculated over a 4,000 square foot area to include the impact of aisles on space utilization. The result indicated that the new hybrid configuration should provide a 72% increase in net-cube-per-square-foot over the current OPR configuration (175% increase over current pallet storage).

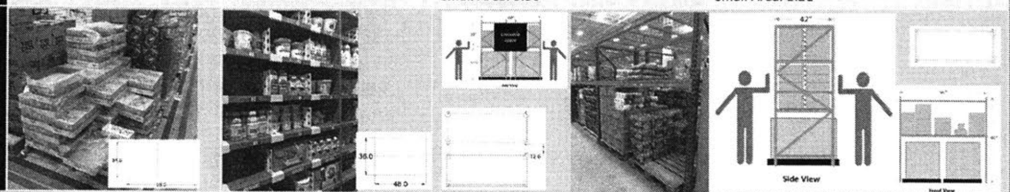
	Standard Pallets	Library Deep Racks	Current Over-Pallet-Racking	New Hybrid Racking Configuration
Outside Dimensions:	Double: 98"D x 57"W x 48"H Each Pallet: 43"D x 51"W x 48"H	One Bay: 18"D x 48"W x 96"H 2 Bays back-to-back: 36"D x 48"W x 96"H	Single Rack: 42"D x 96"W x 96"H Two double-deep pallet racks: 96"D x 96"W x 96"H	42"D x 96"W x 96"H
Spacing & Aisles:	12" gap to adjacent pallet (included above) 72" aisles	48" wide aisles	12" gap to adjacent row for double-deep racks (included above). 72" aisles	Alternating 48" and 72" wide aisles
Storage Cube Dimensions:	48"D x 40"W x 48"H	18"D x 48"W x 81"H	Pallet Zone: Two 48"D x 40"W x 48"H Shelf: 42"D x 96"W x 22"H	Pallet Zone: Two 48"D x 40"W x 40"H Shelves: 42"D x 96"W x 43"H (3.5" beams and 96" high racks)
Cube: *(gross cube)*	106.67	81.00	316.00	189.22
Target Utilization: *(estimated)*	40%	56%	Pallet Zone: 40% Shelf: 20%	Pallet Zone: 40% (standard pallet utilization) Shelves: 56% (library deep utilization)
Net Cube per Square Foot:	Large Area: 0.57 Small Area: 0.51	Large Area: 1.54 Small Area: 1.45	Large Area: 0.85 Small Area: 0.80	Large Area: 1.27 Small Area: 1.21
Configuration:				

Figure 6-16: Cube Comparison by Storage Type

The new configuration lowers the first shelf to 42.5 inches, allocating less space for pallet storage. Estimates used current pallet target utilization of 40% for the pallet space, and current library bay target utilization of 56% for the shelves. However, even if the proposed shelf height configuration (with less vertical space allocated to pallets) is not used, Fresh will still realize an increase in net-cube-per-square-foot due to the improvement in shelf-space accessibility from the single deep rack layout. This configuration will provide a 53% increase in net-cube-per-square-foot over the current OPR configuration, and 135% increase in net-cube-per-square-foot over the current pallet configuration. See Figure C-3 in Appendix C for more information on this calculation.

Potential Risks

Allocating less vertical space for pallet storage may only suitable for a portion of the over-pallet racks. Produce pallets are typically short (average height is less than 36") but any tall pallets will either need to be split until they are short enough to fit in the new racking, or stored in racking configured with higher shelves. There is a potential trip and reach hazard with the 42" wide racking structure which creates an over-hang into the aisles by 3", as illustrated in Figure 6-17.

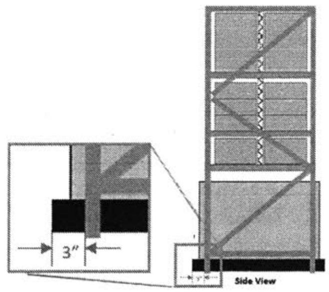


Figure 6-17: Pallet Overhang Risk

Summary

Pallet space is very valuable for high velocity and large cube products, but Fresh needs to improve space utilization in pallet locations. A new configuration and layout of over-pallet-racking can increase storage cube by 175% over current pallet storage locations, and by 72% over the current over-pallet-racking configuration. This configuration may not be suitable for every pallet location due to a reduction in the height of pallet spaces. The new design is currently being tested at a Fresh fulfillment center in Washington State. Additional details about this design, net-cube calculations, and the pilot test can be found in Appendix C.

Principles Applied:

- ✓ Good Product/Storage Fit
- ✓ Eliminate Waste
- ✓ Maintain Flexibility to Adapt

6.5 Challenge #5: Managing Fluctuations

Fulfillment centers are rarely at steady-state. Surges in demand can require resource reallocation to meet deliveries. Waves of shipments from suppliers can cause congestion at the receiving dock. When labor is reallocated to address one need, another area may suffer. If labor is not available to remove expired products, valuable storage space is taken up by products that aren't sellable, overall fullness increases, and pick and stow rates suffer. Constant fluctuations make it very challenging to balance the competing priorities of space utilization and labor productivity.

Common sources of variation were described in Chapter 5 on page 54. At Fresh, variation is seen from unpredictable demand, seasonality of products, delays (including delays in the supply chain, internal process delays, and delays in data and reporting), incorrect shipments (quantities received are different from quantities ordered), variations in suppliers delivery frequencies, labor availability, and spoilage of perishable goods.

The Trade-offs

Operational Decisions:

As previously mentioned, frequent adjustments are required in order to maintain stable operations. Managers can make adjustments by prioritizing one or more of the following:

Picking productivity, stowing productivity, space utilization, bin organization, quality checks and inventory management (counting).

Strategic Decisions:

- **Product Selection vs. Operational Efficiency:** Offering a large variety of products is part of Amazon.com's strategy, as seen in the Amazon flywheel in (Figure 2-1). Amazon wants to attract customers with a broad selection so they have no reason to shop elsewhere. Fresh's competitive strategy is also tied to offering a broad selection of products, because customers may decide against using Fresh if they still have to make a trip to the grocery store to get everything they need. However, offering a large selection requires several trade-offs. A huge selection can lead to inefficient use of storage space, expired inventory, and supply chain complexity.
- **Overages vs. Underages:** The challenge of balancing selection and is rooted in a financial tradeoff between having too many or two few units of a SKU– the classic Newsvendor problem. Fresh doesn't want to stock out of an item, and suppliers have minimum order quantities and typically the price per unit decreases as the quantity ordered increases. Buying more than needed to get a price-break can lead to operational challenges and high inventory holding costs. Over-buying fills up the fulfillment center's capacity and increases waste from spoilage. Labor must be used to pick expired inventory to remove it from the pick area. If a good is not able to be sold, all of the handling costs to stow, store and pick the item are wasted.

Recommendations

- **Pick Algorithm Prioritization Feature:** Fresh should provide the ability to manage conflicting priorities by adjusting the priority of the pick algorithm to reduce the impact of variations. This new feature could adjust to fluctuations in demand and capacity without using indirect labor and without hiring additional associates. Significant improvements to operational performance can be achieved by minimizing the impact of variations with a simple, behind-the-scenes change to the algorithm. Fresh could automate this solution through the use of a dynamic optimization model that monitors conditions and automatically adjusts the algorithm's priority for the optimum result. An optimization model could not only predict the output of changes to the various inputs, but it could also suggest the optimum settings to meet the objective function (e.g. minimize total cost) while remaining within preset constraints for other variables, such as quality or productivity.

- **Order/Delivery Frequency:** Fresh should work with vendors to increase the frequency of deliveries. Ideally, Fresh would have a pull system so inventory is only delivered when it is needed. Just-in-time inventory management would significantly reduce the storage space required at Fresh fulfillment centers. Fresh is currently a small player with low buying power in the grocery industry, so changes to the supply chain processes may be difficult. Fresh could pilot changes in this area by working with a few vendors to improve communication on sales and demand forecasts, and provide more visibility to the status of inventory, potentially reducing lead-time delays in the supply chain.

- **Dynamic Pricing:** Fresh should leverage technology to reduce spoilage. The expiration dates of all products in inventory are recorded in Fresh's electronic inventory record. Fresh could use data from historical sales to predict the likelihood that a product in inventory will spoil before it is sold. If the risk of spoilage is high, Fresh could adjust the price on Fresh's website to sell the product at a discount before it expires. Fresh could sell inventory with limited remaining shelf-life to discount grocery retailers and recoup the salvage value. Even if Fresh sold this inventory for only the cost it takes to pick, pack, and ship the product, Fresh would prevent expired inventory from taking up valuable storage space.

Summary

Constant fluctuations make it very challenging to balance the competing priorities of space utilization and labor productivity. A small change in the pick algorithm can give Fresh the ability to make minor adjustments to meet surges in demand and supplier deliveries, free-up storage capacity, or reduce spoilage—all with minimal disruptions to daily operations. Improvements to Fresh's supply chain operations could help Fresh move towards a just-in-time inventory management model, significantly reducing inventory and required storage capacity. To reduce spoilage, Fresh could leverage technology and historical data to implement dynamic pricing, selling products at discount prices instead of losing 100% of the salvage value.

Principles Applied:

- ✓ Eliminate Waste
- ✓ Enable Smooth Flow of People and Materials
- ✓ Maintain Flexibility to Adapt
- ✓ Minimize Impacts from Variation

Chapter Summary

This chapter illustrated how the guiding principles for Fresh's Ideal Storage System can be applied to address some of Fresh's top storage-related problems. The recommendations strive to balance the trade-offs between labor productivity, space utilization, and flexibility for the future for the best overall solution.

Chapter 7

Conclusions & Future Research

This chapter will review the original hypothesis, highlight key findings from this research, and summarize recommendations to address specific storage challenges at Amazon Fresh. It will also discuss opportunities for future studies to continue this research.

7.1 Key Research Findings

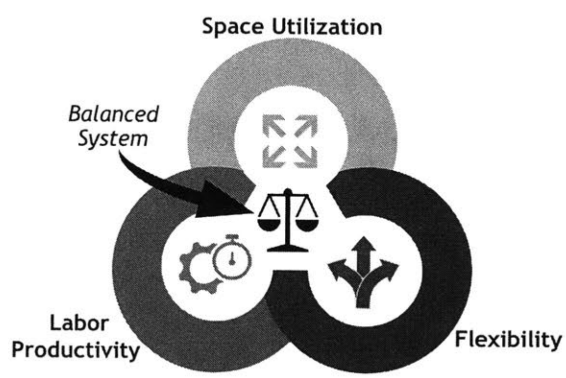
This thesis proposed that an optimum fulfillment center storage system can be achieved by strategically balancing trade-offs between labor productivity, space utilization and flexibility for the future. In addition, significant increases in storage capacity can be realized through optimization of storage and retrieval processes—often with minimal capital investment.

The following findings support this hypothesis:

The Vision for The Ideal Storage System

Chapter 5 examined the overarching goals of high-rate fulfillment centers and the primary challenges that cause imbalance in storage systems. This information was used to create a vision of the ideal storage system.

The Vision: The ideal storage system balances conflicting priorities of labor productivity and space utilization, it provides flexibility for the future, and it minimizes impacts of variations, operating with speed, agility and a competitive cost structure.



Guiding Principles for a Balanced System

A set of five guiding principles were created to serve as a checklist to ensure good balance in a complex storage system.

1. Pursue Good Product/Storage Fit
2. Eliminate Waste
3. Enable Smooth Flow
4. Maintain Flexibility to Adapt
5. Minimize the Impact of Variation

Unexpected Findings

Several unexpected findings were discovered through this research:

- The space-saving benefits expected from a random stowing policy will not be realized unless picking processes are also aligned with the stow policies. See Section 6.1.
- Simple solutions, such as grouping products by packaging type, may have been overlooked, but may provide significant improvements in space utilization. See Section 6.2.
- A change with obvious benefits could unintentionally create major capacity limitations. Changes need to be evaluated for potential unintended consequences to the overall system. See Section 6.3.
- Warehouse fullness and operational performance are highly correlated. A warehouse reaches maximum capacity when the flow-rate peaks, often long before it runs out of room for additional inventory. After this point, without changing the system, increasing capacity utilization will result in non-linear increases in variable cost. See Section 6.3.
- A small change to the layout and configuration of storage hardware could increase net-cube without capital investment. See Section 6.4.
- Constant fluctuations make it very challenging to balance the competing priorities of space utilization and labor productivity, but small changes to processes can provide operational agility and minimize the impact of variations. See Section 6.5.

7.2 Recommendations for Amazon Fresh

Chapter 6 explored real storage challenges at Amazon Fresh. An evaluation of the trade-offs underlying each challenge illustrated why achieving a balanced storage system can be so challenging. A summary of the recommendations for Fresh include the following:

- Increase storage capacity by 34% with a small change to the pick algorithm.
- Improve space utilization while maintaining flexibility for the future by grouping similar package types into new storage zones and by using modular storage hardware solutions to improve product/storage fit.
- Increase net-cube-per-square-foot in pallet locations by re-configuring over-pallet-racks.
- Strive to operate at the economically optimal space utilization level.
- Reduce the *ladder penalty* by adding step-ladders to pick carts. (5-year NPV for Fresh FCX estimated at more than $660,000). Implement a velocity-based stowing policy by-shelf to improve picking labor productivity.
- Minimize impact from variations by adding a feature to the pick algorithm to balance the competing priorities, improve supply-chain operations by moving towards a just-in-time inventory management model, and leverage dynamic-pricing to improve storage space utilization and reduce loss from product spoilage.

7.3 Opportunities for Future Research

Improved Granularity of Storage & Fulfillment Costs

Through the process of conducting research on storage-related costs, the need for a higher level of granularity of variable cost data became apparent. Armed with a better estimate of the actual costs required to store, pack, shop and deliver a specific products could lead to improved buying logic and better resource allocation of fulfillment center storage space.

Background: When a new fulfillment center is designed, required storage capacity is estimated by using demand forecasts of the number of units Fresh expects to sell (total units, not product-specific). Once in operation, fulfillment centers calculate variable cost per unit (VCPU) by dividing variable fulfillment cost by the total number of units sold. But the actual cost of fulfillment varies substantially by product. For example, consider the relative fulfillment costs of two products: a gallon of milk and a stick of deodorant. Milk must be refrigerated, it has a short shelf life, it is relatively large and heavy, and the profit margin is traditionally quite low. On the other hand, a stick of deodorant doesn't need to be refrigerated, it has a long shelf-life, it doesn't require a lot of storage space and it's lightweight. Variable cost per unit averaged over all products does not give an accurate estimate of actual fulfillment costs of different products. Pricing decisions are set by using specific procurement costs for each product and the *average* fulfillment costs.

Gross margin is a common metric used by grocery retailers. Vuijst, Kesteloo and Hoogenberg (2018) argue that online grocers need a new metric that incorporates the variation in picking and distribution costs; two expenses not part of the cost model in traditional grocery stores. Their study of online grocers found that unprofitable orders tended to have a high number of bulky items (e.g. cases of soda, family-packs of toilet paper) lower absolute-margin items (e.g. low-end, private-label goods), slow-moving items and items with promotional discounts. They suggest a new metric: *net margin contribution*[33].

Net Margin Contribution=(Gross Margin)-(Direct Picking and Distribution Costs)

The Net Margin Contribution concept could be expanded to include other storage costs. At Fresh FCX, 7,971 units of paper products (e.g. paper towels and toilet paper) take up 8.2% of the total storage space. Storing a huge box of paper towels takes up a lot of space, but this is currently not factored into retail decisions. Similarly, refrigerated and frozen space is more expensive to maintain than ambient space, but the way cost data is tracked. The fulfillment costs of one unit of Product X is equivalent to the fulfillment costs of one unit of Product Y, regardless of the variation in actual fulfillment costs between the two products.

Potential Benefits: If Fresh were able to associate the costs of fulfillment to particular products, a more sophisticated buying logic could be created. Fresh might discover it's losing money on bottled water and decide to adjust the price or revise the advertising strategy for bottled water. Similarly, Fresh may discover that some products have very low fulfillment costs and high margins—information that could provide additional flexibility by allowing Fresh to compete on price or increase advertising and promotion of low fulfillment cost/high margin products. This information could also be used to make better strategic selection decisions on which products Fresh should offer.

Approaching the Problem: While it may be extremely difficult to track the actual variable costs of each product, a parametric model could be one way to quickly and easily assess relative differences in fulfillment costs. For example, a weighted sum model (such as the model described on Page 23) could be used to combine multiple factors that correlate with fulfillment costs (e.g. product size, refrigeration requirements[1], product weight, risk of spoilage, and special handling requirements. Each product could be scored on each factor. The weighting for each factor could be adjusted to improve the model as Fresh learns more about the impact on each factor has on actual cost of fulfillment.

Summary: Averaging the fulfillment costs of all products does not provide an accurate estimate for the actual cost of fulfillment. Better buying decisions could be made if Fresh had more insight into the storage-related variable costs.

7.4 Closing Remarks

Regardless of the unique characteristics of a storage system, it's imperative to look beyond the visible results and understand the complex system of interconnections and interrelationships between labor productivity, space utilization and other aspects of the system. Knowledge of these trade-offs can be leveraged to make more informed business decisions, avoid sub-optimization and achieve new levels of operational excellence[3].

[1]For example, the cost of chilled and frozen space is more than the cost of ambient space due to capital investment in chillers, utility costs, and the challenges associated with expanding climate-controlled areas. A model could use the capital-price-per-square-foot for each temperature zone to establish a value for each temperature zone.

Appendix A

Terminology

Warehousing terminology varies significantly by industry, company and even across organizational boundaries of a company. Common terms, as they are used in this document, are defined below:

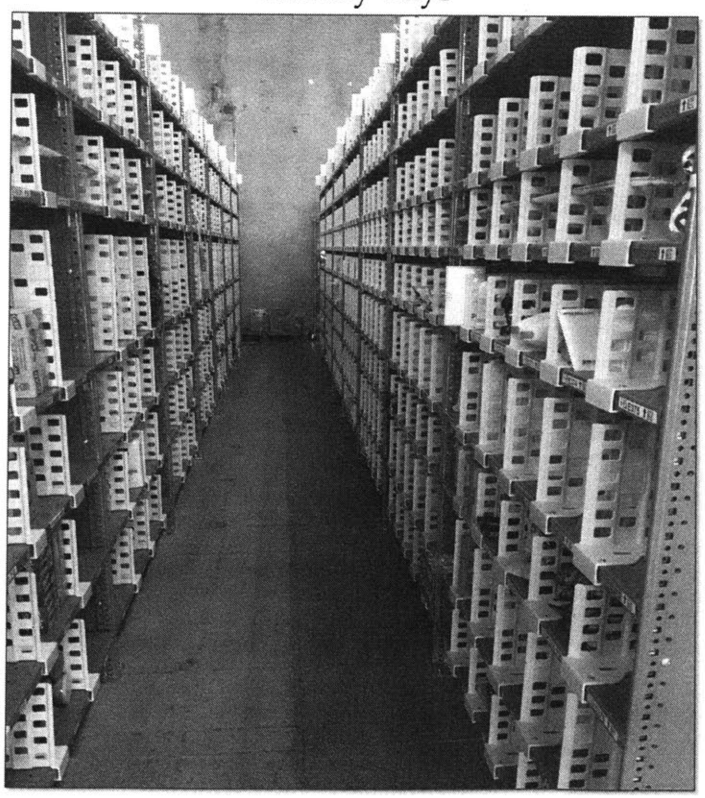
- **Bay:** a shelving unit. For example: one bookshelf, which is a collection of individual shelves, is a bay.
- **Bin:** the smallest indivisible storage location. At Amazon Fresh, shelving structures are divided vertically by shelves and horizontally by shelf dividers, creating individual bins. Every bin has a unique bin identification number and label.
- **Designed capacity:** the theoretical maximum storage capacity of a facility. It is the sum of the cubic volume of all storage locations.
- **Effective capacity:** also called working capacity; the maximum storage capacity that is actually achievable given constraints of the system, such as inventory characteristics, facility layout, storage hardware, product characteristics, and operational processes.
- **Efficiency:** used to describe the output or value achieved relative to the non-labor resources used. In this document, efficiency refers primarily to space utilization—the volume of space used in the storage of a product, relative to the total space allocated to the product.

- **FCX or Fulfillment Center X:** the terms created for the purposes of this document to identify the fulfillment center that was the subject of the data analysis without revealing proprietary information.
- **Fullness:** the percentage of storage capacity that is used. In this document, fullness is calculated as: (inventory cube)/(storage cube). Fullness is used to discuss warehouse fullness or bin fullness.
- **Gross capacity:** the total physical storage capacity, measured as the outer dimensions of a storage area (e.g., bin, bay or pallet location).
- **Productivity:** the output achieved relative to the labor used. In this document, productivity refers specifically to labor resources.
- **Net capacity:** also called available capacity or net cube; the portion of gross capacity that is assumed to be usable; calculated as (gross capacity) * (target utilization).
- **Pick density:** represents the number of picks for a given area or travel distance[16]. High pick density typically reduces the travel distance between picks.
- **SKU:** a stock keeping unit; a number or code assigned to one individual product.
- **Storage cube:** the cubic volume of a shelving unit.
- **Storage policy:** a policy that impact the final storage location of inventory within the warehouse. This may include rules related to which inventory is directed to a storage type or location, how much inventory can be stored in a storage type, and in what method the inventory is stored.
- **Target utilization:** Amazon's term for the planned portion of gross capacity that is expected to be used when the bin is full; defined by bin-type.
- **Utilization:** the portion of gross capacity that is actually filled by product.
- **Working storage capacity:** see effective capacity.

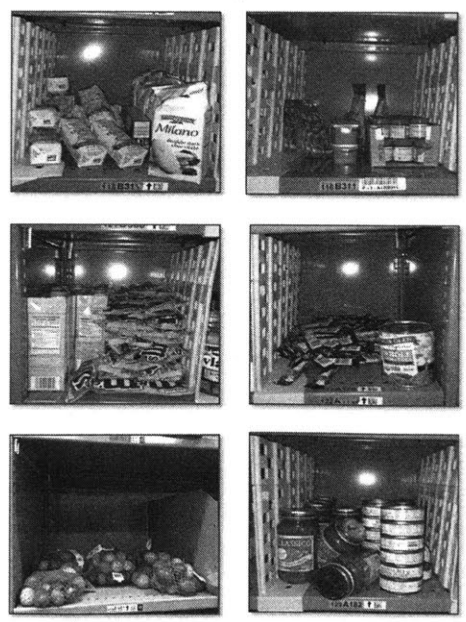
Appendix B

Storage Hardware at Amazon Fresh

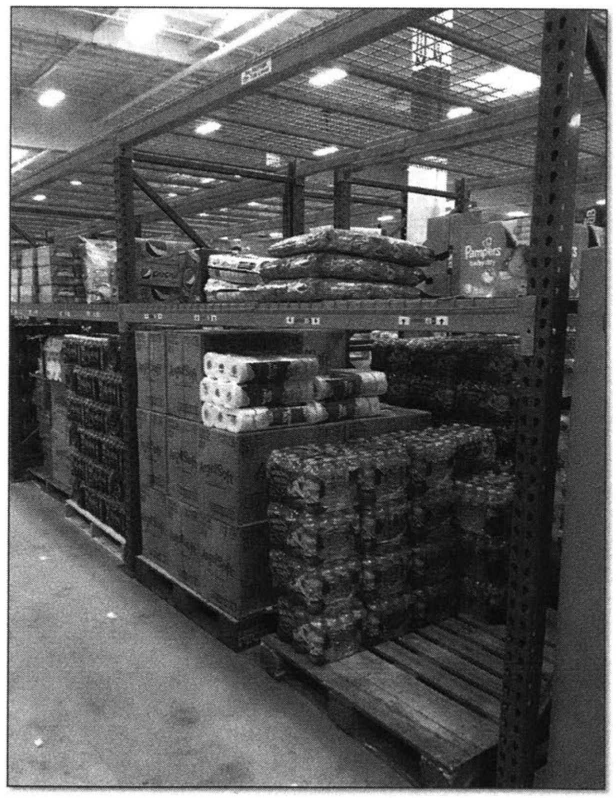
Library Bays



Library Bins



Over Pallet Racks



Pallets

Appendix C

Hybrid Racking Pilot Test Proposal

The following pilot test proposal was created for Fresh Fulfillment Center BFI6 in Washington State.

- **Problem Statement:** Fresh fulfillment centers use library-style shelving and pallet storage. Utilization of pallet space is typically less than 40%, and the vertical space above a pallet is unused. Pallet space is valuable for high velocity product like produce. Fresh needs a way stow pallets while using space more efficiently.
- **Current Situation:** BFI6 has 31 pallet locations for chilled produce storage. Produce pallets are typically less than 36" high, as many produce cases are not easily stackable. BFI6 needs additional pallet locations and would like to turn the vertical space above the pallets into valuable storage space.

  Several Fresh FCs use 48" deep over-pallet-racks (OPR) in a double-deep configuration. The shelves improve the use of vertical space above pallets, but only 20% of the shelf space is accessible.
- **Proposed Solution:** This change request is for a small-scale pilot test of a new configuration of over-pallet-racks in BFI6 Chilled produce. The racks will add valuable pallet space and shelving space above the pallets.
  - ◇ 42" deep racks in a single-deep configuration can provide shelves that are pickable from both sides, eliminating the unreachable dead space in current OPR configurations.

- ◇ This configuration can use alternating wide and narrow aisles. Wide aisles will provide access to maneuver pallets and the narrow aisles will provide access for picking and stowing of eaches.
- ◇ Since produce pallets are typically less than 36", the first shelf of the OPR can be set at a lower, and more accessible height than the typical OPR configuration with a shelf height of 57.5" from the floor. The new configuration will test a variety of shelf heights.
- ◇ The configuration consists of twenty 96" wide x 42" deep racks and two 144" wide x 42" deep racks for 46 pallet locations with 2-3 shelves above each pallet. All the racks are 96" tall.

- **Benefits:** This configuration will add 15 pallet locations for a total of 46 pallets. With the addition of the over-pallet shelves, the net cube per square feet will increase from 0.57 for standard pallet configuration to 1.27 for this new configuration.
- **Risks:** Pallet Overhang: The use of a 42" deep rack for pallet storage will cause pallets to extend beyond the racking, creating a 3" overhang into the aisles. This is a potential safety concern, potentially making it difficult for associates to reach the shelves. This is expected to be less of an issue than the current OPR high-shelf configuration, but is still a concern that needs to be evaluated as part of this test. Low Pallet Height: This test will evaluate the impact of allocating less space for pallets. It's not expected to be a problem in produce, but may require additional labor to reslot of tall pallets.
- **Cost:** Cost information has been omitted from this document.
- **Success Criteria:** The purpose of this test is to verify assumptions and identify unforeseen challenges. Feedback on the configuration will be factored into design iterations prior to network-wide implementation. Success will include:
  - ◇ Identification of optimal rack dimensions for pallet zones and shelves.
  - ◇ Identification of challenges with of 3" pallet overhang and aisle widths.
  - ◇ Significant increase in net cube.
  - ◇ Establishment of a realistic target utilization rate for new storage structure.
- **Methodology:** Net cube per square foot calculated over a 4,000 square foot area to include the impact of aisles. Proposed configuration lowers the first shelf to 42.5", allocating less space for pallet storage. Estimate uses standard target utilization for pallet area (40%) and the target utilization for library deep bays (56%) for the shelves. However, even if we don't lower the shelf height, net cube per square foot will increase because the single rack deep configuration will make the shelf space accessible, improving utilization.

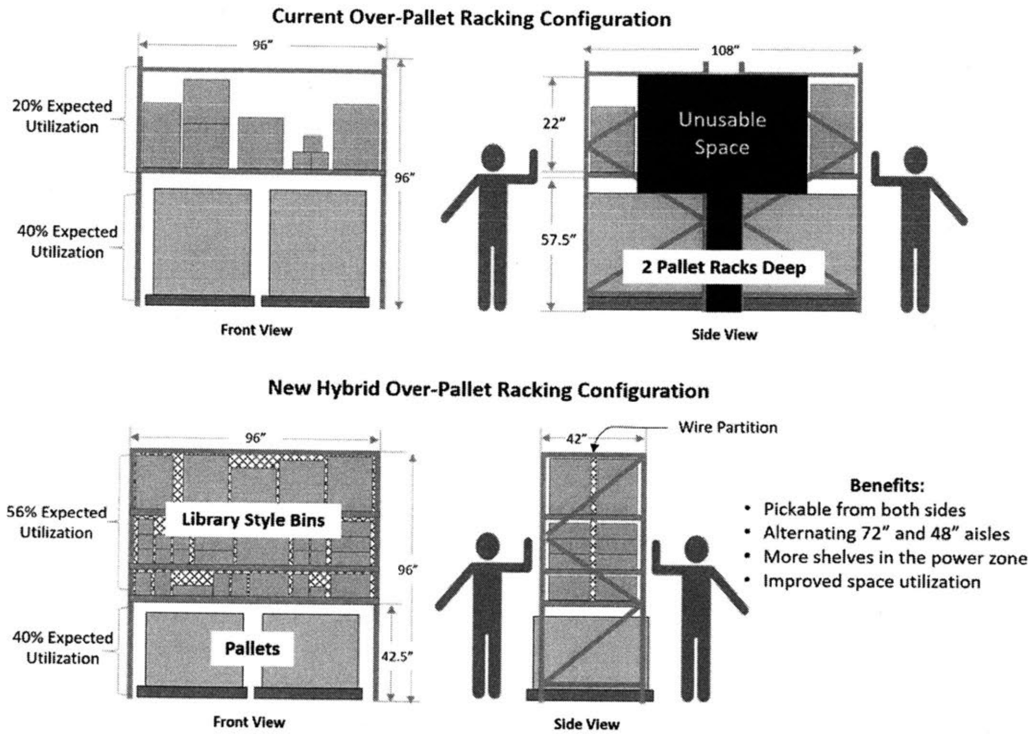


Figure C-1: Proposed Change to Hybrid Racking

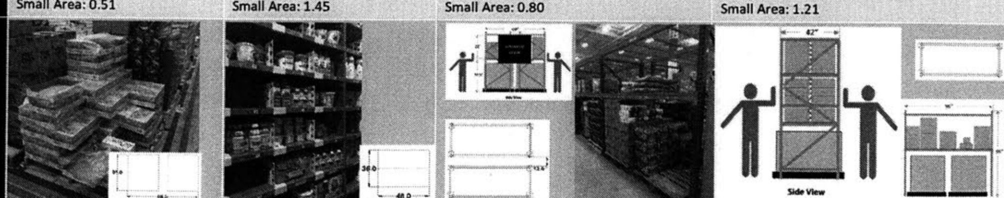
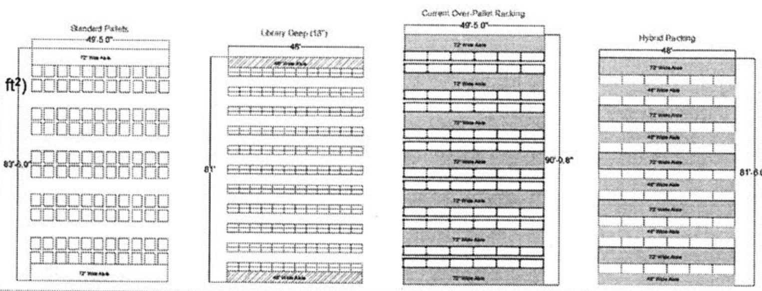
	Standard Pallets	Library Deep Racks	Current Over-Pallet-Racking	New Hybrid Racking Configuration
Outside Dimensions:	Double: 98"D x 57"W x 48"H Each Pallet: 43"D x 51"W x 48"H	One Bay: 18"D x 48"W x 96"H 2 Bays back-to-back: 36"D x 48"W x 96"H	Single Rack: 42"D x 96"W x 96"H Two double-deep pallet racks: 96"D x 96"W x 96"H	42"D x 96"W x 96"H
Spacing & Aisles:	12" gap to adjacent pallet (included above) 72" aisles	48" wide aisles	12" gap to adjacent row for double-deep racks (included above). 72" aisles	Alternating 48" and 72" wide aisles
Storage Cube Dimensions:	48"D x 40"W x 48"H	18"D x 48"W x 81"H	Pallet Zone: Two 48"D x 40"W x 48"H Shelf: 42"D x 96"W x 22"H	Pallet Zone: Two 48"D x 40"W x 40"H Shelves: 42"D x 96"W x 43"H (3.5" beams and 96" high racks)
Cube: *(gross cube)*	106.67	81.00	316.00	189.22
Target Utilization: *(estimated)*	40%	56%	Pallet Zone: 40% Shelf: 20%	Pallet Zone: 40% (standard pallet utilization) Shelves: 56% (library deep utilization)
Net Cube per Square Foot:	Large Area: 0.57 Small Area: 0.51	Large Area: 1.54 Small Area: 1.45	Large Area: 0.85 Small Area: 0.80	Large Area: 1.27 Small Area: 1.21
Configuration:				

Figure C-2: Net Cube Estimates for Storage Configuration

Large Zone (approximately 4000 ft²)

	# of Bays	Net Cube	Zone Width	Zone Length	Zone SqFt	Net Cube per SqFt
Double Pallets	55	2346.67	83.5	49.5	4133.3	0.57
Back-to-Back 18" Deep Library Bays	132	5987.52	81.0	48.0	3888.0	1.54
Current Double-Deep Over-Pallet-Racks (42"Hx96"W with 2 pallets & 1 shelf)	36	3811.20	91.0	49.4	4496.9	0.85
New 42"D x 96"W Hybrid Racking	54	4954.08	81.5	48.0	3912.0	1.27



Small Zone (approximately 1800 ft²)

	# of Bays	Net Cube	Zone Width	Zone Length	Zone SqFt	Net Cube per SqFt
Double Pallets	22	938.67	37.0	49.5	1831.50	0.51
Back-to-Back 18" Deep Library Bays	60	2721.60	39.0	48.0	1872.00	1.45
Current Double-Deep Over-Pallet-Racks (42"Hx96"W with 2 pallets & 1 shelf)	18	1905.60	48.0	49.4	2372.00	0.80
New 42"D x 96"W Hybrid Racking	24	2201.81	37.9	48.0	1820.00	1.21

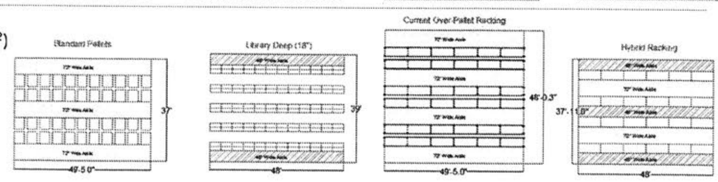


Figure C-3: Layouts Used to for the Net Cube per Square Foot Estimates; Net Cube Estimates Over Large Areas to Account for Impact of Aisles

- **Impact to Existing Storage Configuration:** Figure C-4 illustrates the storage configuration before and after the proposed changes.

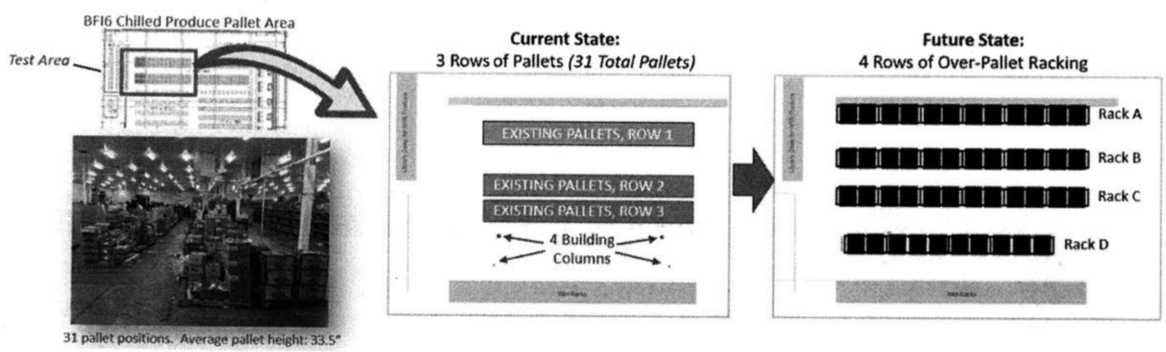


Figure C-4: Changes to The BFI6 Chilled Produce Pallet Area

- **Existing Inventory Relocation Plan:** The installation of four rows of racking will occur in phases so existing inventory (31 pallets) can be moved with minimal effort and without additional holding space.

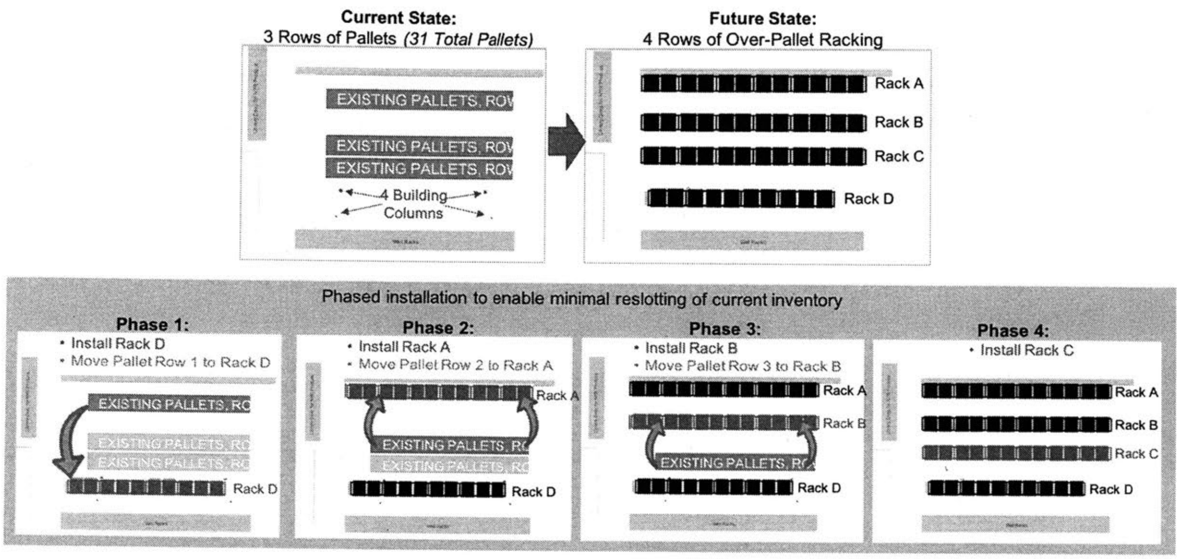


Figure C-5: Phased Implementation to Relocate Existing Inventory

- **Bin Configuration:** Each shelf will be divided horizontally into bins. In addition, each rack will have pickable bins with unique bin IDs on each side of the rack as shown in the side view. Each pallet location will have one bin ID with identical labels on both sides of the bay.

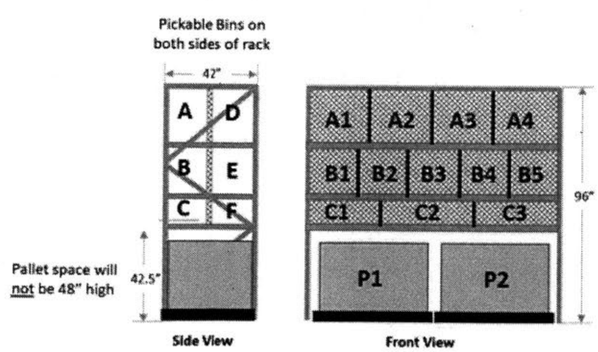


Figure C-6: Bin Labeling to Enable Picking from Both Sides of Rack

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