Case Study: The effect of pallet design on the performance of semi-automatic &fully-automatic warehouses.

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SCHOLARLY ABSTRACT

Pallets form the base of the unit load, which is the basis for global trade transportation. In order to achieve better performance, improve efficiency, and compete in much more versatile markets, industrial activities and pallet management service firms are becoming more automated than ever; they are adopting advanced manufacturing technologies and flexible manufacturing systems.

This study focuses on the investigation of the most common compatibility issues between pallets and material handling systems in semi-automatic and fully-automatic warehouses. At the same time, it establishes an understanding of the downtime and frequency of problems caused by pallets in these types of facilities.

This research was conducted in two phases. The primary phase was a mix mode questionnaire (phone interview and hard copy questionnaire) that was used to survey members of different industries, such as pallet manufacturers, equipment manufacturers, and pallet users. The secondary phase surveyed multiple general warehouses and storage facilities around the U.S., and surveyed warehouse professionals from manufacturing companies in the pharmaceutical, petroleum, dairy, beverage, chemical, and tobacco industries, to name a few.

Results showed that 3% of the respondent warehouses are fully automatic, and 20-30 % are semi-automatic. Additionally, block class wooden pool pallets were identified as the most common pallet class used in semi/fully automatic warehouses, followed closely by the use of stringer class recycled wooden pallets. Despite this, stringer class recycled wooden pallets were identified as the main pallet class involved in pallet related downtime in semi/ fully automatic warehouses/ DC facilities.

Further results present a guideline for improving automatic warehouse performance, determine the pallet characteristics needed for this type of applications and expands the knowledge around downtime frequency cause by pallet related issues in these types of systems.

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GENERAL AUDIENCE ABSTRACT

Pallets are the main tool used to transport unit loads throughout the different supply chains worldwide. Currently, industrial activities are becoming more automated than ever; in order to achieve better performance, improve efficiency, and compete in much more versatile markets.

This study investigates the most common compatibility issues between pallets and material handling systems, used in semi-automatic and fully-automatic warehouses. Additionally, it presents the downtime and frequency of problems caused by pallets in these types of facilities.

This research was conducted in two phases. The first phase identified the most common compatibility issues between pallets and these types of systems; this phase was achieved by surveying members of different industries such as pallet manufacturers, equipment manufacturers, and pallet users.

The second phase targeted multiple general warehouses and storage facilities around the U.S.; during this phase, the frequency and downtime of the most common compatibility issues were determined.

Results from this investigation present a guideline for improving automatic warehouse performance, determine the pallet characteristics needed for this type of application, and expands the knowledge around downtime frequency cause by pallet related issues in these types of systems.

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Chapter 1: Introduction

Pallet applications became industrially significant after the 1940s. The Second World War pioneered a demand for material handling speed (LeBlanc,2011). The military used pallets as a valuable tool to meet this demand. After World War II, pallets were no longer used exclusively by the military (Gerber, 2018). Since then, pallets have been adopted by different industries and have helped modernize and improve material handling efficiency by helping to move and store materials quickly, reducing product damage and minimizing the risk of worker injury. Pallets have become a key component of warehousing and transportation (McCrea, 2016).

Pallets form the foundation of the unit load, which is the basis for global trade transportation (Shiner, 2018). "A unit load is a single item, a number of items, or a bulk material that is arranged and restrained so that it can be stored, picked up, and moved between two locations as a single mass (White and Hamner, 2005)." This means that any item that doesn't have exceptionally large dimensions can be palletized. Ninety-three to ninety five percent of all unit loads have a pallet beneath them (White and Hamner, 2005). According to the 2015 market report from Freedonia Group Incorporated, a leading international industry study/database company, the total number of pallets in use in the U.S. was forecasted to increase 1.9 percent annually through 2019 to 2.6 billion units, supported by gains in U.S. manufacturing and warehousing activity.

Wood pallets are the most popular material of pallet on the market, making up 84 % of the total stock in 2019 and 93% of sales in unit terms (The Freedonia Group,2015). Plastic pallets are rising in popularity, specifically in the pharmaceutical and food & beverage industries, due to the ease of cleaning, long lifespan, and resistance to insects, fungi, and other types of biological infestation.

Currently, manufacturing is the largest market for pallets. Nevertheless, warehousing and construction markets show faster growth. The growth in the warehousing market is driven by higher industrial activity and the increased use of pallet management service firms (The Freedonia Group, 2015). Industrial activity and pallet management service firms are becoming more automated than ever. In order to achieve better performance, improve efficiency, and compete in greater markets, industries are adopting advanced manufacturing technologies and flexible manufacturing systems (FMS) (Dixit and Raj, 2018). According to the 2019 automation report from Modern Material Handling magazine (MMH), more companies are looking to automate their operations, driven by the need to manage high velocity operations with limited labor resources, while meeting the ever-changing needs of their customers.

Material handling systems (MHS) are an important part of product flow in the supply chain and a crucial component in automated systems. Despite this, MHS may not receive attention at first, because they do not add value. This topic is often treated superficially by companies (Groover, 2001). It is important to understand that MHS are involved at all stages in the supply chain and account for 30-75% of the total cost of a product along the production chain (Sule,1994 and Sujono and Lashkari, 2007). According to the Material Handling Industry of America (MHI), "Material handling is the movement, protection, storage and control of material and products throughout manufacturing, distribution, consumption, and disposal. Material handling incorporates a wide range of manual, semi-automated, and automated equipment and systems that support logistics and make the supply chain work" (MHI, 2019).

Material handling equipment form an important component of flexible manufacturing systems (FMS) and using proper material handling equipment can enhance the production process, provide effective utilization of manpower, decrease production cycle times, and improve system flexibility (Dixit and Raj, 2018). Kulak et al, 2004 stated that the selection of appropriate MHS can decrease manufacturing lead time, increase the efficiency of material flow, improve facility utilization, and increase productivity. Efficient material handling can be responsible for reducing the manufacturing system operation cost by 15% - 30%, according to Sule(1994) and Sujono and Lashkari (2007). Therefore, item production costs can be lowered significantly by saving in material handling costs (Dixit and Raj, 2018).

As Tompkins (2010) stated, proper selection of appropriate material handling systems has become a very important parameter for modern manufacturing concerns. The majority of time materials

/products spend in warehouses is due to handling activities (queues and transportation). Handling activities are categorized as non-value added, and it is desirable to reduce these times, whenever possible. To achieve this goal, MHS are designed using a logical sequence, so that handling is unidirectional and takes advantage of gravity when possible (Dixit and Raj, 2018). Also, during the design phase, standardized equipment is preferred because it facilitates interchangeable usage, better utilization of handling equipment, and less spare holding (Dixit and Raj, 2018). Other factors considered when designing an efficient MHS are the existing plan layout, the handling equipment, the nature of the products to be handled, production processes, equipment, and quantities involved. From an economic point of view, the cost of MH equipment, operating cost, and repair and maintenance are all considered in the design. Pallets design do not seem to be considered when designing MHS, even though pallets are the most common unit formation platform used for holding or carrying materials in standardized unit load forms during transportation and storage. Pallets are the main interface that allows the product to be moved through the material handling systems.

Typically, pallets are designed to be handled by material handling equipment such as pallet jacks, forklifts, manual or power operated hand trucks, or conveyors, and they are often stored in different types of rack systems or AS/RS (Shiner,2018). Despite this, they are frequently ignored during the MH design phase and regular operation. Pallets are often looked at as an annual expense by companies. Pallets are commonly damaged during operation. There are a number of reasons pallets fail when interacting with MHS, but it is not until a significant failure occurs, causing an economic impact, that attention is paid to the science behind a pallet. When a pallet fails, this translates into the loss of the pallet itself, loss of the product loaded on top of the pallet, damage of the product carried by the pallet, and the product near the pallet failure location. Pallet failure also implies safety issues, production downtime, equipment damage, extra cleaning, equipment repair, etc.

Wood pallets have always been attractive to pallet consumers because they allow for a broad choice of design options, including overall dimensions, wood species used, number of stringers, and deck boards, deck board width and thickness, height and width of stringers, and deck board spacing (Shiner, 2018). Additionally, a large proportion of wooden pallets can be recovered, repaired, or downcycled. (Gerber,2018). In 2011, it was estimated that 474 million pallet cores were recovered (Bush, 2014). Of that number, approximately 326 million pallet cores were either reused without repair or repaired and then put back into use (Bush, 2014). The repair market is estimated to be comprised of 80% stringer pallets and 20% block pallets (Bejune, 2002).

The flexibility and choice wooden pallets offer have made them very attractive to the industry. These exact characteristics makes them less attractive for their use in modern production systems. Modern manufacturing systems, in general, are automated, highly standardized, and optimized. The use of non-standardized pallets could translate into compatibility problems when interacting with highly standardized automated systems. In a 2002 interview with Pallet Enterprise, Dr. Mark White commented on the challenges created by the lack of standardization stating that "there are six international pallet sizes in the draft standard and that is five too many." The standardization of pallet sizes would save energy, conserve natural resources, and eliminate costs from the global supply chain (Buehlmann et al, 2009). Pallets that vary in use and quality critically affects the production flow and downtime of modern production systems.

When working with modern systems, it is crucial to understand the compatibility requirements needed for pallets to interact correctly with automated MHS. It is also important to be aware of the ability of MH equipment to access and handle pallets without causing damage. There are significant implications that purchasing the wrong pallet brings to modern logistical operations. Pallet purchasing for modern production systems must be carefully considered in order to match handling equipment, storage, production processes, warehouse type, and warehouse spaces. “It’s is not about the pallet price, it is about the pallet cost,” according to Dr. Mark White.

Currently, there is no literature citing the common problems occurring when pallets interact with automated or semi-automated MHS, and companies could be treating this superficially, which in fact, might be affecting their modern logistical operations and reducing their profits. This groundbreaking research investigated common pallet issues that occur when pallets interact with automated, or semi-automated, storage systems, material equipment, and palletizers /de-palletizers, in addition to quantifying the frequencies of pallet related issues in different industries. The results of this study are intended to help companies identify pallet characteristics that companies should pay attention to, in order to reduce downtime in the supply chain, eliminate money losses due to failure, reduce product damage, and prevent accidents. The results will help pallet and material handling professionals.

Chapter 2: Objectives

- To identify the most common compatibility issues between pallets and material handling / storage equipment in semi-automated and fully-automated warehouses.

- To understand the downtime and frequency of problems caused by pallets in semi-automated or fully-automated warehouses

Chapter 3: Literature Review

3.1 Pallets

3.1.1 Introduction and history of pallets

Pallets form the foundation of the unit load, which is the basis for global trade transportation (Shiner, 2018). "A unit load is a single item, a number of items, or a bulk material that is arranged and restrained so that the load can be stored, picked up, and moved between two locations as a single mass" (White and Hamner, 2005). This means that virtually any item that doesn't have exceptionally large dimensions can be palletized; hence, 93-95% of all unit loads have a pallet beneath them (White and Hamner, 2005).

According to the 2015 market report from The Freedonia Group Incorporated, a leading international industry study/database company, the United States' pallet demands represent 28.5% of global pallet consumption, followed by Western Europe with 25.1%, China with 16.3%, other Asian/Pacific countries with 8.2%, Canada & Mexico with 3.9%, and Japan with 3.8%.

The total number of pallets in use in the U.S. was forecasted to increase 1.9% annually through 2019 to 2.6 billion units, supported by gains in U.S. manufacturing and warehousing activity. Additionally, North America is not only the largest worldwide consumer of pallets, but also the largest regional pallet supplier, accounting for 32% of both global shipments and demand in 2012. The greatest consumer market demanding pallets is "other manufacturing markets." Other manufacturers' global demand for pallets represents 51.9%, followed by "warehousing" with 23.9%, "food & beverage manufacturing" with 22.1%, and "construction & others" with 2.1% (The Freedonia Group, 2015).

3.1.2 Classification

Pallets can be categorized based on classes, uses, accessibility, style, bottom deck orientation, location of the deckboards compared to the stringer ends, and size. Most simply, pallets can be divided into stringer and block class pallets. Stringer pallets are built with two or three stringers connected by top and bottom deckboards (Figure 1). Some stringer pallet designs have notches which are openings located along the length side of the pallet. Notches allow fork lifts to access the pallet, but due to the size of the openings (notches), they do not allow pallet jack access (NWPCA, 2014).

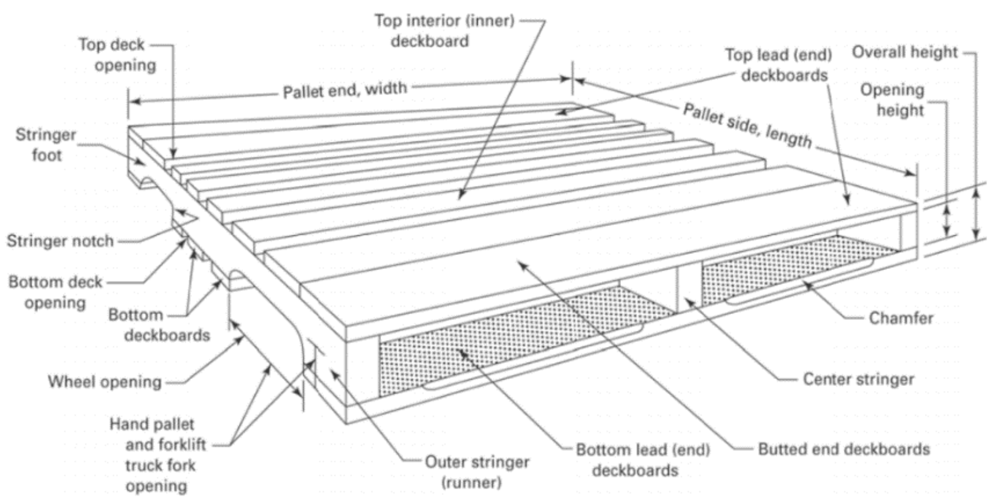


Figure 1. Typical stringer class pallet with principal parts labeled (MHI, 2016).

Block class pallets are composed of six-to-nine blocks connected together by stringerboards (Figure 2). Top deckboards are then connected to the stringerboards while the bottom deckboards are connected directly to the blocks (NWPCA, 2014).

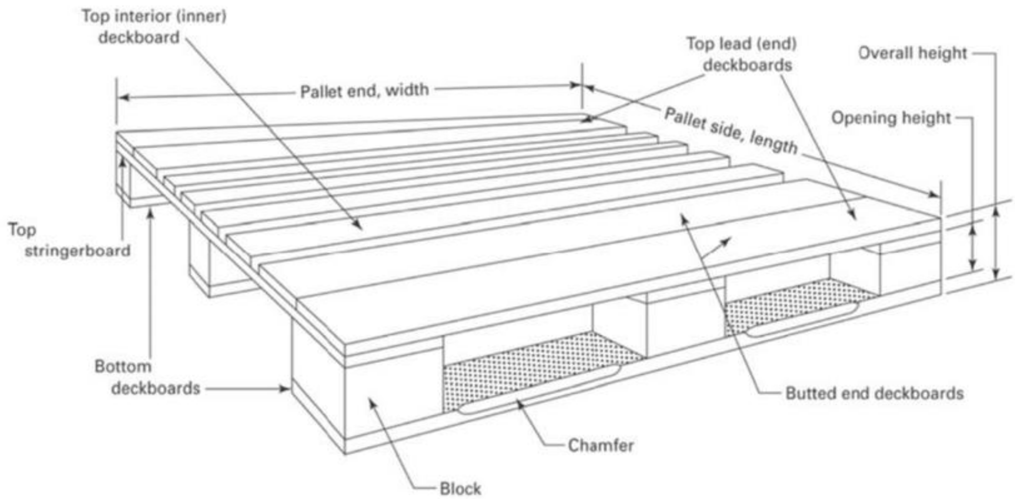


Figure 2. Typical block class pallet with principal parts labeled (MHI, 2016).

Pallets also can be classified according to their use. Pallets designed to be used for more than one trip are called reusable pallets while the ones that are designed to be used for only one trip are called single use pallets. Single use pallets are often used for exporting goods due to their light weight design and because product export only requires one trip.

The entry type is also a feature that differentiates pallets. Two-way pallets can be handled with both fork trucks and pallet jacks from only the two ends, while partial four-way entry pallets have openings on both ends and notches on both sides. The notches provide limited accessibility to the fork truck on the sides and then full accessibility, to both fork trucks and pallet jacks, from the two ends. Full, four-way entry pallets have full size openings at both ends and both sides; allowing full accessibility for any type of material handling equipment (NWPCA, 2014).

Based on their construction style, pallets are categorized as single face, double-face non-reversible, or double-face reversible (Figure 3). Single face pallets only have top deckboards, not bottom deckboards; thus, they only can be loaded on one face. Double-face, non-reversible pallets have both top and bottom deckboards; however, the number and locations of the top and bottom deckboards are different, so they only can be loaded on the top deck. Single-face and double-face non-reversible pallets both can be handled with a pallet jack. The third style is the double-face reversible pallet, which has identical top and bottom deckboards and allows the pallet to be loaded on either face. However, this design cannot be handled with a pallet jack (NWPCA Standard, 2014).

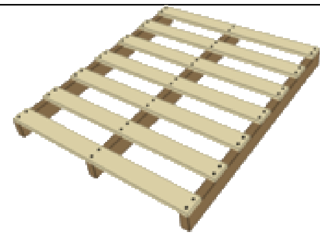
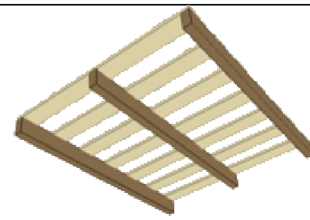
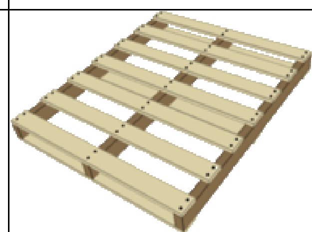
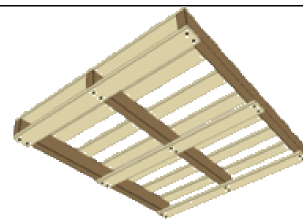
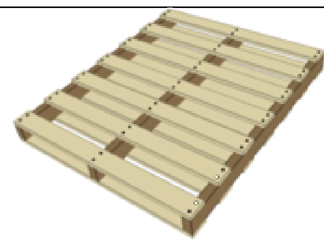
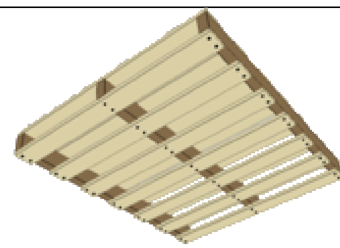
Pallet Style	Top View	Bottom View
Single face		
Double face non-reversible		
Double face reversible		

Figure 3. Pallet styles based on the number and location of deckboards.

Pallets have four subcategories based on the design of their bottom deck construction: unidirectional, overlapping, perimeter, and cruciform. This classification is important due to the fact that each different design performs better in specific support conditions. Unidirectional pallets have bottom deckboards, that are all parallel to either the length or the width. Perimeter pallets have two end boards, two butted side boards, and one butted center board. Meanwhile, cruciform pallets have all of the components of the perimeter base pallet, but they have two center boards (Figure 4). Overlapping pallets contain both bottom deckboards and bottom stringerboards (NWPCA, 2014).

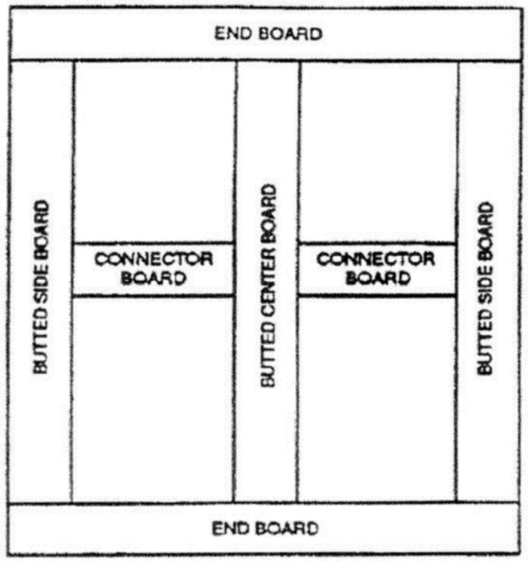


Figure 4. Bottom deck board diagram with component names for perimeter and cruciform pallets (MHI, 2016).

Additionally, pallets can be classified based on the alignment of the ends of the deckboards compared to the stringers. When the ends of the deckboards are flush with the stringers, the pallets are classified as a "flush" pallet. If only the top deckboards overhang the stringers, the pallet is classified as a "single-wing" pallet. On double-wing pallets, both the top and the bottom deckboards overhang the stringers (Molina et al., 2017).

Pallets can also be classified by size. Currently, the most popular pallet size in the USA is 48" x 40". This pallet is widely used in the grocery industry and represents 35% of annual pallet production in the U.S. (Gerber, 2018). Table 1 below presents other common pallet sizes used in various industries in the U.S.

Table 1. Common New Wood Pallet Sizes in the United States in 2018 (Gerber, 2018).

Pallet size	Annual production (%)
48" x 40"	35%
48" x 48"	6%
48" x 45"	5%
42"x 42"	5%
40" x48"	4%
48" x 42"	3%
48" x 36"	1%
800 x 1200 mm	1%
37" x 37"	0%
Other	39%

3.1.3 Materials

Pallets are manufactured from four main materials: wood, plastic, metal, and corrugated. Wooden pallets are the most popular in the U.S. market. In 2015, Fredonia Group predicted that wooden pallets would represent 84% of the total stock by 2019. Studies have shown that for 93% of the industries using pallets, their systems use wooden pallets (Modern Material Handling, 2017).

In the last decade, with the implementation of ISPM 15, plastic pallets have become particularly important to the food & beverage and the pharmaceutical industries due to their resistance to fungi, insects, and other types of biological infestations that wooden pallets are prone to experience. Additionally, plastic pallets have been welcomed by markets due to their significantly greater durability, longer life spans, and recyclability features. Starting in 2017, plastic pallets' global demand was expected to advance 9.1% annually (The Freedonia Group, 2015).

Metal pallets represent a small share of global sales; despite this however, they are constantly in demand in settings where extremely heavy items are being transported or in settings where there is a need to transport hazardous products such as chemicals (The Freedonia Group, 2015).

Wooden pallets are the most popular in the market (McCrea, 2016). Their popularity is due to many different features, but most importantly, their lower price. Companies look at pallets as part of their operating costs while their material handling systems are considered capital expenses. Most companies' focus is on reducing operating costs which translates to reducing the amount of money available to purchase pallets. This focus is the reason that, when most companies purchase pallets, they prefer less expensive wooden pallet; even though the wooden pallets' design might not be compatible with the material handling systems in their facility (Modern Material Handling, 2017).

Wood

Wood pallets can be manufactured with softwood or hardwood. This choice is mostly determined by the area where the manufacturer is located within the U.S. The United States has many different wood species; in the northwest region, spf, hemlock/fir, Douglas-fir, and red alder are the most common. Maple, birch, spf, and mixed hardwoods are the most common species in the northeast region. On the other hand, spf and red alder are the most popular species used in the southwest region of the U.S. Oak, yellow poplar, southern pine, and other mixed hardwoods are common in the southeast region. Species such as aspen and spf are most common in the middle of the country. And, finally, southern pine, oak, and mixed hardwoods are the species found most often in the center-south region of the U.S. In general, the west coast grows mostly softwood, and the east coast grows most of the hardwood available in the American market (Gerber, 2018).

When wood is purchased to manufacture pallets, it can be kiln-dried, heat-treated, or green. Kiln-dried means that the pallets' moisture has been reduced using a kiln. When referring to softwoods, kiln-dried is normally dried to 15%, 19%, or 23% moisture levels. On the other hand, hardwood can only be dried to 10%. Heat-treated wood refers to a different process; this heat process kills insects, but does not significantly reduce the moisture level. Green lumber refers to wood with a moisture content above the fiber saturation point (25-30%).

Being inexpensive is not the only advantage that wooden pallets have over other pallet materials. Wooden pallets are easy to prototype. Prototyping a wood pallet is easy due to current pallet design software available in the market; the Pallet Design System (PDS) (NWPCA, Alexandria, VA), Best Pallet (White and Company, Blacksburg, VA), and Best Load (White and Company, Blacksburg, VA) all help to determine pallet performance by evaluating the strength, stiffness, and durability.

Wood pallets, however, also have their disadvantages. For example, they easily host pests and release moisture; the pest issue is regulated by the International Standards for Phytosanitary Measures No.15 (IPSM 15). The other serious issue presented by wood pallets is the protruding of nails, which significantly affects semi-automated and fully-automated facilities because they can cause pallets to get stuck in the system which decreases efficiency. Protruding nails are also a serious hazard to employees, who may get hurt. But, the most widespread disadvantage of wooden pallets is quality variation. It is very uncommon to find wood pallets that are exactly alike due to variations in lumber, specification, and locations of pallet parts (Modern Material Handling, 2017).

Composite wood

Composite wood is another material that pallets can be made from. Wood composite pallets are used by 14% of the companies in the U.S. (Modern Material Handling, 2017). Some of the most popular composites used to manufacture pallets are plywood, Oriented Strand Board (OSB), particle board, Laminated Veneer Lumber (LVL), timber strand, and wood/plastic composites. Composite pallets have smooth deck surfaces, are insect free, and durable. Plywood and OSB pallets can be designed using PDS, which gives them a great advantage due to all of the information that these pallet design software can display. However, composite wood pallets have a higher purchase price and a more expensive repair cost. They are less recyclable than solid wood pallets and less weather resistant than plastic or metal pallets.

Plastic

The demand for plastic pallets in the U.S. in 2007 totaled 909 million; making them about 29% of the total U.S. pallet inventory. This was the pallet material with most rapid gains in market demand expected. They're predicted to increase in demand 2.4% per year to over 130 million pallets during 2012 (The

Group, 2008). The two main materials that plastic pallets are made from are high density polyethylene (HDPE) and Polypropylene (PP).

Even though plastic pallet materials seem to be more expensive than other materials, pallets made from plastic can bring great benefits to a company. Plastic pallets are insect free, easy to wash, weather resistant, recyclable and are durable. Additionally, plastic pallets are moisture resistant, which ensures that their structural strength will not change if exposed to the elements (The Freedonia Group, 2008). These pallets do not use fasteners, which makes them safer to handle and allows the pallet to be transported more efficiently through both semi-automated and fully-automated material handling systems. An additional advantage is their light weight, which causes less stress to material handling equipment and avoids ergonomic injuries, reducing downtime and worker compensation costs. The use of lightweight pallets also reduces freight costs. Other than their high purchase price, plastic pallets do have some other disadvantages such as low friction levels, costly to prototype and, low stiffness levels. Also, these pallets can bend during transit causing the load to slip if it is improperly balanced or poorly loaded (The Freedonia Group, 2008).

In order to increase the friction of the top deckboard of plastic pallets, manufacturers coat the deckboards with different materials. For example, sand or silica mixed with glue are often used to coat the deck. Even though most of the plastic pallets currently on the market are repairable, they are recyclable. Plastic pallets can be ground-up after damage occurs and this granulated material can be mixed with new plastic material in order to manufacture recycled pallets. It is important to note that this process is cost effective when done by the manufacturers; for pallet users, it is generally more profitable to just buy a new plastic pallet.

Another significant difference between plastic and wood pallets are the fire-retardants added to modify plastic pallets. These chemicals are added in order to slow down the heating process of the plastic materials, so the plastic pallet will take longer to reach its burning temperature (The Freedonia Group, 2008).

The U.S. national fire code classifies both pallets and packages into different commodity classes. These commodity classes are based on which products are being stored on the pallets; the more combustible the item stored, the higher the commodity class (National Fire Protection Association, 2016). This is important to highlight because the insurance costs increase according to the commodity class. Often old sprinkler systems will need to be upgraded if a higher commodity class is obtained (triggering an expensive capital investment). Unit loads on some plastic pallets without fire retardants automatically increase their commodity class by one or two points over unit loads stored on wood pallets. But, adding fire retardants to the plastic reduces the load capacity and durability of the pallet by making it more brittle.

Currently there are two entities that certify plastic pallet fire performance. These are Underwriters Laboratories (UL) and Factory Mutual (FM). These companies measure how much heat a plastic pallet (or a stack of plastic pallets) would produce if they caught on fire. Finally, they study how the melted plastic will flow and affect the warehouse during a fire.

Corrugated

Paper-based materials are the fourth material option used to manufacture pallets. These pallets can be made from corrugated (most common), honeycomb, solid fiber, or molded pulp. According to The Freedonia Group’s industry report, 152.5 million paper-based pallets were produced in 2007, and by 2016, paper-based pallets will still represent only 3% of the global pallet market (The Freedonia Group, 2015). Paper based pallets have one unique characteristic when compared to pallets manufactured from any other material; this is their weight. Corrugated pallets are the lightest pallets on the market. They are normally built using double or triple corrugated paper board, and their average weight is 12 lbs. per pallet (Gerber, 2018).

Companies that work with paper-based pallets have lower freight costs, especially during air transportation (The Freedonia Group, 2008). Being ergonomic, insect free, and recyclable are some of the other advantages that companies can benefit from by using paper-based pallets. Nevertheless, they do have some disadvantages. Paper-based pallets' purchase price is higher than others. Their properties are very susceptible to moisture, which causes the material to degrade; hence, they aren't recommended for companies that work in moist environments or for carrying loads of moist products. Other disadvantages to paper-based pallets are limited bending strength, short durability, and poor performance under flexible loads. Also, once they are damaged, paper-based pallets are not repairable; they must be thrown away or recycled (The Freedonia Group, 2008).

Metal

Metal is the last material from which pallets are manufactured, and they represent only 1% of the U.S. pallet demand in 2007 (The Freedonia Group,2008). They represent the smallest share of the market due to customers increasingly desiring lightweight, low-cost alternatives. Steel, stainless steel, and aluminum are the main metals used to manufacture pallets. These pallets are recognized for having the highest load capacity when compared to pallets made of any other material. Metal pallets perform at high temperature environments. The many advantages of metal pallets are stiffness, durability, and a high level of sanitation. Also, metal pallets don't require fasteners, which eliminates the hazards relating to fasteners. The disadvantage of metal pallets are a high purchase price and a heavy weight. Metal pallets weigh significantly more than other pallets; this automatically creates a negative impact by increasing shipping costs for companies. Additional detriments are low friction, susceptibility to rusting, and sharp edges (which can create many hazards to products and people).

3.1.4 Support conditions for pallet use

In the supply chain, pallets are used to store and transport products throughout manufacturing facilities. Later, on these same pallets, products are stored in warehouses, loaded as unit loads of the same or different products into trailers, and finally transported to locations outside their original facilities in order to distribute the products. The support conditions which pallets normally experience inside a facility are floor support, fork tine support, rack support, sling support, and conveyor support (International Standard 8611, 2004).

Floor stacking

Floor support is also known as block stacking; this condition basically sets loaded pallets on the floor in an organized manner. Some products are stacked easier than others; often the materials stored using this condition are shipped in large quantities and don't require their unit load configuration to be changed before reaching their final destination. Cost of storage can be significantly reduced by using this form of block stacking, but this condition works best when dealing with a large number of units loads of the same SKU (the same item). "It makes economic sense to floor stack them together to help in retrieval and to facilitate inventory control" (Howie, 2008). Floor stacking is also used in warehouses with lower ceiling heights when installing racks would take up much needed ceiling space; up to 7 units load are stacked on top of each other while inside a facility and during road/freight transportation up to 3 units can be stacked on top of each other.

Racking

Pallets can also be stored in a rack support condition. Racks are storage devices usually fabricated from formed or structural steel. The size and gage of the steel is determined by the storage capacity needed and the weight to be supported. There are a variety of rack systems; for example, welded wire rack decking, load beam, drive through storage racks, drive-in racks, flow through racks, push back racks, cantilever racks, and mobile sliding racks (Howie, 2008). Unit loads stored in racks can be racked across their stringers or racked across their deckboards. To further explain, block pallets that are racked across their stringers have the rack beams spanning and supporting the stringerboards. Likewise, when plastic pallets are racked across their stringers, they are being supported across their length. When block pallets are racked across their deckboards, it means that their stringerboards are parallel to the rack beams. And, when plastic pallets are racked across their short dimension, they are being supported across their width (International Standard 8611, 2005).

Fork tine

Fork tine support is frequently referred to as the "Dynamic Support" condition, because it is a moving/movable condition. The pallet is lifted by the forklifts' fork tines and transported to a different location. While this transportation is happening, the pallet can be supported across the stringers or across the deckboards (International Standard 8611, 2005). The following figures represent the two ways that pallets can be supported using fork tines (Figure 5& 6).

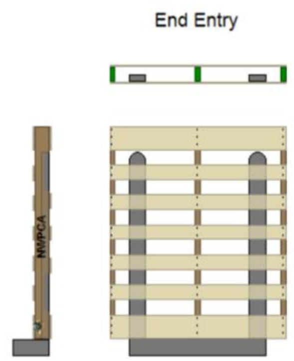


Figure 5. Forktine across the deckboards (PDS, 2018).

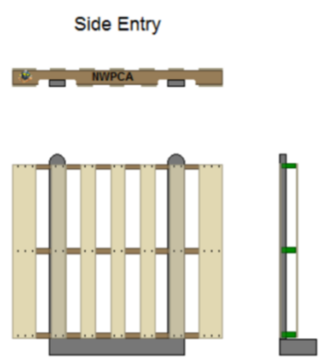


Figure 6. Forktine across the stringers (PDS, 2018).

Sling Support

Sling Support is the condition used when the pallet is being handled by a crane. It is frequently used to load ships with break bulk loads or to move shingles to the top of a roof. This support condition normally uses winged pallets (International Standard 8611, 2004).

Conveyor

Final, is the support condition of "conveyor support." There are a variety of conveyors designed for different situations that a pallet could be transported in a warehouse. Conveyors are divided in two broad categories; those driven by gravity and those that are power-driven. Conveyors also can be categorized as roller or chain conveyors. When twin-track, chain conveyors are used, the pallet is often supported under the bottom deckboard, which creates significant stresses. Pallet tested under this support condition can detect the load capacity of the pallet supported in a twin-track conveyor (International Standard 8611, 2004).

3.1.5 The manufacturing process of pallets

The process used to manufacture pallets is determined by the material being used to build them. For example, the process for manufacturing wooden pallets starts by cutting the cants to length. Afterwards, these are transported to a saw to be ripped into stringers (circle gang saw) or deckboards (horizontal band saw). The assembly process can vary according to the level of automation available in the pallet manufacturing facility. The different assembly methods are explained bellow (Forest Products Laboratory, 1971):

- <u>Manually Assembly</u>: The total pallet is built by hand with only the help of nail guns.
- <u>Semi-Automated Equipment</u>: This assembly type can use a single-head pallet nailer or a double-head pallet nailer.
- <u>Fully Automated Equipment</u>: The sourcing of lumber and all pallet construction is done completely by machinery.
- <u>Robotic Assembly</u>: This method uses a robot to build the pallet, but it requires an employee to feed lumber into the robot (to "source" the robot).

Manufacturer’s designs are incredibly diverse when manufacturing plastic pallets due to the flexible molding techniques that can be used with plastic materials. This allows both standard pallets and custom designs. The manufacturing processes used to construct plastic pallets are:

- Injection molding
- Structural foam molding
- Rotational molding
- Profile extrusion
- Thermoforming
- Compression molding

High pressure injection molding is designed for use by high-tech machinery. It can produce a higher volume of pallets than any other thermoplastic process. And, having a high manufacturing volume reduces the cost per unit produced (LeBlanc, 2012).

Structural foam molding uses less pressure than high pressure injection molding, and it results in thicker, lower density ribs. This is also a high-volume process, which reduces the cost per unit. This process requires less raw materials and creates items with a higher strength or weight ratio (LeBlanc, 2012).

Rotational molding is the third process used to manufacture plastic pallets. If we compare it with the two processes described previously, rotational molding has a relatively a lower equipment cost. The materials most commonly used are low density polyethylene (LLDPE) and across-linked polyethylene (LeBlanc, 2012).

The extrusion method is basically a two-step process; first the extrusion of pallet parts and second the pallets’ assembly. The assembly of the components can be done using fasteners, glue, or welding. Due to this manufacturing process, pallet sizes can be modified easily according to clients’ requirements (LeBlanc, 2012).

Nestable pallet designs are built using compression molding or thermoforming. Compression molding uses different types of recycled materials such as plastics, rubber, synthetic resins and other recycled wasted products. Thermoformed pallets are typically lightweight, and they have lower load capacities and durability levels than injection molded pallets, but the molds for manufacturing thermoformed pallets are substantially less expensive.

3.1.6 Repair of pallets

As with any product on the market, pallets have a projected useful lifespan depending on the pallets' materials. Pallets' lifespan can be extended after repairs. A pallets' lifespan is determined assuming correct handling of the pallet, but pallet handling techniques are often harsh which can damage pallets sooner than expected. Many companies continue using pallets with minor damages until they reach the point where the pallets' strength or functionality is compromised (Gerber, 2018). Once it reaches this point, the pallet is sent to a pallet repair facility. Pallet damage can be caused by regular "wear and tear", by employees while handling pallets, or by exceeding the load capacity of the pallet when in its usual support condition (Shiner, 2018).

It is important to differentiate between repaired and remanufactured pallets. Remanufactured pallets refer to using the unbroken wood leftover from broken pallets to construct entirely new pallets. Repaired pallets refer to broken pallets which have had just the broken part replaced or had supports added to strengthen the damaged areas (Gerber,2018). Damages can be fixed by replacing broken boards, adding companion stringers to support the original stringers, and /or adding metal plates to maintain the pallets strength (Park et al., 2016). Wooden pallets are the most likely to be repaired, and the most common damages found are split notches and missing top deck boards (Frost & Large, 1975).

Repaired pallets can be categorized into three classes. Class 1 or Class A pallets can have repaired top and bottom deckboards, and one or more stringers can be repaired using metal plates. However, none of the stringers can be repaired using companion stringers in this repair class. Class

2 or Class B pallets may contain one or two repaired stringers using any type of companion stringer. Class 3 or Class C pallets have such extensive damages that they do not meet the criteria for Class 1/A or 2/B repaired pallets (MHI, 2016). Wood pallets are repairable, but not for an unlimited time. For example, if a deckboard breaks, it can be replaced, but only a certain number of times.

PDS (Best pallet, and best load) helps analyze the number of cycles a pallet can survive after having parts replaced. Once a certain number of components have been broken, the pallet cannot be repaired any longer. This type of information is found through the software. It is significant to have this type of knowledge in order to be consistent, especially when comparing plastic pallets to wooden pallets. It is necessary to know how many times you can fix the pallet and the cost of each repair. Once these values are obtained, they can be compared to the plastic pallets' costs.

Pallets that cannot be repaired anymore can still be dismantled and converted into other products: colored/non-colored landscape mulch, animal bedding, biofuels, or fiber for engineered wood products (Gerber, 2018). The recovery, recycling, and remanufacturing of wooden pallets has been one of the leading sectors of growth in the pallet industry (Bejune et al., 2002). In 2016, 551 million pallets were received by pallet repair companies. Out of these, 356 million pallets were repaired and sent back into the supply stream, and 195 million pallets were recycled into other products (Gerber, 2018).

3.1.7 Performance Specification for pallets to be used in Automated Unit Load Material Handling Equipment.

The growing use of automatic unit load handling devices in the USA, and the sensitivity to variations, deflections and deformations which occur in pallets during issue, motivated pallets experts to explore the requirements for pallets used automatic material handling and storage systems. The research study conducted by Virginia Tech established that when both automatic and manual systems are used together, pallets should meet the requirements of the most sensitive component, which is typically an automatic device (MHI,2016)

According to MHI standard (2016) in order for a pallet to perform satisfactory in automatic material handling systems, it should meet the test criteria for flatness, size and shape uniformity and stiffness described in the section ten of this standard. The standard also emphasized that the pallet cannot have broken or loose components because it would cause jams and break downs of the equipment. In addition, due to equipment compatibility, the quality of the bottom deckboards were highlighted throughout the standard. The required performance specifications for pallets used in automated material handling and storage system are presented in Figure 7.

Pallet size and shape variation	
length	+0.13/-0.25 in. (+3.3/-6 mm)
width	+0.13/-0.25 in. (+3.3/-6 mm)
height	+0.13/-0.38 in. (+3.3/-9.5 mm)
squareness	Diagonals shall be within 0.50 in. (25 mm)
Flatness of decks (supporting no load)	Within 0.25 in. (6 mm) of target level [Note (1)]
Minimum static coefficient of surface friction: Top and bottom surface of top deck and bottom surface of bottom deck	0.15
Component placement variation	Within 0.25 in. (6 mm) of target location
Maximum deflection of the pallet under load	0.50 in. (13 mm)
Minimum clearance between pallet under load and handling equipment	0.50 in. (13 mm)
Maximum deflection of pallet components under load	0.25 in. (6 mm)

GENERAL NOTES:
(a) No standard pallet design is implied by these recommendations. Pallet design shall be specified by the system designer.
(b) In addition, the following requirements must also be met:
(1) no broken or loose components
(2) no exposed fasteners
(3) no loose stretch wrap, packaging, etc., that may interfere with equipment
(4) no companion stringers, half stringers, or plug stringer repairs
(5) metal repair plates are allowed if covered with dark, non-reflective paint
(6) bottom deck components should span the center-to-center distance between rollers and skate wheels
(7) pallets with mesh or ribbed bottom deck components may experience difficulty in conveyance on skate wheel conveyors. Interactions between the mesh or rib spacing, bottom deck stiffness, unit load weight, and skate wheel configuration determine the ability to convey. One solution is to incorporate solid regions at least 3 in. (76 mm) width in all bottom deck components.
(8) pallets with low bottom-deck compression strength (typically plastic post designs) may experience difficulty in conveyance on rollers

NOTE:
(1) Intentional protrusions exceeding these limits may be acceptable by mutual consent by both buyer and seller.

Figure 7. Performance specifications for pallets to be used in automated unit load material handling equipment (MHI,2016)

3.2 Warehouses

The warehouse is an integral part of the supply chain. It is commonly thought of as just the location where goods are being stored, but actually, they involve more than that. A warehouse is an active place where materials are received, housed in a logical manner, and distributed according to the needs they serve (Howie, 2008). One of the major challenges in managing a supply chain is that demand changes quickly, but inventory supplies takes longer to change. Warehouses allow companies to respond more quickly when demands change, and warehouses provide them with a place to store buffers against unreliable demands or price increases (Bartholdi & Hackman, 2017). The warehouse is an essential point in the supply chain; it links all of the activities between manufacturers and customers.

There are two main resources that warehouses consume: space and time (Bartholdi & Hackman, 2017). Space and time equal expense, and that's the reason engineers are always working on improving the performance of warehouses. Local conditions dictate different designs and operations in warehouses around the world. Different business environments also generate significant differences in warehousing needs and operations.

Warehouses' two main operations are the storing and movement of goods in a timely manner. In the past, most warehouses were just used to store unit loads (pallet loads) for a period of time. Presently, warehouses' functions have evolved. In order to reduce supply chain cost and increase revenue, warehouses have adapted their operations according to customer and market needs.

3.2.1 Warehouse types

Warehouses (WH) can be differentiated according to the type of customer they serve. They are commonly categorized as Retail Distribution Centers, Services Parts Distribution Centers, E-commerce Distribution Centers, 3PL Warehouses, and Perishable Warehouses (Bartholdi & Hackman, 2017).

Retail Distribution Centers' immediate customers are retail stores. This type of WH serves a large number of stores. A single retailer may order an extensive variety of items, and these orders change based on the different customers and their marketing plans. This translates to massive production flow in the WH. This type of WH is easy to distinguish because the sku's arrive as pallet loads of the same product and then leave as pallet loads of differing products (Bartholdi & Hackman, 2017).

Services Parts Distribution Centers' direct customers are Dealers, independent owners, and independent repair shops. These facilities tend to hold spare parts for expensive equipment such as automobiles, airplanes, computers systems, or medical equipment. Stock orders from dealers tend to be large and made up of fairly predictable popular consumables. On the other hand, stock orders from independent owners and repair shops are frequently smaller, unpredictable, and urgent. This is due to the expensive capital equipment that is likely waiting for repair. This warehouse type is the most difficult to manage because the demand varies according to customer type. A great amount of extra handling can also be expected due to returns from customers who order the wrong parts. Also, this type of WH faces long replenishment lead times for most items, which can force them to hold large quantities of safety stock (Bartholdi & Hackman, 2017).

E-Commerce Distribution Centers are a third type of warehouse, and they generally receive orders directly from individuals. These facilities receive products as unit loads, store them as unit loads, but then deliver them as individual products. These warehouses' customer orders are relatively small but require instant response; the orders must be filled and shipped immediately after receipt (Bartholdi & Hackman, 2017).

3PL warehouses are contract warehouses to which multiple customers have outsourced their own warehousing operations. Many customers use this type of facility to take advantage of the economy of scale or as overflow facility to handle a surge in product flow (Bartholdi & Hackman, 2017).

Perishable warehouses are different from the others due to the products they handle. Perishable products require refrigeration and fast turn-around due to short shelf life. Perishable warehouses face extra requirements like shipping their products according to FIFO (First In-First Out) or FEFO (First-Expired-First-Out), and there are many restrictions on how to correctly handle each perishable product (Bartholdi & Hackman, 2017).

Warehouses can be differentiated by their level of automation: fully-automated, semi-automated or non-automated. They can also be classified according to the degree of access such as public, private, or contract warehouse.

3.2.2 Warehouse operations

Even though there are many ways to differentiate warehouses, they all work based on the same logistical operations. Essentially, the product is received, put away, stored, and then the order is picked and shipped.

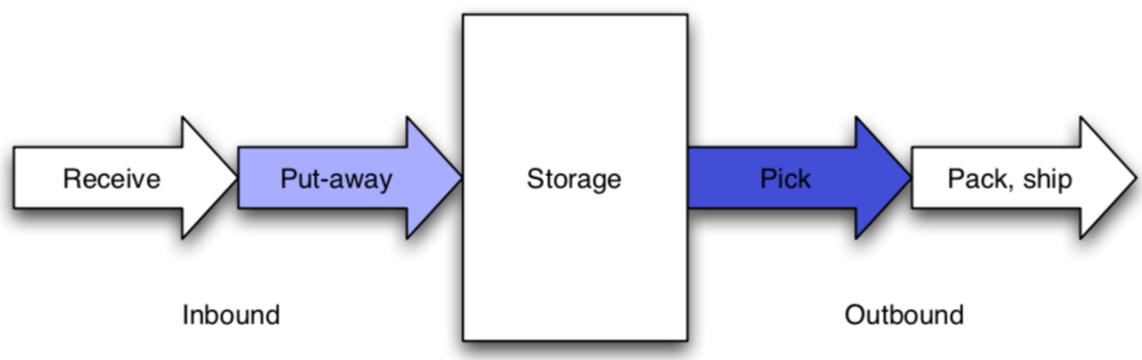


Figure 8. Warehouse Logistic Operations (Bartholdi & Hackman, 2017).

Receiving Product Operations involve communication between the supplier and the warehouse. There is an understanding on the products' arrival time, and this section of the warehouse involves the unloading of the products and possibly staging them for put away. During this process, incoming product is inspected, scanned, and registered as having arrived. Any type of damages, incorrect counts, wrong descriptions, or other errors are noted at this point. Incoming product is most likely arriving on pallets. They can be consolidated pallets (loaded with only one product) or mixed pallets (containing different products). When these loaded pallets are received, the labor requirements are not usually very high. Only 10% of operating costs in a distribution center come from receiving products (Bartholdi & Hackman, 2017).

Put-away is an operation that may seem basic and easy to accomplish, but there are many interconnected activities behind efficient put-away operations. Put-away often accounts for 15% of warehouse operation expenses due to the amount of labor required. Planning is crucial for this operation. Determining storage locations beforehand is very important because that determines, to a large extent, how quickly and at what cost you can later retrieve these products for the customer. The put-away process requires the management of product inventory (including an understanding of the individual characteristics of the products that need to be stored), but there is also the need to manage storage locations.

Managing storage locations requires a complete, real-time understanding of all locations; their availability, their unit load capacity, and their weight capacity, but it does not end there. Once the product is placed in its correct storage location, it must be scanned to record the location. This is important information that is used later to create efficient pick-lists to guide the order pickers in retrieving products for customers (Bartholdi & Hackman, 2017).

Storage involves the placement of products in specific locations within the warehouse. Storage locations are expensive due to the space, cost of rent, heating and/or air conditioning, security, and other expenses. Additionally, storage locations can use specialized storage systems such as load beam racks, push back racks, flow racks, drive through racks, As/Rs racks, and others. Storage also often requires equipment, such as conveyors, forklifts, pallet jacks, and others, to handle the products that are being stored.

Currently, there are two strategies that are commonly used to store products. The first strategy is called “Dedicated Storage,” which reserves specific locations for specific products; only this product is allowed to be stored in this location. The bright side of this strategy is that the storage locations are fixed; they do not change. This is beneficial because warehouse management can arrange to store the more popular items in the more convenient locations in order to make picking more efficient. The disadvantage of Dedicated Storage is that, on average, they only utilize 50% of the WH's storage capacity (Bartholdi and Hackman, 2017).

The second strategy is called "Shared Storage." It stores the same product in more than one storage location. The science behind this strategy is to fill storage locations once they're empty with any product (even if it's a different product then was just stored there). Shared storage strategies eliminate the time that any storage location is empty by filling the location with any product that is ready to be stored. This provides a better utilization of space. The disadvantage of this strategy is that employees cannot learn locations due to the high rotation of different products stored in all locations, and so pickers must be directed to correct locations using a warehouse management software system, which comes with a cost.

Order picking is the next step in WH operations. Once a customer's order is received, the product's availability in inventory is verified, and the order-picking process starts. The warehouse must produce a picking-list, schedule the order-picking, schedule the shipment, and produce any shipping documentation that is necessary. Usually warehouses accomplish these activities using warehouse management system software in order to expedite customer orders. When warehouse operating costs are studied, the order picking process accounts for the 55% of the operating costs (Bartholdi & Hackman, 2017). It can be broken down as follows (Figure 9):

Activity	% Order-picking time
Traveling	55%
Searching	15%
Extracting	10%
Paperwork and other activities	20%

Figure 9. Warehouse activity time consumption (Bartholdi & Hackman, 2017).

Traveling is the activity that consumes the majority of time in the order picking process (which, as previously mentioned, is itself the most expensive process in warehousing operations). For this reason, engineers spend a significant portion of their time working to re-design order picking processes in hopes of reducing unproductive travel time.

Shipping is the last operation in a warehouse. The shipping process usually handles packages that have been consolidated into fewer/smaller containers (cases, pallets). Labor requirements are not usually high for this process; products are likely to already have been staged for scanning and loading into freight carriers. During this process, the trailer is also scanned to register its departure from the warehouse (Bartholdi & Hackman,2017).

In general, the five processes described previously (receiving, put-away, storage, order-picking, and shipping) are the basic operations that are performed in any warehouse. In addition to these processes, warehouses may also perform many other operations such as ticketing/labeling, monograming/ alterations, repackaging, kitting, postponement of final assembly, and/or invoicing in order to comply with customer requirements.

3.2.3 Types of packages handled in a warehouse

Warehouses around the world share similarities based on the types of packages they handle. They are designed to store and handle specific packages. Packages are containers of different sizes, shapes, and colors that consumers rely on to protect, contain, preserve, and present information about the products contained therein (Lee & Lye, 2003). Packaging can be categorized as primary packaging, secondary packaging, tertiary packaging, or a unit load.

Primary packaging is the packaging that has direct interaction with the product; it contains the product and protects it. Normally, it is the packaging that showcases the graphics for the product (for example, the wrapper around a protein bar is its primary packaging). Secondary packaging is packaging that is in direct contact with the primary packaging; it both contains the primary packaging and protects it during commercial distribution (for example, a box of six individually wrapped protein bars – the box is the secondary packaging). Tertiary packaging is packaging that aggregates and supports several secondary and/or primary packages. Tertiary packaging can contain different units of same product (for example, a larger corrugated box that contains multiple boxes of protein bars) or a mix of different products (for example, a Sephora box that contains a mix of individually packaged makeup items). Tertiary packaging is basically there to help to avoid damages during the handling and transportation of products – tertiary packaging is generally removed before final sale to the consumer. Unit loads are used to contain and move a large number of tertiary packages, and for the most part, the main benefit of this type of packaging is that it reduces handling time for products by allowing for mass movement.

Despite these basic packaging categories, from a warehouse's point of view, there are only three types of items handled in their facilities: unit loads, cases, and individual items. In a warehouse, a unit load is formed by a pallet loaded with several cases of products. A case can be either a single secondary package or a shipper package (for example, one printer in a box and a 12-pack of soda cans are both secondary packages that are considered "cases" by warehouses). A shipper package can contain multiple individual items of different products that fills a specific customer's order (for example, a shipment to Target that contains shampoo, herbal tea, and toothpaste in the same box would be a" shipper package" that would be considered a "case" by the warehouse). Or, a shipper package could contain multiple individual packages of the same product (for example, a corrugated box full of cereal boxes). From the warehouse's stand point, individual items are products either in their primary packaging or their secondary packaging (one can of tomato sauce or a decorative box containing one bottle of perfume are examples of primary packaging and secondary packaging, respectively, but both are considered "individual items" by warehouses).

Based on the type of packaging handled, warehouses can be divided into three basic Package Handling Areas (PHA):

- **Pallet Storage/Picking Area**: this is the warehouse section where full unit loads are stored until customer orders are received. After a customer order is received, the palletized unit load must be picked.
- **Case Picking Area**: this is the warehouse section where individual cases are separated from their original unit loads, and then either shipped out individually, formed into new unit loads with other cases, or moved to the Individual Package Picking Area.
- **Individual Package Picking Area**: this is the warehouse section where individual products are removed from their cases and grouped with other individual products in order to fill specific customer orders.

The three package handling areas are very important to warehouse operations, and their efficiency (space utilization and travel time) reflects directly in overall warehousing costs. In order to maximize their performance, each of these areas use specialized storage and material handling systems. This research project specifically focuses on the systems used in the Pallet Storage/Picking Areas.

3.2.4 Storage and material handling systems

Storage Equipment

The selection of the right storage and material handling systems for a Pallet Storage/ Picking Area is largely determined by the warehouse's space, product mixing requirements, and turn rates. Additionally, understanding pallet specifications will assure compatibility between pallets and equipment. Compatibility is critical because it allows continuous work flow. If the wrong system is chosen, it could slow down both the picking and storage processes, and this could result in damage, re-work, extra cleaning costs, and ultimately, delayed deliveries.

The most common storage systems that interact with pallets are called racks. Currently, there are a wide variety of racks on the market: load beam racks, push back racks, flow racks, drive through racks, As/Rs racks, etc. There are also a large variety of material handling systems that can be used to handle pallets within a warehouse: conveyors, forklifts, pallet jacks, and others.

Racks are usually manufactured from formed or structural steel (Howie, 2008). They have sections specially designed to facilitate easy assembly, with perforations along the length of the uprights for attaching connections, such as bracings or beams. These systems provide high density storage allowing for the storage of a greater number of products in a reduced area, due to their vertical characteristics (Guilherme et al., 2018). The different types of racks are described below:

Load beam racks: These are the most popular type of storage racks. Pallets are placed into openings and supported by beams. Load beam racks can be used for standard storage (which is single pallet deep storage that uses counterbalanced forklifts), narrow aisle storage (which is storage requiring the use of narrow aisle forklifts), and deep reach storage (which is deeper than standard storage, typically at least double pallet deep storage) (Howie, 2008).

Push back racks: These allow the first pallet to sit on the first cart in a lane; when a second pallet is loaded into the lane, the first pallet is "pushed back" while the second pallet remains in front. The second pallet is either placed on the rails in a 2-pallet-deep system, or placed on another cart in a 3-to-6-pallet-deep system. This process continues until the lane is filled (CiscoEagle, 2019). Instead of a single deep standard rack, push back rack systems let you store palletized unit loads 2 to 6 deeps. Access to pallet loads in this system is limited to just the front pallet in the lane, so the system is considered last-in-first-out (LIFO) (Howie, 2008).

Some of the advantages of Push back racks are (CiscoEagle,2019):

- Color coded carts for easy visual inventory.
- Large target for loading and unloading.
- Maximizes space utilization by filling the vertical cube.
- Unlike drive-in racks, each level is independently accessible.

Flow racks: These types of racks allow pallets to move using gravity. Pallets are loaded at the higher rear end and unloaded from the lower front end (Howie, 2008). This type of storage system is recognized as having the highest performance level of the high-density storage systems. This also makes the best use of available warehouse space, and reduces the potential for inventory write-off due to expirations (WestfaliaUSA, n.d.). This type of rack allows for pallets, boxes, and totes.

Some of the advantage of having this system in the warehouse are:

- Automated First-In-First-Out inventory control.
- Minimizes warehousing and handling costs.
- Maximizes warehouse capacity/cubic storage space.
- Operates in temperatures ranging from -30F to 150F.

Drive-in racks: These types of racks are the most likely to be used for high-density storage. Warehouses that use these systems move high volumes of palletized materials in and out of their storage racks via forklifts. Block stacking is not suitable for high volume. In this system, forklifts are driven between upright beams; therefore, similar-width loads are required for this type of system to operate efficiently. Drive-through racks have openings at both ends, which allows access from both ends. This means that product movement, when working within this system, is First-In-First-Out (FIFO) (Howie, 2008).

As/Rs Racks: These types of racks are used in highly automated warehouses. When using this system, products are automatically brought in and out of storage. As/Rs racks are normally paired with a warehouse software that manages the storage and retrieval processes and helps warehouse personal process customer orders. This is a great option when pallet-level storage is limited and quick retrieval is critical (Ziegler, 2018). Unit load As/Rs racks come in many forms, including:

Fixed-Aisle Unit-Load AS/RS Cranes: In fixed-aisle, unit-load AS/RS systems, pallet racks are arranged with narrow aisles between them. A crane travels down these narrow aisles, moving both vertically and horizontally, in order to both store and retrieve products. Each crane is fixed to a single aisle of racks (Ziegler, 2018).

Movable-Aisle Unit-Load AS/RS Cranes: This type of AS/RS also consists of a crane moving between narrow aisles of pallet racks, and it functions in much the same way as a fixed-aisle AS/RS system. The key difference is that each crane is not fixed, but can service multiple aisles (Ziegler, 2018).

Some of the benefits of using AS/RS systems are (Ziegler, 2018):

- Maximizes available storage space in existing structures, avoiding off-site storage and expansions.
- Minimizes overall building footprint up to 50% versus conventional warehouses.
- Reduces energy costs by 40% in cooler environments.
- Reduces labor and product damage costs.
- Increasing inventory accuracy and improves customer service.

Material handling system equipment

When it comes to material handling systems, **conveyors** are one of the main pieces of equipment that are associated with pallet movement within a warehouse. This device is highly used for applications involving the transportation of heavy or bulk materials in high-density storage (Howie, 2008). Currently, warehouses also use them to transport smaller items such as shipper boxes. There are many types of conveyors and configurations; they can be designed for just about any situation that a warehouse worker could face (Howie, 2008). Some of the different conveyors offered in the market are: gravity wheel conveyors, powered roller conveyors, belt accordion conveyors, and others. Warehouses that handle pallets or cases that move in regular patterns may find conveyors to be the best method of handling.

A **forklift** is motorized truck with forktines that serve to pick up an object, usually a pallet. Forklifts are one of the most popular pieces of equipment associated with product movement. These machines can be powered by battery, gas, or propane. They are designed to work both indoors and outdoors and over a variety of different surfaces. There are a wide variety of forklifts on the market; many are designed for use in crowded or cramped areas. Others are designed for placing products in storage areas that are not easily accessible (Howie, 2008).

Some of the different types of forklifts on the market are as follows: stand-up counterbalanced lift truck, narrow-aisle straddle truck, narrow aisle counterbalanced lift truck, turrret truck, and order picking truck. Forklifts are preferable when large volumes of products must be moved between different points in the warehouse (Bartholdi & Hackman, 2017).

A **pallet jack or pallet truck** is a device frequently used to remove individual unit loads from a trailer or to move them around the facility. These devices have front wheels mounted to the inside at the end of their forktines as well as a rear wheel (Howie, 2008). Pallets jacks can only handle single face or double face, non-reversible pallets. The height of the pallet openings are defined by the thickness of the pallet jack's tines. Currently, the market offers a variety of pallet jacks, such as: walkies stacker, platform truck, pallet truck, powered pallet jack, and the manual pallet jack.

3.2.5 Warehouse performance

Due to the increasing complexity of logistics networks, warehouse performance analysis has become an important issue (Wu and Dong, 2007). A performance analysis is a periodic measurement and comparison of the actual levels of achievement with the warehouses' specific objectives. It measures the efficiency and the outcome of the corporation's policies and procedures (Lu & Yang, 2010). A performance analysis is done with the objective of helping managers evaluate the performance of their warehouse and helping them to make decisions based on said performance (Staudt et al., 2015).

In order to assess overall warehouse performance efficiency, managers choose the most appropriate indicators for their performance analysis. Indicators can be direct or indirect. Direct indicators look at quantitative measurements such as order cycle times, fill rates, and costs; these are easily computable as simple mathematical expressions (Staudt et al., 2015). On the other hand, indirect indicators deal with qualitative measures such as the managers perception of customer satisfaction and loyalty; these require more sophisticated types of measurements (e.g. regression analysis, fuzzy logic, data envelopment analysis, etc.) (Staudt et al., 2015).

A performance analysis generally evaluates four factors: time, quality, cost, and productivity. The following table presents the classic direct indicators classified according to these four basic performance factors (Figure 10).

Dimensions	Indicator name
Time	Order lead time
	Receiving time
	Order picking time
	Delivery Lead Time
	Queuing time
	Putaway time
	Shipping time
	Dock-to-stock time
	Equipment downtime
Quality	On-time delivery
	Customer satisfaction
	Order fill rate
	Physical inventory accuracy
	Stock-out rate
	Storage accuracy
	Picking accuracy
	Shipping accuracy
	Delivery accuracy
	Perfect orders
	Scrap rate
	Orders shipped on time
	Cargo damage rate
Cost	Inventory cost
	Order processing cost
	Cost as a % of sales
	Labour cost
	Distribution cost
	Maintenance cost
Productivity	Labour productivity
	Throughput
	Shipping productivity
	Transport utilisation
	Warehouse utilisation
	Picking productivity
	Inventory space utilisation
	Outbound space utilisation
	Receiving productivity

Figure 10. Direct performance indicators (Staudt et al., 2015).

Warehouse managers usually apply optimization methods to the areas of interest, so better results can be obtained in upcoming evaluations. Warehouses managers should aim to maximize space utilization and minimize traveling time. In order to do so, there are methodologies, policies, models, etc. that can be used to achieve different goals. Warehouse performance can be studied from two different focus points. These are WH Operations and WH Design. WH operation problems take into consideration throughput and storage optimization, warehouse design, routing, order picking problems, etc. WH design problems cover the overall structure, department layout, operation strategy, equipment selection, and sizing and dimensioning.

3.2.6 Warehouse operation methods

Specific methods have been designed to target/solve problems in each warehouse operation.

Receiving and shipping process: these processes take care of the goods arriving at the receiving docks; and also loading the products into a carrier and releasing them to the customer based on shipping orders. (Tsui & Chang, 1990; Tsui & Chang,1992) formulated a bilinear model to assign inbound and outbound trucks to strip and stack doors. Gue (1999) proposed a model to estimate operational costs by assigning inbound trucks to strip doors and the assignment of destinations of outbound trucks to stack doors. He uses a local search procedure to find an efficient door layout. Bartholdi & Gue (2000) considered the cross-docking warehouse door layout problem with the objective of minimizing the total travel and waiting time incurred due to congestion. They modeled the total travel and waiting time for a fixed door layout using transportation and queuing models and then embed the cost model in a simulated annealing algorithm to find an efficient door layout (Frazelle, 2002).

Storage: this is the major function of a warehouse. The target of this process is storage efficiency (holding capacity) and access efficiency (resources consumed by storing/order picking processes). Warehouse managers face two main types of problems in this process which are lot sizing & staggering and storage assignment problems.

When it comes to lot sizing and staggering there are plenty of methods that simplify inventory control, such as the single resource multi-item inventory system by Gallego et al (1996). Gallego developed a tactical and strategic model to establish and coordinate order quantities in order to minimize inventory ordering and carrying costs. Hariga and Jackson (1996) formulated a mixed integer, non-linear programming formula in order to minimize long-term inventory holdings and order costs per unit of time.

Storage assignment challenges involve assigning SKUs to various storage departments, scheduling inventory movement between departments, assigning SKUs to different zones(zoning), and storage location assignment problems (SLAP) within a department/zone.

- Assigning SKUs across departments is a design decision that is made prior to product arrival. Once the departments are specified, one needs to determine which SKU should be stored in which department, in what quantity, and what are the corresponding interdepartmental moves for that SKU (Jinxiang et al., 2006). The literature provided methods created to facilitate storage assignment such as knapsack-based heuristic method developed by Hackman and Rosenblatt (1990). Its objective is to minimize the total material handling cost of order picking and replenishing. In 1994, Frazelle et al. extended the knapsack-based heuristic method considering the size of the forward areas as a decision variable and included the equipment cost of the fast pick area and the material handling cost of order picking and replenishment.

- Zoning is another challenge that occurs during the storage assignment process. Its primary objective is to organize order picking activities. Zoning can be beneficial because it limits the travel space pickers cover while picking an order. Also, it increases the familiarity of the pickers with the SKUs and reduces order picking time when zones are picked in parallel. Methods dedicated to Zoning are diverse. Gray et al. (1992) developed the hierarchical framework for designing warehouses with zone picking; determining the number of zones and pickers, zone sizes (storage space/zone), storage assignment across and within zones, and order batches.

Petersen (2002) simulated the effect of the number of aisles per zone and the length of aisles on the operational cost. Other algorithms for assigning SKUs to zones has been created by Jane (2000) and Jewkes et al. (2004). Jane (2000) proposed a heuristic approach that assigns SKUs to zones to balance the workloads of pickers. Jewkes et al. (2004) considers a specific sequential zone picking method in order to minimize the expected total order picking cost.

- Storage allocation assignment within department/zone are tasks that assign incoming products to storage locations in departments/zones in order to reduce material handling cost and improve space utilization (Jinxiang et al.,2006). There are different models created to improve this task such as the Vector assignment problem developed by Goetschalckx (1998). Kallina & Lynn (1976) discussed the implementation of the COI policy and how it is optimal in minimizing the material handling cost in dedicated storage. Wilson (1977) demonstrates that the lot sizing problem and the storage allocation problems should be considered simultaneously in order to achieve an optimal total cost including both inventory cost and material handling cost. Algorithms for integrated lot sizing and SLAP problems can be found in Wilson (1977), Hodgson and Lowe (1982), Malmborg et al. (1986), Malmborg & Deutsch (1988), and Malmborg et al. (1988).

Order picking is generally recognized as the most expensive warehouse operation, because it tends to be either very labor intensive or very capital intensive (Frazelle, 2002). Different order picking methods can be employed in a warehouse, such as single order picking or batching and sorting (either while picking or after picking) (Yoon and Sharp,1996). Each of these activities have different methods or models that can be applied in order to optimize their performance. For example, there is literature about "batching" activities that focuses on the objective of minimizing lead time and tardiness. Elsayed et al. (1993) presents a heuristic model for batching orders that have due dates with the objective of minimizing earliness and tardiness penalties. Elsayed & Lee (1996) consider the batching and sequencing of both storage and retrieval orders so that the total tardiness of retrieval orders is minimized. Won and Olafsson (2005) developed both mathematical and heuristic models that solve the joint problems of order batching and picking by taking into consideration both picking efficiency and order lead time.

Additional methods have also been developed for optimal order batching algorithms. For example, Armstrong et al (1979) presented a mixed-integer formulation for batching in a semi-automated order-picking system with the objective of minimizing total picking time. Chen and Wu (2005) proposed a method to calculate the association between orders, which is regularly used as an integer-programming model to maximize the total association measurements (Frazelle, 2002).

Sorting operations involve decisions such as wave-releasing and order-to-lane assignment, so orders can be efficiently sorted in a given wave. Some of the research in this area was done by Bozer and Sharp (1985) who used simulations to analyze the dependence of system throughput on factors such as induction capacity, the number of lanes, and the length of lanes. Bozer et al. (1988) determined how and when the orders should enter the sorting lanes. Meller (1997) proposes an optimal order-to-lane assignment method that minimizes the sorting time for a pick-wave based on a set-partitioning model.

3.2.7 Warehouse design methods

The same way warehouse operations are critical for good warehouse performance; **Warehouse Design** plays an important part in operational performance measures since operational efficiency is strongly affected by warehouse design. Warehouse design can be very expensive and it is often impossible to change design decisions once the warehouse is actually built (Jinxiang et al., 2006).

A good performance evaluation model can help designers quickly evaluate the many design alternatives and narrow down the design choices early in the design process. Performance evaluation methods include benchmarking, analytical models, and simulation models (Jinxiang et al., 2006).

Warehouse design involves five main areas: overall warehouse structure, department layout, operational strategy layout, equipment selection, and sizing/dimensioning. Following below there is a description of the critical functions of each of these warehouse areas and the methods / models that can be used to improve performance in each area.

Overall Structure is what determines the functional departments, which technologies are used, and how orders will be assembled. When designing the overall structure of a warehouse the goal is to meet storage and throughput requirements and to minimize costs (Jinxiang et al., 2006). Multiple models have been created such as one by Gray et al (1992) who proposed a multi-stage, hierarchical approach that evaluates tradeoffs and prunes design space. Yoon and Sharp (1996) developed a structured approach for exploring the designed space around order picking systems. Park and Webster (1989) use a simple analytical equation to estimate initial investment costs and annual operational costs for different alternative designs.

Sizing and dimensioning are very important aspects to study when designing a warehouse due to their implications on construction costs, inventory holding space, replenishment, and material handling. Sizing methods vary according to the control scenarios of the warehouses' operations (a warehouse either has or does not have control of their inventory levels). White and Francis (1971) studied the appropriate storage capacity for a single product over a finite planning horizon in a warehouse with no control over its inventory. Hung and Fisk (1984) and Rao and Moroe (1988) determined fixed and changeable warehouse sizes using different cost formulations. Models that include not only warehouse construction costs, but also inventory holding and replenishment costs have been developed by Levy (1974), Cormier and Gunn (1996) and Goh et al. (2001). Cormier and Gunn (1999) and Goh at al. (2001) consider a more realistic piecewise linear model for warehouse construction costs (instead of the traditional linear cost model) by developing a nonlinear programming formulation for optimal warehouse expansion over consecutive periods.

Warehouse dimensioning translates the warehouses' capacity into floor space in order to assess construction and operating costs (Jinxiang et al., 2006). Rosenblatt and Roll (1984) developed a simulation model which evaluates the storage shortage costs. This is a function of storage capacity and number zones; this simulation was based on a model created by Bassan et al (1980).

A single warehouse can arrange different departments by different methods in order to compare alternative space allocations amongst the different departments. This method was developed in order to compare such alternatives by Pliskin and Dori (1982). Azadivar (1989) proposed optimal allocation of space between two departments. Heragu et al. (2005) developed the method of assigning SKUs to different storage areas, as well as optimizing the size of each functional area in order to minimize the total material handling and storage costs. They did this by using an optimization model and a heuristic algorithm.

Department Layout considers layout problems such as pallet block stacking pattern (storage lane depth, number of lanes for each depth, stack height, etc.), storage department layout (door location, number of aisles, etc.) and AS/RS configuration (dimension of storage racks, number of cranes.)

Diverse methodologies have been developed to treat each of the cited problems (P1 represents Pallet Block stacking pattern, P2 represents storage department layout, and P3 represents AS/RS configuration). Figure present a list of the some of the literature that treat each of the problems previously cited.

Problem	Citation	Objective	Method	Notes
P1	Moder and Thornton (1965)	O4	Analytical formulae	
	Berry (1968)	O2, O4	Analytical formulae	
	Marsh (1979) Marsh (1983)	O3, O4	Simulation models	
	Goetschalckx and Ratliff (1991)	O4	Heuristic procedure	Mainly on lane depth determination
	Larson et al. (1997)	O2, O4	Heuristic procedure	For class-based storage
P2	Roberts and Reed (1972)	O1, O2	Dynamic Programming	Consider the configuration of storage bays (unit storage blocks)
	Bassan et al. (1980)	O1, O2	Optimal design using analytical formulation	Consider horizontal and vertical aisle orientations, locations of doors, and zoning of the storage area
	Rosenblatt and Roll (1984)	O1, O2, O3	Optimal two-dimensional search method	Based on Bassan et al's work with additional costs due to the use of grouped storage
	Pandit and Palekar (1993)	O2	Queuing model	Include not only the ordinary travel time, but also waiting time when all vehicles are busy
P3	Karasawa et al. (1980)	O1, O2, O3	Nonlinear mixed integer problem	The model is solved by generalized Lagrange multiplier method
	Ashayeri et al. (1985)	O1, O2	Nonlinear mixed integer problem	Given rack height, the model can be simplified to a convex problem
	Rosenblatt et al. (1993)	O1, O2, O3	Nonlinear mixed integer problem	System service is evaluated using simulations, if not satisfactory, new constraints are added and the optimization model is solved again to get a new solution
	Zollinger (1996)	O1, O5	Rule of thumb heuristic	
	Malmborg (2001)	O1, O5	Rule of thumb heuristic	A more elaborated variation of Zollinger's rules that consider explicitly operational policies
	Lee and Hwang (1988)	O1	Nonlinear integer program	For the design of an automated carousel system. The model is solved with a simple search algorithm

Figure 11. Summary of the literature on warehouse layout (Jinxiang et al., 2006).

Operation Strategy involves the selection of various operational strategies for the warehouse. It focuses on strategic operations. Once selected, these strategic operations have important effects on the overall warehouse system and are not likely to be changed frequently. Storage and order picking are two operations needing strategies.

Comparison methods using analytical models and simulations have been used by researchers such as Gu et al (2006), Hausman et al (1976), Graves et al (1977) and Schwarz et al (1978). These methods compare random storage, dedicated storage, and class-based storage in single command and dual command AS/RS.

It is common for warehouses to be ruled by policies; Goetschalckx and Ratliff (1990) and Thonemann and Brandeau (1998) displayed the theoretically promising DOS based storage policies which tend to minimize traveling costs. Additionally, analytical models that evaluate the performance of dedicated storage and randomized storage in less than unit load warehouses were developed by Malmborg (1998).

Lin and Lu (1999) used order quantity and the number of ordered items to determine optimal picking strategies between single order picking and batch zone picking. Petersen (2000) simulated five order picking policies using the number of daily orders and the demand skewness as variables.

Equipment Selection target the level of automation in a warehouse. It determines the type of storage and material handling systems that will need to be employed. The literature on equipment selection can be found at Cox (1986) decided that different levels of automation can be evaluated based on a cost productivity ratio. White et al (1981) compared block stacking, single deep and double deep pallet racks, deep lane storage and unit load AS/RS using an analytical model in order to define a minimum space design. Additionally, Matson and White (1981) demonstrated the effect of handling equipment requirements on optimum storage design by developing a cost model based on space and material handling costs.

After a literature review of the aspects/operations involved in warehouse performance. It becomes noticeable that there are a great variety of methodologies, models, policies, algorithms, and other practices that can provide scientific support and help professionals to improve warehouse performance. Despite this, there is a lack of literature and knowledge about how a pallets design can affect the performance of a warehouse. This is the topic that is going to be studied in this research. This topic is significant for warehouses and distribution centers because 80% of goods distributed globally are moved in a unitized form (Raballand & Aldaz-Carroll, 2005) and 93-95% of all unit loads have a pallet beneath them (White and Hamner, 2005). The results of this survey will stimulate a higher level of collaboration between pallet manufacturers and material handling and storage equipment manufacturers, leading to significant improvements in supply chain operation, efficiency, and safety.

Chapter 4: Methods

A mixed-mode questionnaire was used to obtain information on the role of pallets in the performance of material handling and storage equipment in semi-automated and fully automated warehouses.

4.1. Phase 1. Mixed-mode Questionnaire (Phone Interview & Visible Questionnaire)

4.1.1. Design

In order to identify pallet related issues occurring in industry, I used a mixed-mode questionnaire, which combined the use of a visual questionnaire during a telephone interview.

Telephone interviews are one of the most common methods of surveying in the United States, and it is a method used to collect fresh / current information (Dillman et al, 2008). Telephone interviews guided by a visual questionnaire facilitated the respondent's navigation of the questions (Japec, 2008), as well as my own, as interviewer. The use of an interviewer helped to ensure that the respondents understood each question and that their answers were recorded accurately (Dillman et al, 2008).

The method that I used to design this mixed-mode questionnaire was described by Dillman et al (2008). The questionnaire consisted of a total of five questions, divided in three sections: pallet design (one question), pallet compatibility issues (three questions), and downtime (one question). These included open-ended and closed-ended questions. A specific questionnaire was designed for each particular group listed for interviews (see appendix A).

The questionnaire was reviewed by university professors who have survey research expertise and by industry experts who were able to evaluate the questionnaire's comprehensibility. Changes to the questionnaire were implemented based on these experts' recommendations. A general interview procedure was established following Dillman et al (2008) guidelines.

4.1.2. Data Collection

In order to collect points of view from different parties affected by pallet performance, participants were divided in three groups: pallet manufacturers (group 1), equipment manufacturers (group 2), and pallet users (group 3). Four interviewed companies represented pallet suppliers. Equipment manufacturers and pallet users were represented by three interviewed companies each.

Prior to the phone interviews, each potential respondent received an email containing the research proposal and the questionnaire. A 60-90-minute telephone interview was scheduled to go over the questions. Telephone interview was the method chosen because it allowed the participant to detail their answers, provide specifics, and give examples. This allowed me to obtain a more tangible understanding of the pallet related issues experienced by the industry.

I performed all telephone interviews, in order to maintain standard interview procedure, which ensured the quality and accuracy of the answers collected (Dillman et al, 2008).

4.1.3 Limitations of the Study

There was a small collaboration from companies to be part of the interview process, which impact the amount of information collected for this section.

4.2. Phase 2. Online Survey

4.2.1. Survey Design

Based on the information collected during Phase 1, an online survey was created using the Qualtrics online survey software (Qualtrics, Provo, Utah, USA). An online survey method had been selected, due to cost considerations (Schmidt, 1997) and in order to increase the response rate.

By allowing the participants to fill out the online survey at their convenience, it increased the likelihood of participation (Sax et al, 2003).

The method used to design this survey is described by Dillman et al (2008). Questions included categorical closed-ended inquiries and partially open-ended inquiries (such as nominal scaled and multiple-choice questions with “other” as an option). The online survey consisted of a total of 21 questions divided in the seven sections: introduction (one question), facility automation level (one question), company information (two questions), pallet characteristics (three questions), storage, material handling, and palletizer/de-palletizer equipment characteristics (six questions), operational downtime experiences (six questions), and survey closing (two questions). The survey also included a personalized cover letter explaining the research goals and confidentiality policy. The survey was reviewed by university professors who have survey research expertise and by industry experts who evaluated comprehensibility, quality, and response time (Rea and Parker 1997). Changes to the survey were implemented based on these experts’ recommendations.

4.2.2. Data Collection

The email address list for the survey was purchased from NAICS. It included warehouse managers, operation supervisors, manufacturing supervisors, maintenance supervisors, plant engineers, plant managers, packaging engineers, and packaging managers from across the U.S. The survey was also distributed by Modern Materials Handling Magazine (Peerless Media Group, LLC, Framingham, MA, USA) and Prologis (Denver, USA). Virginia Tech directly distributed the survey using the aforementioned database of email addresses, while Modern Materials Handling Magazine and Prologis distributed the survey to their U.S. subscribers and portfolio of U.S. customer addresses, respectively. Because these three databases were not comparable, it was not possible to ensure that the same person did not receive the survey from multiple sources. However, the IP addresses of the responses collected from the online survey were analyzed and duplicates were removed. Duplicate address detection (DAD) ensured the uniqueness of all configured interface identifiers (IID) which meant I knew if one IP address visited and filled out the survey multiple times (Al-Ani1, 2018). The survey was distributed to the MMH and Prologis marketing departments.

The survey was sent out May 1, 2019. A follow up email was sent out two weeks after the first mailing, and a final reminder email was sent after four weeks.

4.2.3. Response Rate

The survey was sent out utilizing three distribution sources. During the 10-week-long duration of the survey, 259 valid responses were obtained from MMH subscribers, six responses were received from NAICS contacts, and 23 responses were recorded from Prologis for a total of 288 valid responses which gave me an overall response rate of 6%. However, the number of responses obtained per question varied because not all questions were answered by all respondents.

4.2.4. Data Analysis

Descriptive statistical analysis, including frequency counts, means, median scores, and SDS were mainly used to interpret the data collected.

4.2.5 Limitations of the Study

Survey results have limitations that must be considered when reading, interpreting, and applying the results (Alreck and Settle, 2003).

Chapter 5: Results and Discussion

5.1. Phase 1. Mix mode questionnaire results and discussion

The following topics were discussed in a guided interview format performed with multiple companies, each one of them representing one of the sectors studied (pallet manufacturers, equipment manufacturers, and pallet users).

5.1.1. Topic: Pallet Design

The participants were asked to characterize the types of pallets with which they generally work.

Pallet supplier or manufacturers collaborating with this research mainly produce reusable block class wooden pallets and reusable block class plastic pallets. Recyclable stringer pallet manufactures did not participate in this investigation. Manufacturers mentioned that pallet characteristic such as cruciform bottom deck, single face, full four-way pallets are the most common when producing pallets for automatic applications.

Equipment manufacturers stated that their systems are mainly designed to fit block pallets. When GMA or other pallets designs are used in their systems, the system will need to be retrofitted to handle the different class of pallet. However, their equipment is adaptable to various customer needs. They mentioned that the most popular pallet used in their system was 48 in. x 40 in.

Pallet users commented they use a large variety of pallets in their systems. The most common types are wooden stringer pallets, wooden block pallets, and plastic block pallets. Some of their pallets are two-way pallets but most are partial and full four-way non-reversible pallets.

5.1.2. Topic: Pallet Compatibility Issues

During the discussion, participants provided examples of pallet related issues that had occurred when pallets interfaced with material handling and storage equipment.

Pallet manufacturers expressed that their clients tend to report pallet related issues most commonly when interacting with drive in racks, AR/RS systems, conveyors, forklifts, pallet jacks, AGVs and palletization systems. The most common issues are described according to equipment type. The following table summarizes the pallet related issues with each system.

Table 2. Description of pallet related issues according to pallet manufacturers.

Storage Equipment	Pallet related Issues
Selective load beam racks	• Damaged components tend to get stuck on wire deck reinforced rack structures.
Flow Racks	• Missing boards tend to affect speed capability of the system. • Missing lead bottom deck boards tend to cause stability problems.
Drive in or Drive through racks	• Missing components in bottom deck boards tend to cause instability on rails.
Push back racks	• Coefficient of friction varies according to pallet material; low coefficient of friction tends to affect speed during movement.
AS/RS systems	• Missing wood on lead board and/or sides tends to cause Jams. • Loose components or unattached components on bottom deck board stop operations until the issue is fixed. • Correcting pallet related issues in these systems creates operator safety risks.

Material Handling Equipment	Pallet related Issues
Conveyors (rollers, chain, etc.)	• Loose components on the bottom deck get caught in between the rollers creating twisting / jams. • Plastic pallets with hollow blocks experience increased vibration during transportation. • Photo eyes face complications detecting issues when using aluminum and some plastics due to brightness.
Forklift	• The total issues described by manufactures reflect a lack of operators training. None of the issues described were directly related to the pallet design.
Pallet Jacks	• The total issues described by manufactures reflect lack of operator training. None of the issues described were directly related to the pallet design.
AGVs	• Pallet with missing components tend to have indexing issues that results in errors during pickup. • Pallet dimension consistency is critical to guarantee efficient operation.
Palletization / De palletization equipment	Pallet related Issues
Robotic or conventional	• Missing top deck components cause most of the problems in this system. Missing top deck components increase the risk of product tipping.

Equipment manufacturers agreed that systems have different tolerance and their operation sensitivity varies from one another. Equipment manufactures shared the most typical pallet related issues that occur per equipment. The following table summarizes the pallet related issues.

Table 3.Description of pallet related issues according to equipment manufacturers.

Storage Equipment	Pallet related Issues
Selective load beam racks	• Weak bottom and top deck board tend to cause instability of the load on the racks and deflection prohibit an easy pallet retrieval from the system.
Flow Racks	• This system is very sensitive to pallet quality, weight and type. • Deep lane separation at the discharge end must be managed properly so that excess back pressure on pallets can be avoided.
Drive in or Drive through racks	• Low quality pallets cause splinter leaving pieces or entire broken boards on the rails creating jams and faults.
Push back racks	• The issues recorded for this system are not related to pallet type or quality. Most of the issues described by the respondents were created due to product weight or product over hanging.
AS/RS systems	• Damage boards tend to prohibit easy access during pick up. • Missing components cause load to skew or fall from the system.

Material Handling Equipment	Pallet related Issues
Conveyors (rollers, chain, etc.)	• Protruding nails tend to cause jams. • Loose pallet components getting stuck in the system produce jams. Damages to the equipment is created when operators need to unjam pallets on conveyors. • Equipment manufacturers recommend using nine block pallets to assure proper conveyance on rollers. • Bottom boards orientation is critical to optimal system performance. Bottom boards on GMA pallets must be running perpendicular to the rollers, in order to avoid "bumpy" ride for the pallet and product. • Damaged/missing lead edge/top deckboard of pallets cause issues when using photo eye to position pallets. • Bottom boards must be running parallel to the chain, this position allow chain conveyors to be more forgiving with pallets that have minimum damage; however, transitions over end sprockets may cause issues if transitions are not properly planned.
Forklift	• The total issues described by manufactures reflect lack of operator training. None of the issues described were directly related to the pallet design.
Pallet Jacks	• The total issues described by manufactures reflect lack of operators training. None of the issues described were directly related to the pallet design.

AGVs	• AGVs have a large variety including lift top, forked and conveyor deck configurations. Lift top AGVs, rely on the bottom boards to be in place and/or good quality. When bottom boards are missing or broken, load stability while traveling on the AGV could cause load shift, product falling and creating faults in the system due to drop off errors. • Forked AGVs, rely on quality top deckboards. • Conveyors deck AGVs rely on quality bottom deckboards to move pallets on and off the vehicle. Broken/missing boards can jam leading to faults on the AGV requiring operator intervention. • Damage pallets produce load skewing or fall from the system.
Palletization / De palletization equipment	Pallet related Issues
Robotic or conventional	• Pallets with damaged or missing components and pallets that are not square tend to create faults and damaged products.

Equipment manufacturers companies agreed **that** automatic storage systems require a higher degree of pallet quality checks prior to allow pallets into the system; as any significant variance in size can be problematic. The following table summarizes the pallet related issues according to user experiences.

Table 4.Description of pallet related issues according to pallet users.

Storage Equipment	Pallet related Issues
Selective load beam racks	• Pallet users did not describe any issue on this system.
Flow Racks	• Pallet users did not describe any issue on this system.
Drive in or Drive through racks	• Pallets tend to deflect in the center, which produce a deformation. This deformation makes it more difficult to retrieve the pallet from the system.
Push back racks	• Pallet users did not describe any issue on this system.
AS/RS systems	• Pallet users did not describe any issue on this system.
Material Handling Equipment	**Pallet related Issues**
Conveyors (rollers, chain, etc)	• Missing bottom deck boards cause pallet to twist and create jams.
Forklift	• The total issues described by manufactures reflect lack of operator training. None of the issues described were directly related to the pallet design.
Pallet Jacks	• The total issues described by manufactures reflect lack of operator training. None of the issues described were directly related to the pallet design.
AGVs	• Broken/missing boards can cause jams leading to faults on the AGV requiring human intervention.
Palletization / De palletization equipment	**Pallet related Issues**
Robotic or conventional	• Missing top deck board causes instability issues.

5.1.3. Topic: Effect of Pallet Design on Equipment Performance.

The participants discussed on the pallet characteristics that had to be considered in order to avoid interface issues between their pallets and equipment.

Pallet manufacturers responded that they considered maximum allowed deflection, number of bottoms deck boards, bottom deck coverage, thickness of the bottom boards, friction, top deck resistance as the main characteristics' pallets required to avoid interface issues with equipment.

Equipment manufacturers indicated that pallet consistency is the number one requirement for a system to function properly. They mentioned if pallet size and quality are not consistent, the performance of the equipment is hard to manage. Pallets entering the system must be in good condition with no missing/broken bottom or top deck boards and protruding nails. Pallets must meet the required specifications and must reliably and smoothly convey through the system.

If that variability of the pallet size and quality become hard to manage, they recommended to:

- Limit amount of trip and the load.
- Utilize pallet support boards to handle pallet through the system.
- Incorporate a pallet exchanger.

Pallet users indicated that pallet consistency is the main characteristic they try to assure before allowing pallets into their facilities, in order to avoid safety issues and equipment damage. Pallet users indicated to have established a pallet inspection stations, previous to introducing pallets into their systems. These inspections are made in order to identify pallets with damages such as broken boards, nails protruding, end boards in place.

5.1.4. Topic: Compatibility

Participants were asked to describe the most common reason why pallets and automatic equipment have interface issues.

Pallet manufacturers responded that split boards, missing bottom boards, raised nails, missing components and twisted boards are the most common cause of pallet related issues in automatic systems.

Equipment manufacturers mentioned that damaged pallets, missing components and variation in pallet quality (lack of consistency) are the most common reason why pallets and automatic equipment have interface issues.

Pallet users responded stated broken boards interacting with machinery, product misplacement during handling are the most common pallet related issue that interrupt production flow in their facilities.

5.1.5. Topic: Downtime

During this topic, participants shared according to their expertise which issues cause the longest downtime when their pallets interface with equipment.

Pallet manufacturers indicated that issues that occur on AS/RS, are the one that takes the longest amount of time to repair, due to the complexity of this equipment.

Equipment manufacturers mentioned that jams in a high-rise rack requires the longest amount of time to repair. Their estimated reaction time is from 30 min. to 90 min. Equipment manufacturers also indicated that pallets failing in conveyors is happening frequently and it could take approx. 15-30 min. to repair.

Pallet users responded that the longest downtime occurs when broken boards interfere with palletizers.

5.2. Phase 2: Online survey results and discussion

5.2.1. Respondent characteristics

The online survey received responses from 204 participants representing many different industries. The number of survey participants equals a 6% response rate. However, the number of responses per given question varied due to the fact that some questions' content may not be relevant to all respondents (Appendix 2. Online Survey/Phase 2). The following chart (Figure 12) shows the number of responses per question. Participant responses were filtered to assure the accuracy of the data collected. Questions 18-21 were open-ended questions allowing respondents to choose to participate in an Amazon gift card raffle and future interviews.

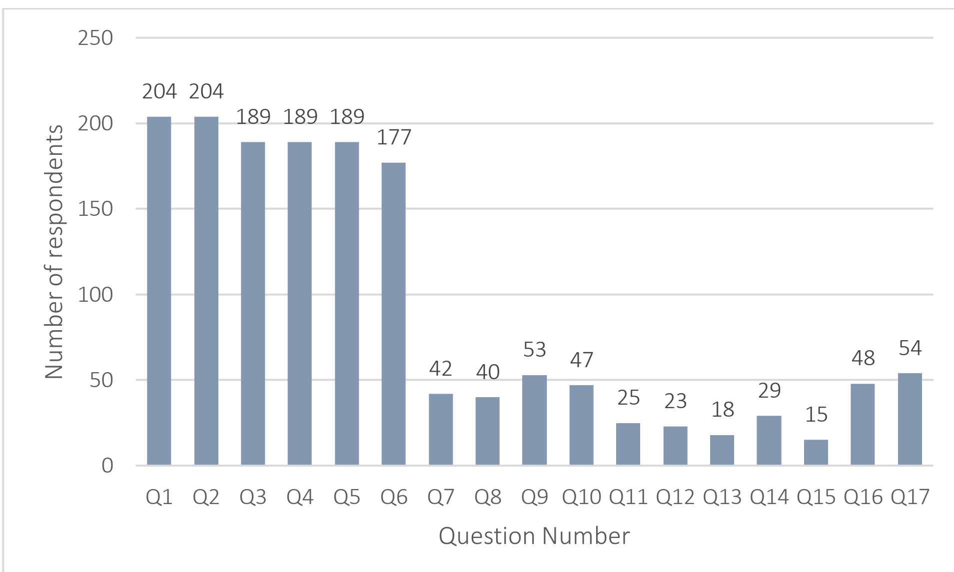


Figure 12. Number of respondents per survey question.

After question six there was a significant decrease in responses. Question six asked the automation level of the material handling systems used by respondents. Sixty percent of the participants reported using manual material handling systems; while forty percent indicated using semi-automatic or fully automatic material handling systems. After question six, the remaining questions were exclusively directed to the participants who reported using semi-automated or fully automated material handling systems. Respondents who indicated use of exclusively manual systems were excluded from rest of the survey. This, at least partly, explains the significant drop in responses after question six.

When analyzing the overall data (responses from both manual and automated facilities), results showed that the majority of responses came from manufacturing companies (29%), followed by distribution centers (16%), and other industries (14%), such as automotive, electronics, government companies. The smallest participation was from industries such as tobacco, petroleum, and aerospace (Figure 13).

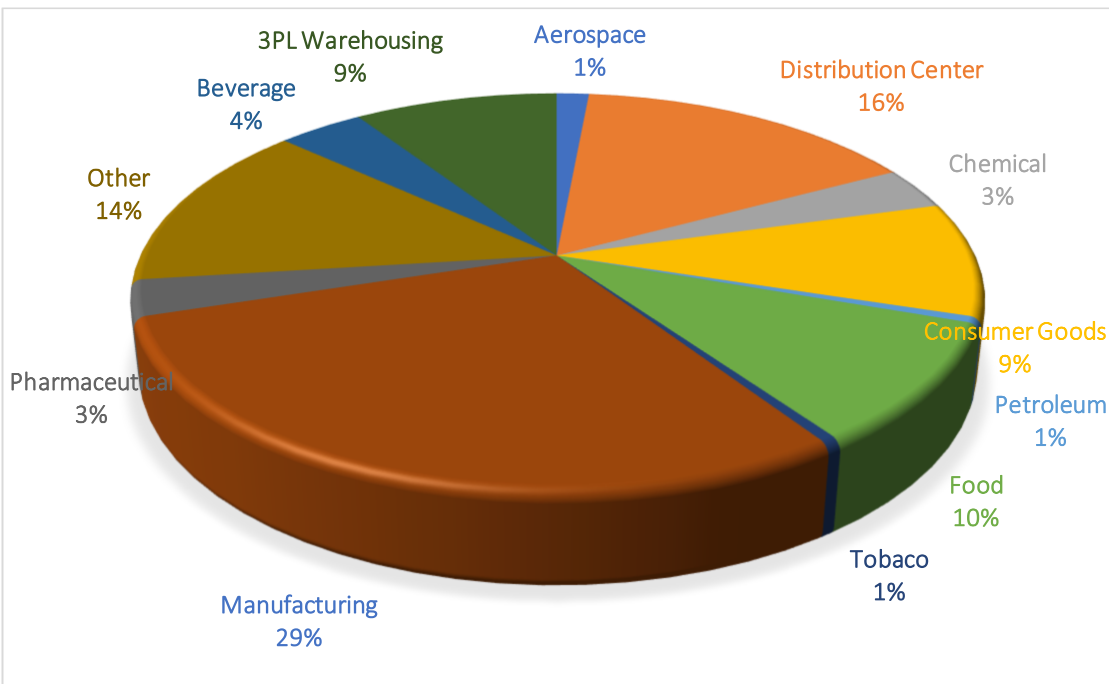


Figure 13. Survey responses received from the different industry sectors.

When analyzing the data according to the respondents' automation levels, results showed distribution centers, the food industry, aerospace, and other manufacturers all had similar automation levels across the industries, but in cases such as 3PL warehousing, other, and the chemical industry, the majority of respondents stated they used manual warehousing. On the contrary, consumer goods, and the petroleum, tobacco, pharmaceutical, and beverage industries had a majority of respondents using semi-automatic or fully automatic warehouses.

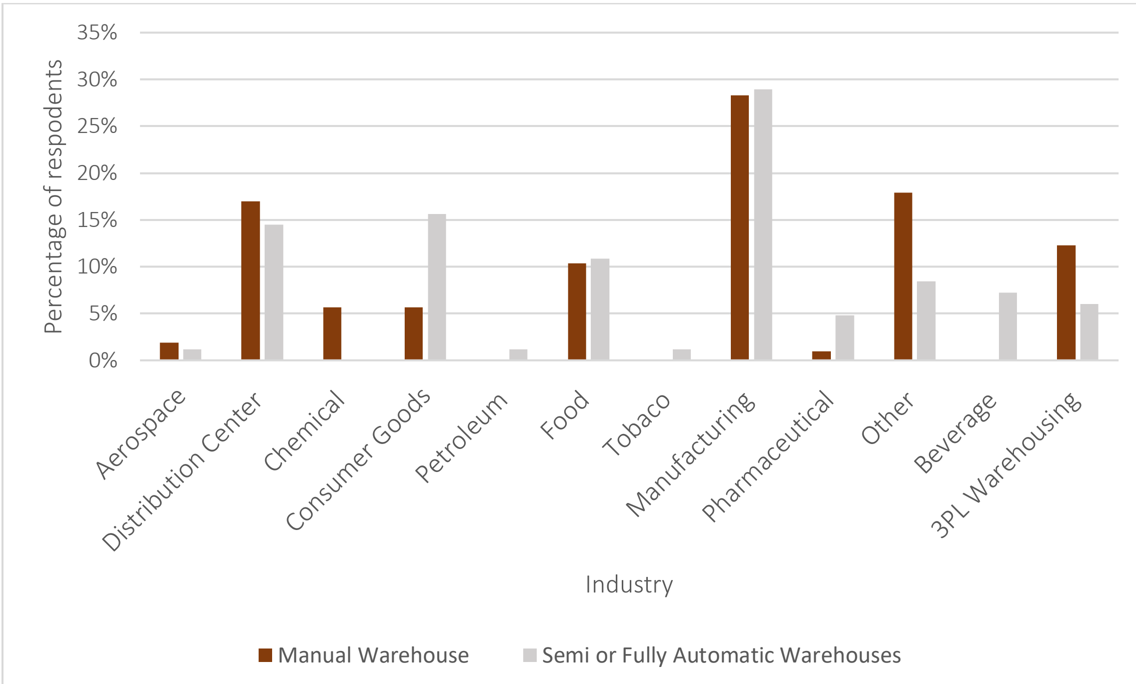


Figure 14. Survey responses according to automation level.

The survey targeted different professionals within the company, but there was significant interest in receiving warehouse manager or supervisor input, due to their daily experiences on the warehouse floor. From the overall data collected (from both manual and automated facilities), 36% of the survey responses came from managers and supervisors, followed by 27% of responses coming from general managers, and 12% of responses came from engineers.

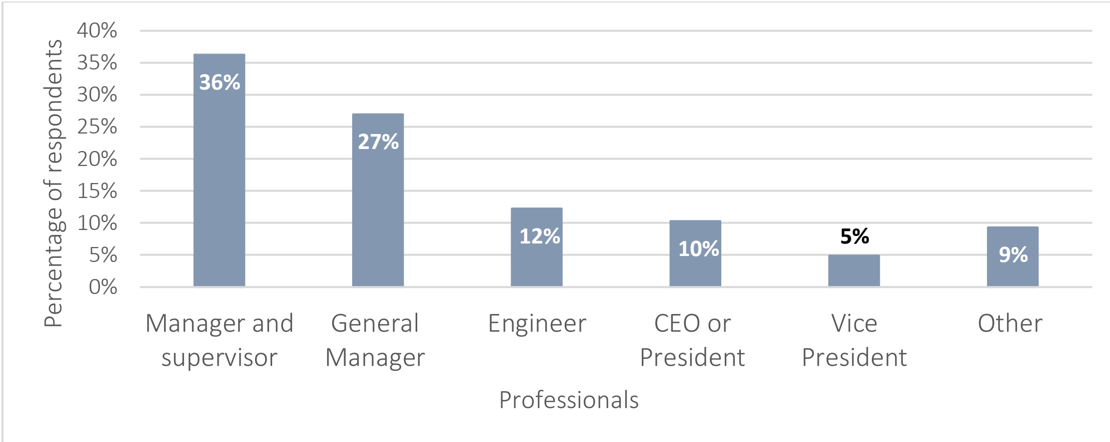


Figure 15. Professional roles of the respondents completing the survey.

When comparing the professional roles of respondents according to the level of automation in their warehouses, the survey showed that the trend was very similar in both cases. The majority of responses were from managers and supervisors, followed by general managers. Despite this, manual warehouses presented a higher response rate from engineers than fully or semi-automatic warehouses.

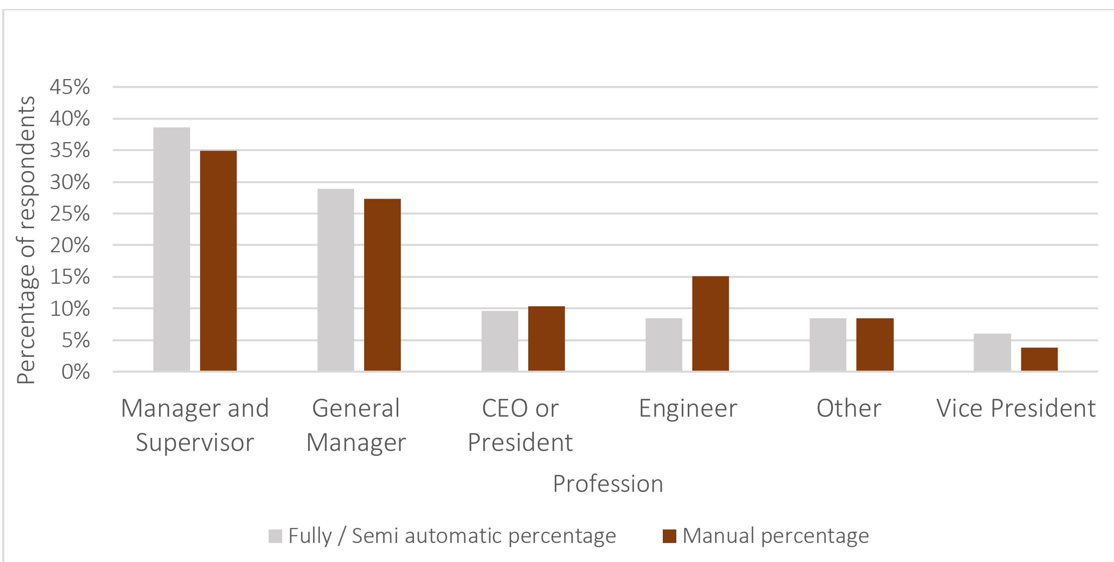


Figure 16. Professional roles of the respondents completing the survey according to the automation level.

From the total 191 respondents for question three (including both manual and automated warehouses), respondents stated that warehouses typically handled 1,000–10,000 pallets in their facilities during 2018. Data collected presented a high variation, which could be an effect of studying different industries and having responses from both small and large firms (Figure 17). Despite this, results show there is not a significant difference between the number of pallets utilized in manual warehouses and the pallet quantity used in automated warehouses. Data collected resulted a median of 5,000 pallets and a mode of 1,000 pallets.

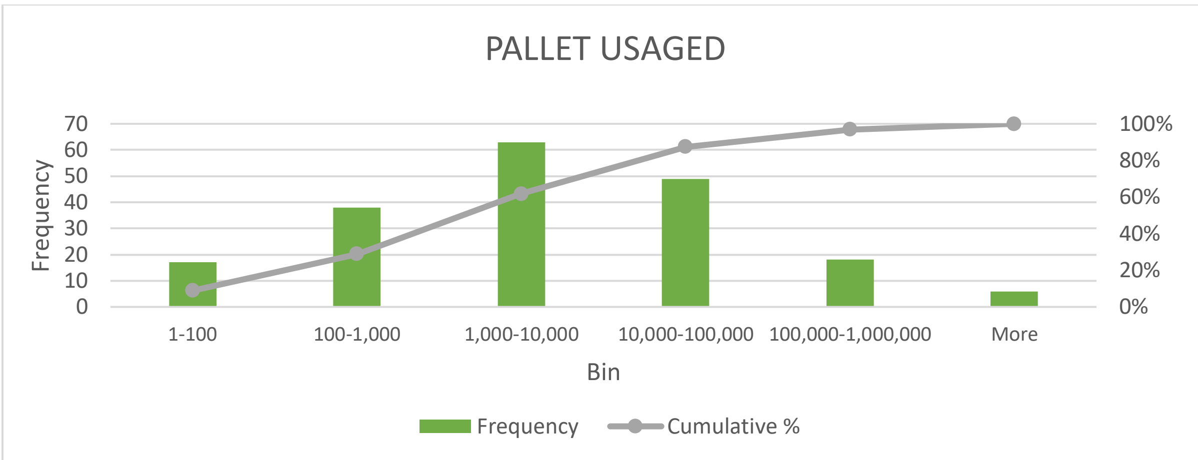


Figure 17. Pallet utilization histogram

Statistics	Manual	Automated
Standard Dev	661,028	567,091
Average	136,282	123,914

Figure 18. Pallet utilization according to automation level by respondents.

Table 5. Results of the Analysis of Variance test

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	7120745907	7.1207e+9	0.0184
Error	187	7.2251e+13	3.864e+11	**Prob > F**
C. Total	188	7.2258e+13		0.8922

Table 6. Statistic output proving pallet mean was not significant different between the number of pallets utilized in manual and automated warehouse.

Level		Least Sq Mean
M	A	136282.12
A	A	123914.06

The class of pallets handled in the responding warehouse/distribution center was variable. Some facilities used the same pallet class throughout their warehouse, and some used an extensive variety of pallet classes simultaneously. From a total of 189 responses to question four, it was determined that the most common pallet types used were stringer class, recycled, wooden pallets (58%), followed by block class, wooden, pool pallets (50%), and stringer class, new, wooden pallets (44%).

The majority of the respondents used wooden pallets which trend is in line with the trend found by MMH's annual pallet research (2011 – 2018) that points to wood as the dominant pallet material in the market. A majority of MMH readers indicated using wooden pallets (93%) (MMH,2018). The survey also found that stringer class pallets, both recycle and new, were popular among the respondents. The popularity of recycled stringer class wooden pallets was also determined by Gerber (2018), who studied the wooden pallet market, and stated that 72% of wooden pallets are stringer class pallets. The MMH surveys (2011-2018) indicated that one of the most important factors in their customers' decisions to use certain pallet types was the purchase price of the pallets which explains the popularity of recycled stringer class wooden pallets.

The overall data collected during this study also revealed that facilities handled a large percentage of block class pool pallets (21%). Gerber (2018) findings differ, but this difference can be explained by the fact that Gerber did not include pallet poolers in his study. The current companies surveyed included both semi and fully automated warehouses, which require tighter dimensional tolerances (MHI 2016) and therefore, tends to use more expensive and more robust pallets such as pooled block pallets. According to the MMH automation report (2019), more automation is being implemented, and this could potentially translate into continuous growth of the pool pallet market. Figure 19 shows the pallet user distribution according to pallet class for 2018.

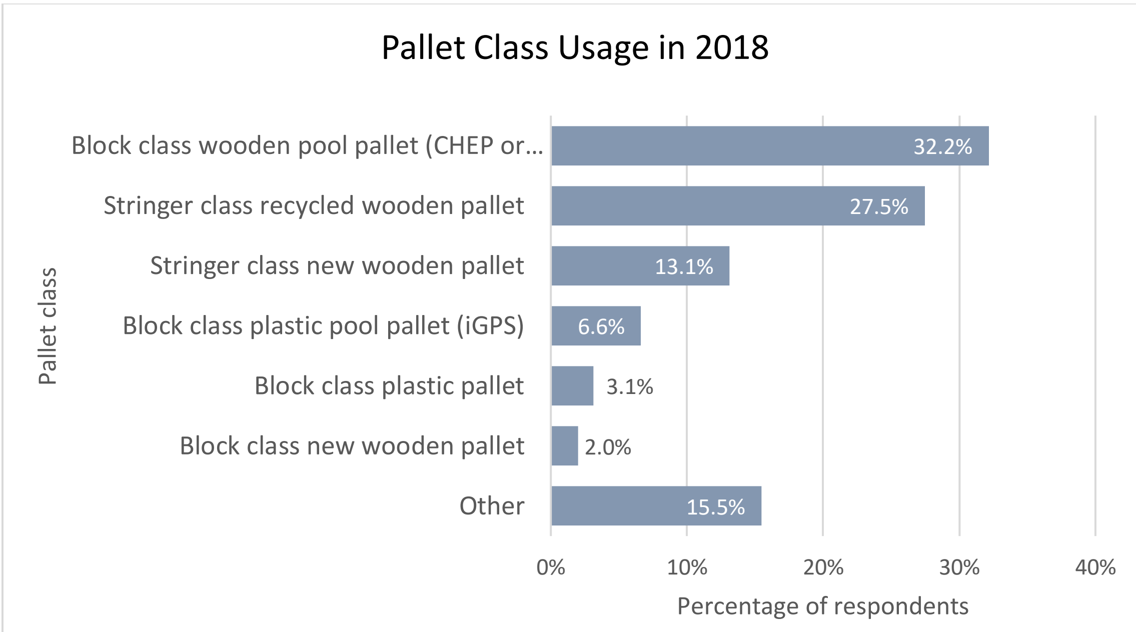


Figure 19. Percentage of pallets used in 2018.

When studying the pallet class usage according to the level of warehouse automation, stringer class recycled pallets were (27%) and the most common type of pallets used in manual warehouses, followed by stringer class new pallets (20%) and block class wooden pool pallets (19%). Purchase price was most common reason listed for why recycled pallets were in such high demand (MMH,2018). On the other hand, for fully automated warehouses the most common pallet type used was the block class wooden pool pallet (24%), closely followed by stringer class recycled wooden pallet (21%) and stringer class new wooden pallet (19%). Automated facilities tend to require pallets with tighter tolerances which can explain their preference for pool pallets. Pool pallets are well known as being less variable than stringer class recycled pallets.

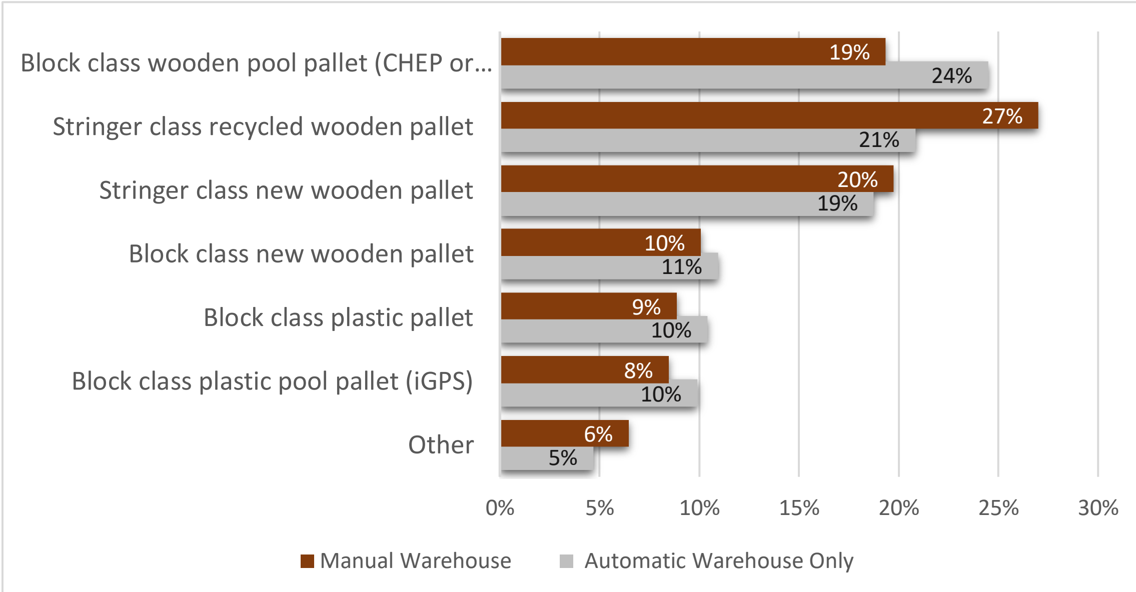


Figure 20. Percentage of respondents using each pallet class according to the automation level.

The same way pallet class varies in a warehouse facility; pallet size requirements vary according to each customers' needs. From the 189 responses to question five, it was reported that 63% of the respondents used 48 in. x 40 in. pallets, 24% used 48 in. x 42 in., 17% used 42 in. x 42 in. Customized pallets represented 29% of the pallets used in participants warehouses. The least common sizes used were 37 in. x 37 in., 1200 mm x 1000 mm, and 800 mm x 1200 mm (Figure 21).

In terms of preferred pallet sizes, the 2018 MMH annual pallet survey reported the 48 in. x 40 in. as the most predominant size used throughout the market. Additionally, Gerber (2018) indicated the significant presence the 48 in. x 40 in. pallet (35%) in the American market.

Pallets with dimensions of 48 in. x 40 in. became popular in the 1960's and 70's during an attempt to standardize pallets for users and producers (Angellotti and Pallet, 2015; Kator, 2016), and they are currently in high use by the grocery industry, in particular. The second most common size used, according to respondents, was the 48 in. x 42 in. which is used by the chemical and beverage industries (Bush and Araman,2008)

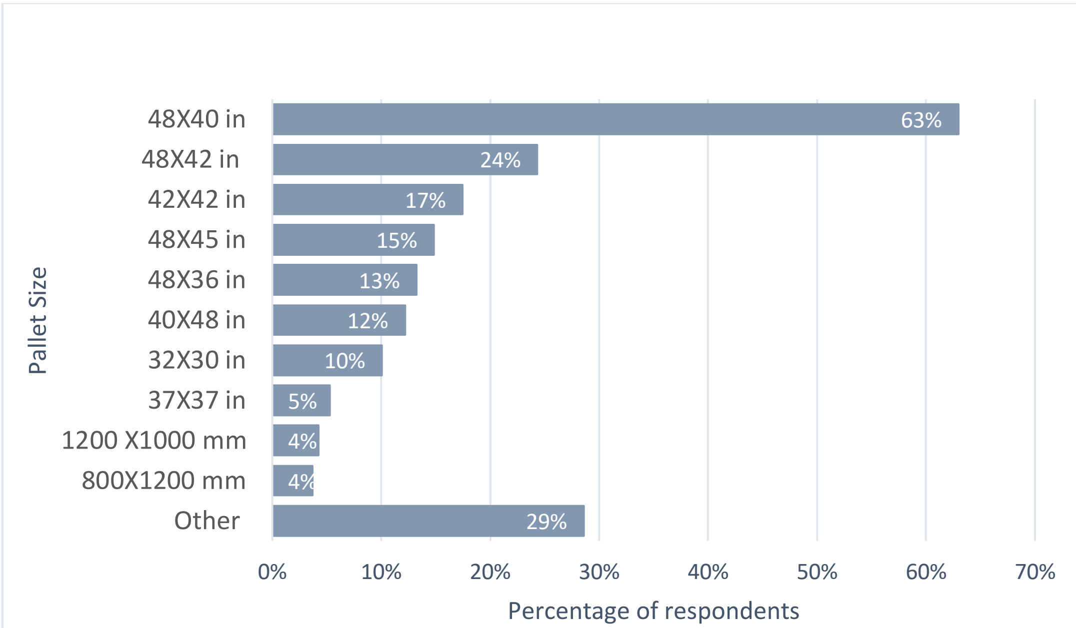


Figure 21. Percentage of respondents that used each specific pallet size in their facilities during 2018.

The overall participant responses (for both manual and automatic warehouses) showed that companies handling between 1,000-10,000 pallets tended to utilize the highest percentage of wooden pool pallets and stringer-class recycled wooden pallets. While companies that used between 1-100 pallets tended to use plastic pool pallets or plastic block class pallets. Results show that the utilization of block class plastic pool pallets and block class plastic pallets considerable decreased when the warehouses requirements surpassed 1,000 pallets. This could be caused by a higher purchasing price or a lack of control in tracking the location of this type of pallet, but it has been demonstrated that when the quantity of pallets needed was small (1-100), facilities tended to avoid purchasing recycled pallets and were more likely to purchase plastic pallets. On the other hand, recycled pallets became the more attractive option when facilities required larger pallet quantities. Figure 22 summarizes the different pallet usage tendencies.

Figure 22. Use of pallet class according to pallet quantities required by facilities.

When analyzing common pallet sizes according to the automation level of the warehouse, it was found that the 48in. x 40in. were the most common size used. Pallet size usage did not seem to be influenced by the level of warehouse automation (Figure 23).

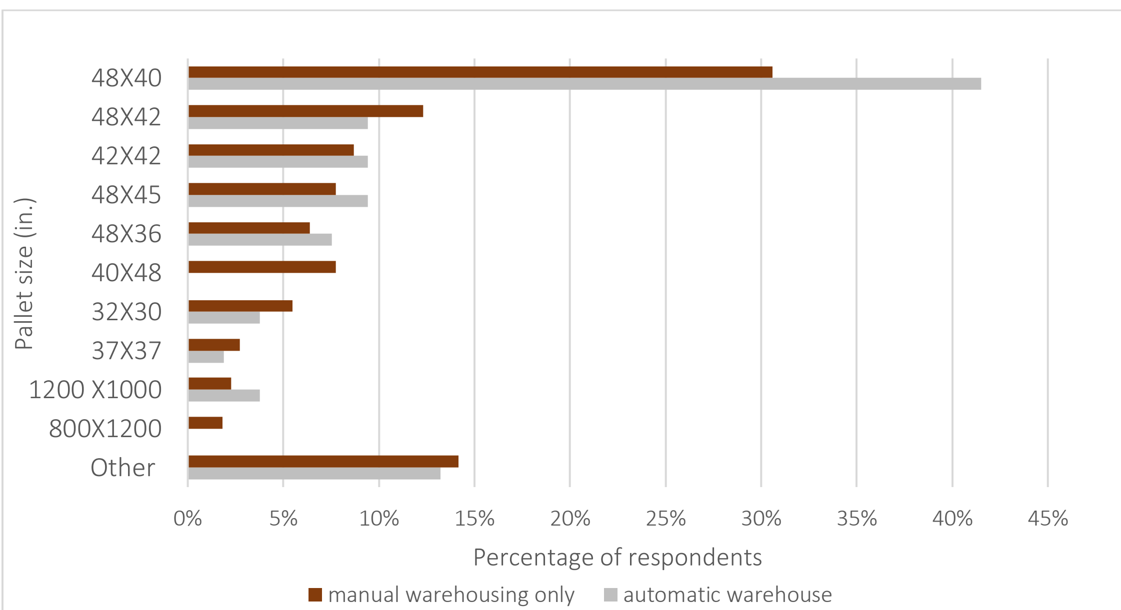


Figure 23. Percentage of respondents using each pallet class according to the automation level.

The overall results show 48 in. x 40 in. pallets was present in facilities that handled small and large pallet quantities. In the same way the use of pallet sizes 42 in. x 42 in., 48 in. x 42 in., and 48 in. x

45 in. did not seem to be determine by the respondent's pallet usage, since the utilization of these sizes were present in both small and large facilities. On the other respondents that handled 1,000-10,000 pallets indicated to use 48 in. x 36 in. pallets, while respondents that utilized 100-1000 express to use 37 in. x 37 in. Respondents that used between 1-100 pallets; indicated to currently use pallets sized 1200 mm x 1000 mm (Figure 24).

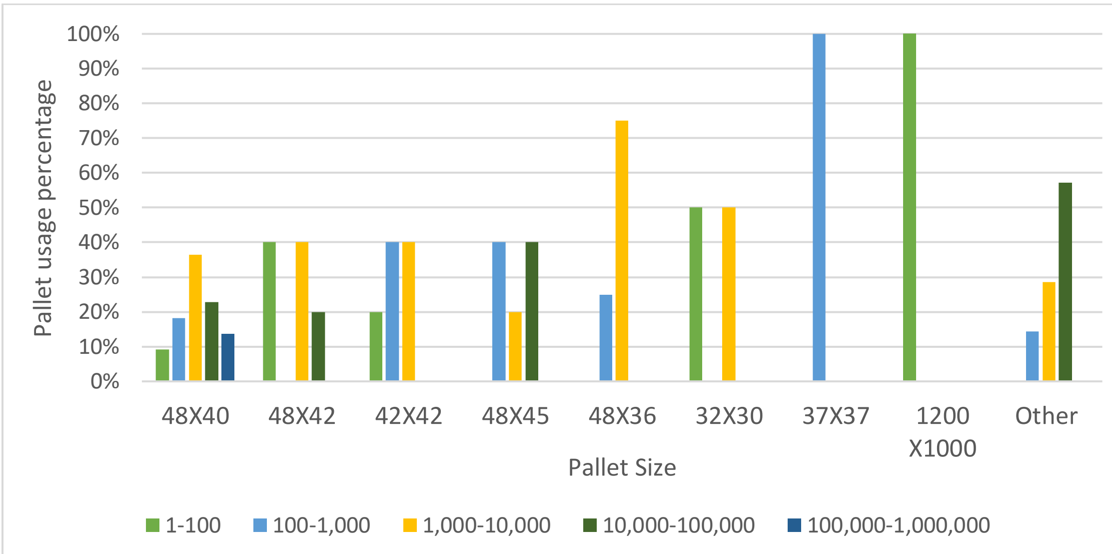


Figure 24.Pallet size utilization according to respondent's pallet usage.

5.2.2. Automation & material handling systems.

Of the 177 responses to question six, 60% reported using manual material handling systems, while 40% indicated using semi-automatic or fully automatic material handling systems. This research studied the level of automation across three specific warehouse operation types: storage, material handling, and palletization/de-palletization. The following table presents the level of automation used by respondents in each specific system.

Table 7. Warehouse automation level used by the respondents.

Systems studied	Respondents automation level			
	Fully automatic	Semi-automatic	Manual	Not applicable
Storage Systems	3%	21%	64%	11%
Material Handling equipment	3%	30%	59%	8%
Palletization / Depalletization	3%	20%	55%	22%

Results show that only 3% of activities in each of the systems studied were fully automated. Participants response indicates that only a small percentage of warehouses is fully automated in the United States. Despite the current small percentage, the MMH 2019 annual automation survey indicated that many companies are looking to automation to help them solve their most pressing fulfillment problems. A desire for more automation is driven by the need to manage high-velocity operations with limited labor resources, while meeting the ever-changing needs of their customers. From all of the different activities performed in warehouse facilities, 42% of respondents indicated that they had fully or partially automated conveyance, while 38% had fully or partially automated their labeling operations (MMH, 2019).

This survey also studied the different types of storage systems used in warehouse facilities. Most respondents (69%) stated that they use floor stacking or stack rack storage. This does not come as a surprise since only 3% of respondents had indicated that they used fully automated systems. The following chart displays valuable information about which storage systems were used in respondents' facilities (Figure 25).

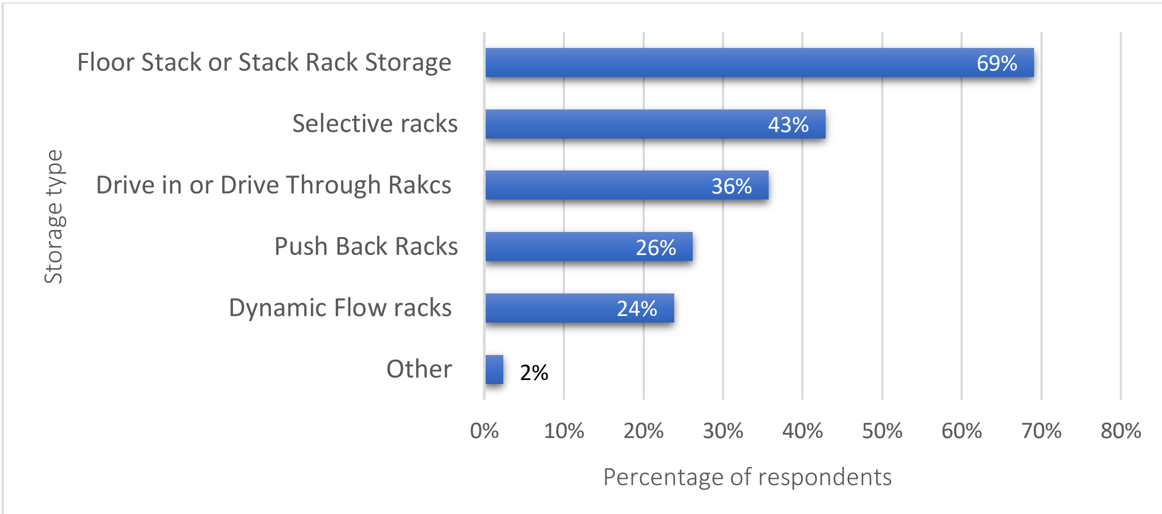


Figure 25. Percentage of respondents that used each storage type in their facility during 2018.

Based on the numerous issues that can occur when pallets interface with warehouse storage systems (issues that were discovered through Phase 1 of this research), the frequency of this type of issues' recurrence was studied throughout this next phase of the research.

Results show that several of the issues found during Phase 1 impact storage system performance on a monthly basis. The frequency of the occurrence of jams and malfunctions caused by poor quality pallets or pallets that were missing bottom boards was very high. These results reveal that only 2.5% of respondents had never experienced these types of issues. In addition, almost half (47.5%) of the respondents experienced issues more frequently on a daily and weekly basis.

The quality of the bottom deck of the pallet is important because this is the pallet component that directly interfaces with many handling and storage equipment. Therefore, broken or missing bottom deckboards could inhibit the ability of the pallet to function in these warehouses. The importance of the quality of the bottom deckboards are also highlighted in the ANSI MH1 standard (MHI 2016).

Issue 1; Improper pallet placement in the equipment caused by missing or damaged components was one other most frequent issue with 17.5% of participants experiencing it at a daily rate. And, 47.5% of respondents indicated that this type of issue impacted their facilities at least monthly (Figure 26).

Issue 3; Retrieval difficulty was also a frequent issue that many automatic warehouses encountered on a weekly basis, and results show that this issue occurred monthly in 65% of respondents' facilities (Figure 26).

Missing or damaged components, resulting in increased unit load speed, seemed to not impact performance as much as the previous two issues. Almost one third of respondents (32.5%) never experienced this issue in their facilities. This was a performance issue specific to the use of flow racks. Since only 24% of respondents indicated that they used this type of system, it was not only a less frequent issue, but it applied to a system not commonly used by facilities (Figure 26).

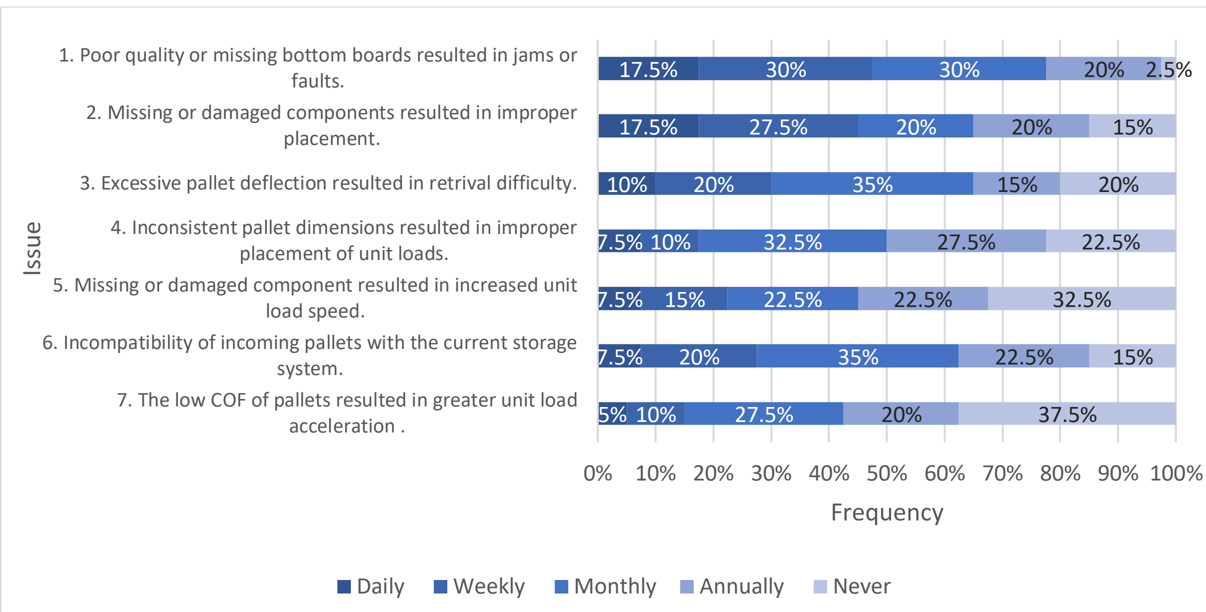


Figure 26. Frequency of pallet related Issues in storage systems

This research also considered the different types of material handling equipment used in warehouse facilities. According to the MMH 2019 automation survey, 92% of respondents utilized forklifts in their facilities, and 63% of the respondent companies used conveyors and sortation equipment. But, when a closer look is taken at the conveyor data, it can be found that 89% of the respondents used conveyors in their automated operations (63% used roller or belt conveyors and 26% used chain conveyors) (Figure 27).

Currently, AS/RS stacker cranes and unit load formers are the least common equipment still regularly used in automated warehouses in the U.S. with 17% and 6% of facilities using these types of equipment, respectively (Figure 27).

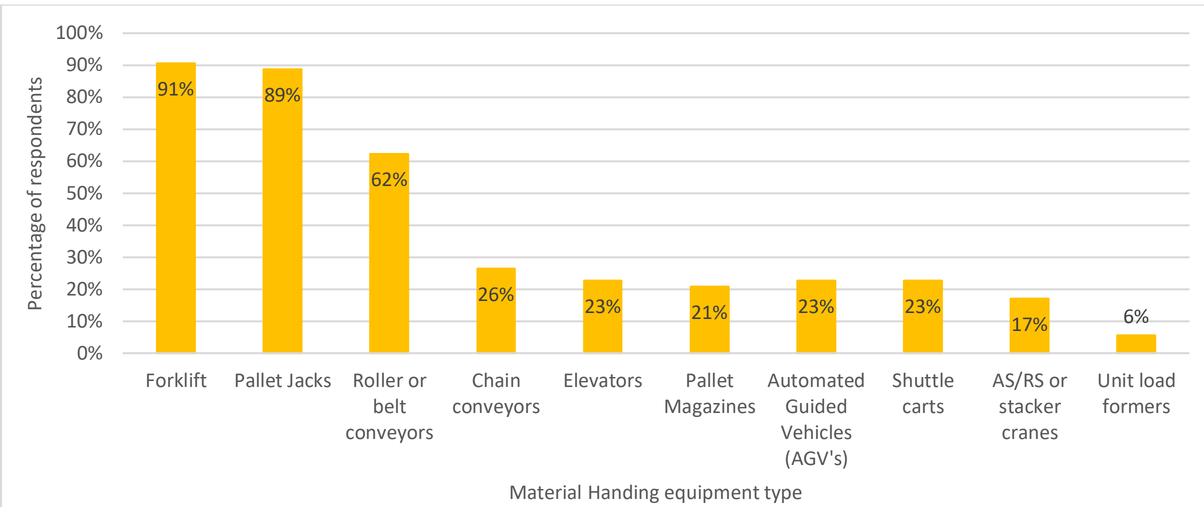


Figure 27. Percentage of respondent that used each specific material handling equipment in their facility during 2018.

Material handling equipment often encountered interfacing difficulties when interacting with different pallet designs. Results indicate that the overall equipment performance was affected by jams or malfunctions caused by pallet design issues. Many respondents indicated that they experienced jams or malfunctions daily (11%), but the majority of facilities were affected by this issue on a monthly basis (57%). Having equipment not performing at 100% capacity, or being regularly disrupted from its continuous flow, is not efficient. When equipment stops due to jams or malfunctions, it not only increases lead time, but it also translates in re-work, cleanup time, extra costs, and possible damage to the product.

The survey revealed that when forklifts interacted with half pallets and euro pallets, they tended to cause instability issues and product damage for approximately 60% of the respondents on a monthly basis.

It was found that a high frequency of pallet related problems was due to having bottom deck boards that were wider than the pallets' blocks. Approximately 55% of respondents stated that they experienced this issue on a monthly basis.

Results of the survey showed that approximately 39% of participants encountered issues at least on a weekly basis due to incorrect placement of the pallets' bottom deck boards, causing the pallets to be damaged when handled by a pallet jack. However, this issue was mainly caused by a lack of training (human error) and was not actually related to pallet design.

Most respondents (53%) reported that they had never experienced increased unit load vibrations on conveyors due to faulty pallet design. The majority of respondents also did not regularly experience issues due to wood splintering and jamming the roller conveyors.

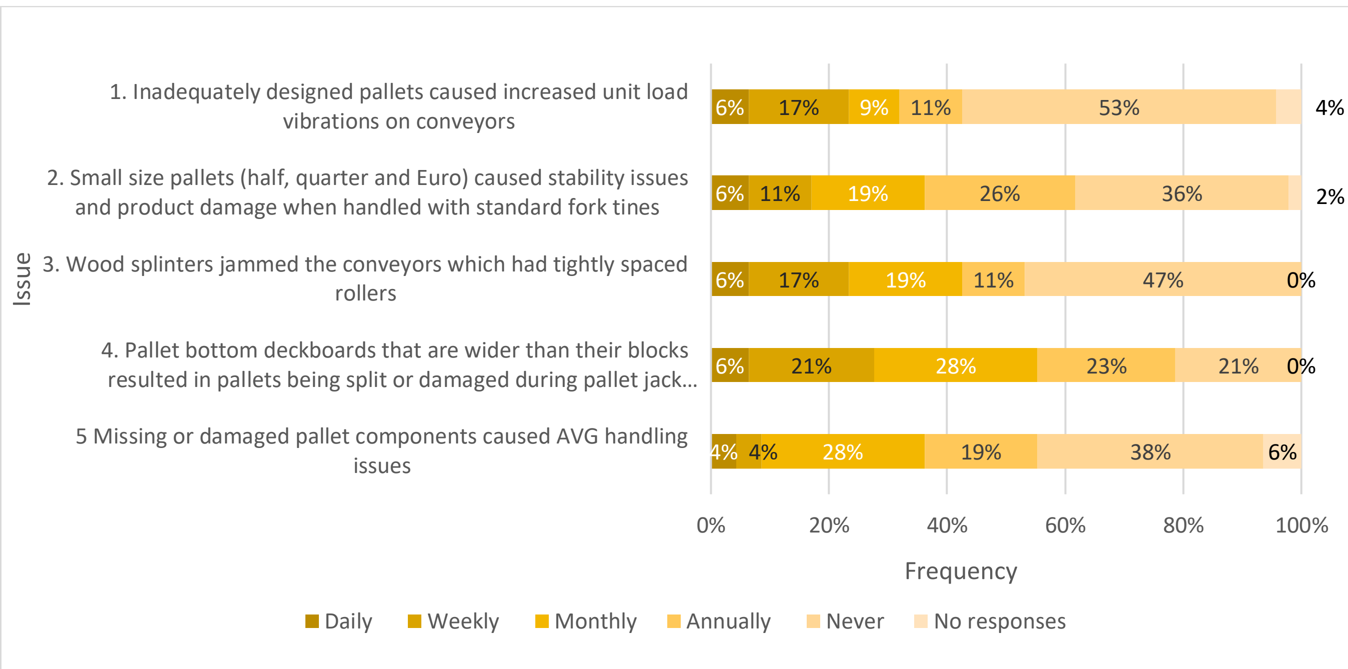


Figure 28. Frequency of pallet related Issues in material handling systems, part 1.

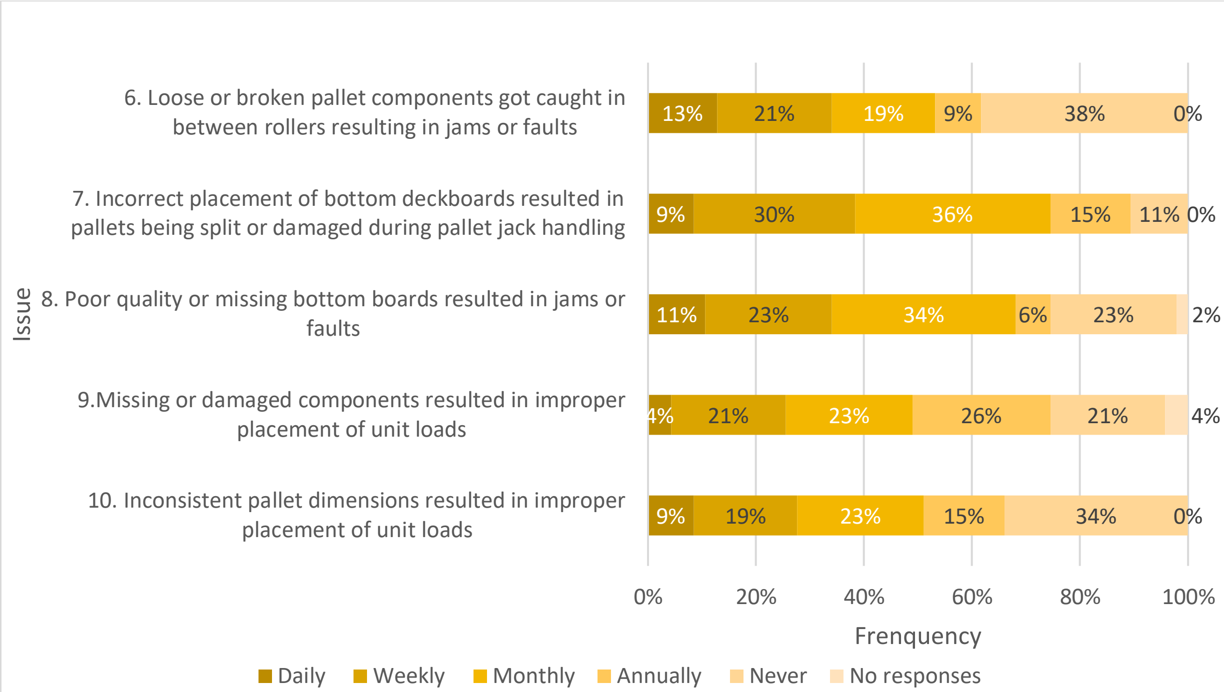


Figure 29. Frequency of pallet related issues in material handling systems, part 2.

When it comes to analyzing the usage of palletizer / de-palletizer equipment, it was found that only 14% of respondents used these types of systems. Results show that of those using this equipment, 72% used robotic equipment and 28% used conventional equipment. Results show that respondents were divided into those who experienced a high frequency of issues related to this equipment (approximately 50% of respondents experienced issues at least monthly) and those who experienced a low frequency of issues (approximately 50% of respondents indicated that they experience this type of issue annually-to-never).

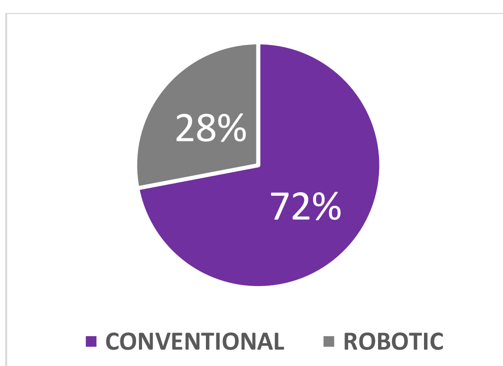


Figure 30. Palletization system used by the respondents during 2018.

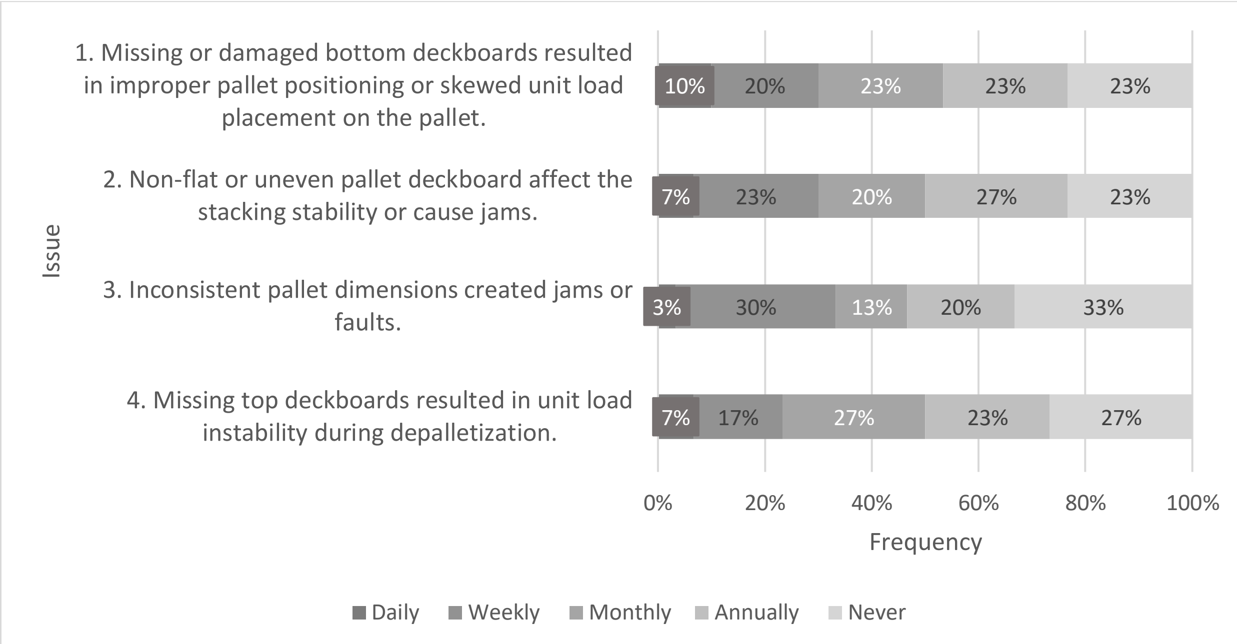


Figure 31. Frequency of pallet related Issues in palletization systems

5.2.3. Downtime and frequency of occurrences of pallet related issues in semi-automated and fully automated warehouse.

Survey participants were consulted about the downtime cause by pallet failure in their systems (storage, material handling, palletization/depalletization). Respondent shared information about the number of minutes specific storage systems stopped due to pallet related issues and the number of occurrences a system shuts down in a month. The following table summarizes the information collect:

Table 8. Pallet related downtime and number of occurrences in storage systems.

Storage Systems		Downtime (minutes)	Number of occurrence (Monthly)	Monthly Downtime (hour)
Load beam racks	Average	**16**	**28**	**7.47**
	Min	1	1	
	Max	60	100	
Push Back Racks	Average	**47**	**22**	**17.23**
	Min	3	1	
	Max	200	75	
Drive through Rack	Average	**31**	**14**	**7.23**
	Min	10	5	
	Max	90	20	
Dynamic Flow Racks	Average	**12**	**7**	**1.4**
	Min	1	2	
	Max	30	14	

The systems presented in the table above, were the only systems on which respondents share information. The number of respondents for this section decrease significantly, this could have been caused due to lack of information that companies currently have when it comes to controlling downtime caused by pallet related issues. Each of these systems show a high variation between the minimum and the maximum downtime as well as a high variation between the number of occurrences. This variation could be the result of different types of pallet related issues. Some pallet issues might take less time to fix, for example, when a damage component cause an improper placement in the systems. Other pallet issues such missing components causing the pallet to jam or pallet failure will require a longer amount of time to repair, which translate in longer operation downtime.

Results such as the downtime in push back racks system is surprising. Respondents mentioned their systems stop 22 times in a month for a period of 47 minutes(average), this meaning the downtime for only this equipment is approximately 17 hours. This means that in a month their equipment is not operating for approximately 2 days (if shift are 8 hours a day). Having expensive equipment performing at 100% of their capacity is the goal for the majority of the companies, goal that is difficult to achieve when using incompatible pallets that cost extensive operation downtime.

The following table summarizes the information of number of minutes specific materials handling systems stopped due to pallet related issues and the number of occurrences a system shuts down in a month.

Table 9.Pallet related downtime and number of occurrences in material handling systems.

Material Handling Systems		Downtime (minutes)	Number of occurrences (Monthly)	Monthly Downtime (hour)
Roller or belt Conveyors	Average	**14**	**17**	**4**
	Min	1	1	
	Max	45	100	
Chain Conveyor	Average	**20**	**5**	**1.6**
	Min	5	1	
	Max	45	12	
Forklift	Average	**29**	**12**	**5.8**
	Min	2	1	
	Max	120	60	
AGV's	Average	**17**	**19**	**5.4**
	Min	10	3	
	Max	25	50	
Pallet Magazine	Average	**13**	**11**	**2.4**
	Min	5	1	
	Max	20	50	

Similarly, to the storage systems results, material handling systems show high variation on the operations downtime and frequency of occurrences. Results highlight AGV's as the system with higher overall downtime in a month. Results show in average an AGV systems could be stop due to pallet related issues approximately 323 minutes (5.3 hours) a month.

When it comes to palletization and depalletization systems, results show a longer period of downtime per occurrence for robotic systems, which can be explain due to these systems are more complex than conventional systems. Despite this pallet related issues seems to be present in conventional systems more frequent. Following table summarizes collected information.

Table 10.Pallet related downtime and number of occurrences in palletizers / de-palletizers systems.

Palletization / Depalletization Systems		Downtime (minutes)	Number of occurrences (Monthly)	Monthly Downtime (hour)
Robotic	Average	**125**	**20**	**41.6**
	Min	5	2	
	Max	700	50	
Conventional (row strip or similar)	Average	**53**	**52**	**46.9**
	Min	5	1	
	Max	120	200	

When respondents were asked to identify the pallet type that was involved in pallet related downtime, the big majority of respondents indicated stringer class recycled wooden pallet was the pallet involved in this event. As previously discussed, recycled wooden pallets lack components consistency, introducing this type of pallets into a system with low variation tolerance create an interaction disconformity that ends up stopping the process, increasing the downtime and rework time. The following chart presents the different pallet types that are involved in pallet related downtime.

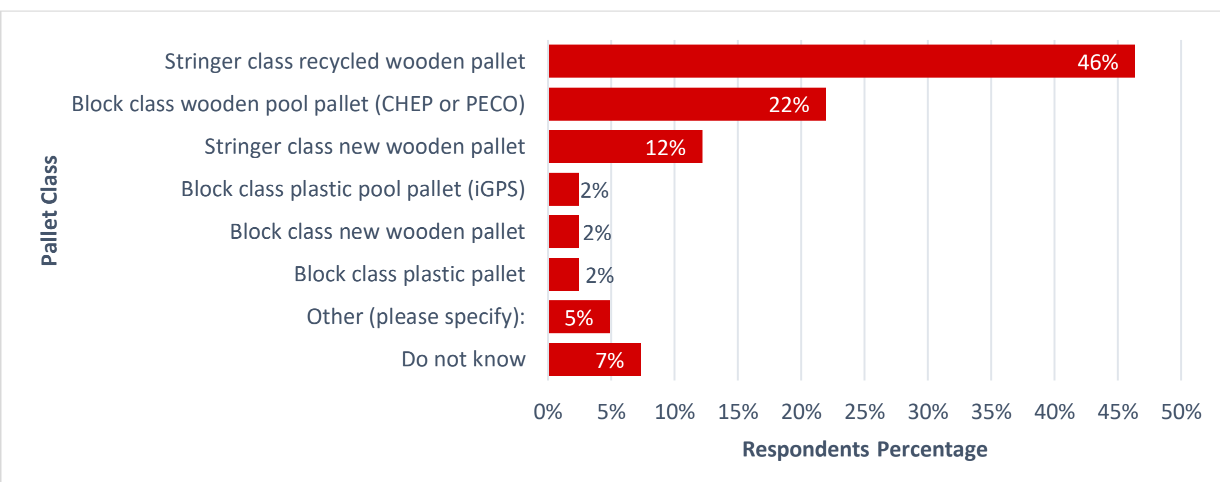


Figure 32. Pallet class involved in pallet related downtime

Chapter 6: Conclusions

Results show that 3% of the respondent warehouses are fully automated, and 20-30 % are semi-automated. The MMH 2019 automation report shows that automation is an upcoming trend for warehouses and DC facilities. This is driven by the need to manage high-velocity operations with limited labor resources while meeting the ever-changing needs of their customers. Because of this, more and more companies are looking to automation to help them solve their most pressing fulfillment problems.

Block class, wooden, pool pallets are the most common pallets used in semi/fully automated warehouses, followed closely by the use of stringer class, recycled, wooden pallets. Automated facilities tend to require pallets with a tighter tolerance which explains the preferred use of pool pallets. On the other hand, purchase price is the most common reason that was listed to explain the high usage of recycled, wooden pallets.

The survey revealed that when forklifts interacted with half pallets and euro pallets, they tended to cause instability issues and product damage for approximately 60% of the respondents on a monthly basis.

The 48 in. x 40 in. pallet size is the most commonly used by semi- and fully- automatic warehouses. This pallet size is especially highly utilized in the groceries industry.

The frequency of jams and storage system malfunctions caused by poor quality pallets, or pallets that had missing bottom boards, was very high. These results revealed that only 2.5% of respondents had never experienced these types of issues. In addition, almost half (47.5%) of the respondents experienced these issues frequently; on a weekly or even daily basis.

The occurrence of pallet related issues in material handling equipment is mainly caused by poor quality or missing bottom pallet boards resulting in jams or malfunctions. Approximately 68% of respondents stated that they experienced this issue on a monthly basis.

The frequency of the occurrences of pallet related issues in palletization/ de-palletization systems was mainly caused by missing or damaged bottom deckboards, which results in either improper pallet positioning or skewed unit load placement on the pallet. Approximately 53% of the respondents stated that they experience this issue on a monthly basis.

Push back racks are the storage systems that present the longest downtime due to pallet related issues. Results showed this system stops an average of 22 times per month for an average period of 47 minutes each time. The downtime caused by pallet related issues for this system is approximately 17 hours a month.

Results highlight AGV's as the material handling equipment with the highest overall downtime per month. Results show, on average, AGV systems stop due to pallet related issues approximately 323 minutes (5.3 hours) per month.

Recycled, wooden pallets are the main pallet class involved in pallet related downtime in semi/ fully-automated warehouses/DC facilities. This pallet class lacks consistency in their components; introducing this class of pallet into a system with low variation tolerance creates an interaction disconformity that ends up stopping the system in many different ways.

The survey also revealed that the majority of responding companies do not track the downtime they experience relating to pallet issues. This makes it difficult to determine the economic and performance impact of pallet related issues in automated systems.

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Appendix A: Questionnaire /Phase 1

Effect of pallet design on the performance of warehouse (Case Study)

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The following survey is direct exclusively to Pallet Users.

This is an interviewed survey, where the graduate student and Dr. Horvath will interview the company representative through a conference call. This document is sent as a guidance of the topics that will be discuss in this interview.

Section 1. Pallet Design

Question 1. Describe the pallet you currently use in your operation?

Example. What class (block, stringer), uses (reusable, single use), entry type (two way, partial four way, full four-way entry), style (single face, double face non-reversible, double face reversible), bottom deck orientation (unidirectional, overlapping, perimeter, cruciform), location of the deckboard to the stringer end (flush, single wing, double wing), and size.

Section 2. Pallet Compatibility Issues

Question 2. Based on your experience, could you provide specific examples for pallet related issues with the following systems:

For example. When pallet speed in flow racks cannot be properly controlled by the speed control wheel due to missing bottom deckboards, unit loads experience a significant amount of horizontal shock at the end of the flow system. This can cause unit load instability and can cause financial losses and/or injuries to workers.

Areas	Issues
Storage Systems:	
Selective/Load Beam Racks	
Flow Rack	
Drive in or Drive Through Racks	
Push Back Racks	
AS/RS Rack Systems	
Material Handling Systems:	
Conveyors (roller, chain, etc)	
Forklifts	
Pallet jacks	
AGVs	
Palletization/Depalletization Systems	
Other General Operations (Cleaning, 5S)	

Question 3. What compatibility issues between pallets and storage and material handling systems have you experienced in your facilities?

For example: When pallets are designed for AS-RS systems, the stiffness of the pallet needs to be high enough to limit the deflection of the pallet to 0.5 in. to avoid compatibility issues with the storage system.

Question 4. Based on your experience, which compatibility issue between storage vs. pallets and material handling equipment vs. pallet is the most common? Why?

Section 3. Downtime

Question 5. Based on your experience, which compatibility issue between storage and material handling equipment and pallets causes the worst downtime? Why?

Appendix B: Online Survey / Phase 2

1. Which of the following best describes the industry in which your company operates?

- Aerospace
- Tobacco
- Chemical
- Pharmaceutical
- Petroleum
- Food
- Beverage
- Other Manufacturing
- Consumer Goods
- Distribution Center
- 3PL warehousing
- Other (please specify): ______

2. Which title best describes your role in your company?

- CEO or President
- Vice President or Senior Vice President
- General Manager or Department Head
- Manager and Supervisor
- Engineer
- Other (please specify): ______

Please answer with regards to what is "typical " for your facility.

3. Could you specify the total number of pallets (all types and sizes) used in 2018?

______

4. Please specify the percentage of each pallet type used in your facility in 2018.

Please make sure the total adds to 100% in order to continue.

Block class wooden pool pallet (CHEP or PECO)	0	%
Block class plastic pool pallet (iGPS)	0	%
Stringer class new wooden pallet	0	%
Stringer class recycled wooden pallet	0	%
Block class new wooden pallet	0	%
Block class plastic pallet	0	%
Other (please specify):	0	%
Total	0	%

5. Please specify the percentage of pallet sizes used in your facility in 2018.

Please make sure the total adds to 100% in order to continue.

48 in x 40 in	0	%
48 in x 45 in	0	%
48 in x 42 in	0	%
48 in x 36 in	0	%
42 in x 42 in	0	%
37 in x 37 in	0	%
32 in x 30 in	0	%
40 in x 48 in	0	%
1200 mm x 1000mm	0	%
800 mm x 1200 mm	0	%
Other (please specify):	0	%
Total	0	%

6. Please select the level of automation your company uses for storage, material handling, and palletized, and/or depalletized equipment used in 2018.

	Automated: operations that are fully automated without any manual intervention.	Semi-automated: operations that uses automated machinery but required some manual intervention	Manual: operations that are conducted predominantly using manual intervention.	I don't have this operation.
Storage equipment	O	O	O	O
Material handling equipment (Conveyors, Pallet jack, AGV's, etc.)	O	O	O	O
Palletized/ De-palletized equipment	O	O	O	O

Thank you for your time. Our study only focuses on semi-automated and fully-automated systems.
We may ask you for feedback at a later date as we are always looking for critical data regarding all types of systems.

7. Please estimate the percentage of pallet locations for each **storage type** in your facility in 2018.

Please make sure the total adds to 100% in order to continue.

Selective racks	0	%
Push back racks	0	%
Drive in or Drive through racks	0	%
Dynamic flow racks	0	%
Floor stack or Stack rack storage	0	%
Other (please specify):	0	%
Total	0	%

8. Please indicate how often the following pallet related issues occurred during your **storage equipment operations** in 2018.

	Daily	Weekly	Monthly	Annually	Never
Poor quality or missing bottom boards resulted in jams or faults	○	○	○	○	○
Excessive pallet deflection resulted in difficulty removing unit loads from racks	○	○	○	○	○
Missing or damaged components resulted in improper placement of unit loads	○	○	○	○	○
Inconsistent pallet dimensions resulted in improper placement of unit loads	○	○	○	○	○
Missing or damaged component resulted in increased unit load speeds in gravity flow racks which caused unit load instability or pallets leaving the equipment.	○	○	○	○	○
The low coefficient of friction of pallets resulted in greater unit load acceleration in gravity flow racks and created unit load instability.	○	○	○	○	○
Incompatibility of incoming pallets with the current storage system required to re-stack the product on a new pallet or to place the unit load (product & pallet) on a pallet board.	○	○	○	○	○

9. Please select all of the **material handling equipment** that was used in your facility in 2018.

- ☐ Roller or belt conveyors
- ☐ Chain conveyors
- ☐ Automated Guided Vehicles (AGV's)
- ☐ Forklift
- ☐ Pallet Jacks
- ☐ AS/RS or stacker cranes
- ☐ Shuttle carts
- ☐ Elevators
- ☐ Pallet Magazines
- ☐ Unit load formers
- ☐ Other (please specify) ______

10. Please indicate how often the following pallet related issues occurred during your **material handling equipment operations** in 2018.

	Daily	Weekly	Monthly	Annually	Never
Loose or broken pallet components got caught in between rollers resulting in jams or faults	O	O	O	O	O
Wood splinters jammed the conveyors which had tightly spaced rollers	O	O	O	O	O
Inadequately designed pallets caused increased unit load vibrations on conveyors	O	O	O	O	O
Incorrect placement of bottom deckboards resulted in pallets being split or damaged during pallet jack handling	O	O	O	O	O
Pallet bottom deckboards that are wider than their blocks resulted in pallets being split or damaged during pallet jack handling	O	O	O	O	O
Missing or damaged pallet components caused AVG handling issues	O	O	O	O	O
Small size pallets (half, quarter and Euro) caused stability issues and product damage when handled with standard fork tines	O	O	O	O	O
Missing or damaged components resulted in improper placement of unit loads	O	O	O	O	O
Poor quality or missing bottom boards resulted in jams or faults	O	O	O	O	O
Missing or damaged components resulted in improper placement of unit loads	O	O	O	O	O
Inconsistent pallet dimensions resulted in improper placement of unit loads	O	O	O	O	O

11. Please select the **palletizer / de-palletizer equipment** that was used in your facility in 2018.

- O Conventional (rowstrip or similar)
- O Robotic

12. Please indicate how often the following pallet related issues occurred during your **palletizer/ de-palletizer equipment operations** in 2018.

	Daily	Weekly	Montly	Annually	Never
Inconsistent pallet dimensions created jams or faults.	O	O	O	O	O
Missing top deckboards resulted in unit load instability during depalletization.	O	O	O	O	O
Missing or damaged bottom deckboards resulted in improper pallet positioning or skewed unit load placement on the pallet.	O	O	O	O	O
Non-flat or uneven pallet deckboard affect the stacking stability or cause jams.	O	O	O	O	O

You are almost done!

13. Provide the estimated downtime and the estimated number of occurrences in 2018; where pallets have caused any unscheduled **downtime** in your facility's **storage equipment operations**.

Please leave the cells empty if your facility doesn't use these systems.

	Estimated downtime per occurrence (Minutes)	Estimated number of occurrences (Monthly)
Load beam racks		
Push back racks		
Drive in or Drive through racks		
Dynamic flow racks		

14. Provide the estimated downtime and the estimated number of occurrences in 2018; where pallets have caused any unscheduled **downtime** in your facility's **material handling equipment operation.**

Please leave the cells empty if your facility doesn't use these systems.

	Estimated downtime per occurrence (Minutes)	Estimated number of occurrences (Monthly)
Roller or belt conveyors		
Chain conveyors		
Forklift		
Automated guided vehicles (AGV's)		
Pallet jack		
AS/RS racks or stacker cranes		
Shuttle carts		
Elevators		
Pallet Magazines		
Unit load formers		

15. Provide the estimated downtime and the estimated number of occurrences in 2018; where pallets have caused any unscheduled **downtime** in your facility's **palletizer / de-palletizer equipment operations.**

Please leave the cells empty if your facility doesn't use these systems.

	Estimated downtime per occurrence (Minutes)	Estimated number of occurrences (Monthly)
Conventional (rowstrip or similar)		
Robotic		

16. Of the total unscheduled downtime in your facility, what **percentage** was caused by pallet related issues?

Percentage:

17. Please select the pallet type that was involved in the most pallet related downtime in 2018.

- ○ Block class wooden pool pallet (CHEP or PECO)
- ○ Block class plastic pool pallet (iGPS)
- ○ Stringer class new wooden pallet
- ○ Stringer class recycled wooden pallet
- ○ Block class new wooden pallet
- ○ Block class plastic pallet
- ○ Other (please specify): ______
- ○ Do not know

18. If you have any initiative you are currently implementing to reduce pallet related issues causing downtime, please describe them.

19. Are you willing to be interviewed with further questions that arise from this survey?

- ○ Yes
- ○ No

20. Would you like to be included in the drawing, to win a **$100 Amazon** gift card?

- ○ Yes
- ○ No

If you answered YES to participate to be interview further, please provide your information.

Name: ______

Email: ______