1.0 BACKGROUND

The project was based on three thrust areas as follows:

1. Developing the “House of Lean for Warehousing” in order to improve our understanding and to document how the Lean principles shown in the “House of Lean for Manufacturing” (also known as the “Toyota House”) apply to the primary operations performed in a warehouse such as put-away, replenishment, and order picking.

2. Identifying fundamental operational or asset-based changes required to implement Lean principles in a warehouse, and explaining how some of the current practices in warehousing are compatible or incompatible with a Lean warehouse. The second step focused primarily on developing a VSM template for the type of warehouse selected for the project, including a better understanding of value-add work, incidental work (also known as non-value-add but necessary work), and non-value-add work (also known as “pure waste”). Since the customer needs depend on the type of warehouse being considered, this part of the project includes a classification system we developed for warehouses.
3. A technical “deep dive” concerned with picker dispatching with takt time, planned cycle time, and order due dates taken into account as opposed to simple or traditional approaches based on simply minimizing picker travel times/distances.

Our two industrial partners on the project were Menlo Worldwide Logistics and Navistar International Corporation (formerly International Harvester Company). Menlo, a unit of Con-way, specializes in the integration of all functions across the supply chain, from sourcing of raw materials, through product manufacturing to the distribution of finished goods. The company is one of the leaders in Lean warehouse applications. Our second partner, Navistar, produces International® brand commercial trucks and military vehicles, IC buses, MaxxForce™ diesel engines, and Workhorse chassis for motor homes and step vans. It is a private-label designer and manufacturer of diesel engines for the pickup truck, van and SUV markets. Through Navistar Parts, the company also provides truck and diesel engine parts warehousing and service. Navistar Parts is the division we worked with for the project. Neither industrial partner directly contributed funds towards the project but both companies contributed substantial staff time and input for the project. Furthermore, Navistar’s Parts Distribution Center (PDC) in Las Vegas, NV played a key role in the project. Some of the examples and applications used in the project are from the Las Vegas PDC, which was a testbed PDC for Lean applications.

The project team consisted of the PI (Prof. Yavuz Bozer) and a U-M Ph.D. student (Rebecca Britten), with assistance provided by the Menlo team and the Navistar team as follows:

- Pedro Fernandez - Navistar (Manager, Las Vegas PDC)
- Beth Myres - Navistar (Manager, Distribution Services, Las Vegas PDC)
- Tim Coppe - Navistar (formerly Manager, Dallas PDC; now at corporate)
- Robert (Rob) Wahlman - Navistar (Corporate Lean Leader)
- Sean Mulcahey - Navistar (Corporate)
- Joe Kory - Navistar (Corporate, VP)
- Mike Wilusz - Menlo (staff)
- Brian Dean - Menlo (staff)
- Jeff Rivera - Menlo (staff)
- Tim Sroka - Menlo (staff)

During the execution of the project, naturally, some changes occurred to the project team. Beth Myres, who was heavily involved early in the project, left Navistar in early 2011. Tim Koppe’s involvement with the project decreased in late 2010, and it remained minimal through the conclusion of the project. This was perhaps due to his promotion from Dallas PDC manager to a corporate position in Navistar’s Chicago office. Mike Wilusz and Brian Dean made valuable contributions at the start of the project but their involvement also decreased in 2011, and it remained minimal through the conclusion of the project. In their place, in a team meeting (that
took place on Dec. 9-10, 2010) it was decided that Navistar would provide additional leadership for the project at the corporate level, and Menlo would provide more continuity by establishing a single point of contact for the project. With that in mind, Robert (Rob) Wahlman, who has extensive experience in Lean, joined the project team as the lead Navistar person. Rob’s responsibility for Lean extends well beyond the Las Vegas PDC. He has corporate responsibility to lead the Lean effort at Navistar, including a new PDC the firm opened outside of Chicago. On the Menlo side, Tim Sroka was designated as the single point of contact for Menlo. Both changes helped keep the project on track and reenergized the team. We deeply appreciate the time and effort both the Navistar staff and the Menlo staff devoted to the project. We learned a great deal from each team member and their insights and experiences. We are especially grateful for Joe Kory’s leadership and support during the project, Pedro Fernandez’s hospitality in welcoming the team and opening the doors to the Las Vegas PDC, and Jeff Rivera’s vision and encouragement throughout the project.

Additionally, Rebecca Britten completed a three month internship with Toyota Motor Sales at the North American Part Center in Hebron, KY (NAPCK). Experiences she gained during this internship, provided the foundation of her understanding of the Toyota Motor Sales Service Part supply chain strategy and structure.

2.0 INTRODUCTION

Lean manufacturing started gaining attention among manufacturing professionals in the United States (US) around the early 1980s under the name “just-in-time” systems. Since that time, significant progress has been made in Lean manufacturing in the US in terms of education and training as well as developing an increasing number of successful applications in industry. Although some of them were not documented thoroughly, many examples emerged of manufacturing companies implementing Lean tools/techniques on the factory floor. Most companies gradually realized, however, that concentrating their efforts on just the factory floor did not allow them to address the broader supply chain issues. At the same time, outsourcing and rapid globalization led to significantly expanded and deeper supply chains. Thus, supply chain management (SCM) emerged as a “hot topic,” with various applications of Lean reported in the supply chain/logistics arena.

Although warehouses and distribution centers are vital facilities in a supply chain, applications of Lean in warehousing has been lagging compared to manufacturing and SCM. This created a gap of knowledge for Lean warehousing. To address this gap, and to improve our understanding of how Lean is applied to warehousing, we embarked on a project that was composed of three thrust areas summarized in Section 1.0.
The third thrust area, that is, the technical deep dive concerned with picker dispatching with takt time, planned cycle time, and order due dates taken into account constitutes the primary intellectual thrust for the project. However, we trust that the training materials we developed, and the definitions we developed around value-add versus non-value-add work in a warehouse will provide a solid foundation for future studies in Lean warehousing.

### 2.1. Lean in Manufacturing, Supply Chain, and Warehousing

Lean manufacturing, back when it was known as a “just-in-time” system, started gaining attention among manufacturing professionals and decision-makers in the US around the early 1980s. The primary focus in those years was reduction of inventories, although a number of early-adopters took inventory reduction to mean “let your supplier carry/own the inventory.” Furthermore, although excess inventories is considered a major source of waste under Lean manufacturing, adopting Lean only to reduce inventories represents a very narrow view of Lean. Despite such an imperfect start, however, significant progress has been made in Lean manufacturing in the last three decades in the US both on the education and training side (as reflected by the number/scope of publications and resources available on Lean manufacturing) as well as on the industrial side (as reflected by the number and diversity of companies that began exploring and applying Lean concepts in their operations).

While the successful implementation of Lean has not been “easy” for many US manufacturing companies, there is a significant body of both conceptual and experiential information available on Lean manufacturing to help manufacturing professionals put Lean into practice in their companies. Not surprisingly, a majority of manufacturing companies that embarked on Lean started their journey with a focus on the factory floor. As a result, many examples have emerged of manufacturing companies that implemented a variety of Lean tools and techniques (such as kanban-based pull systems, set-up time reduction, visual management, and 5S) on the factory floor with varying degrees of positive impact.

However, after a few years (or perhaps when most of the “low-hanging fruit” were picked), many companies realized that concentrating their efforts on just the factory floor amounted to creating “Lean islands,” and it did not allow them to address some of the larger, system-wide issues, which constrained the impact of the gains derived from improving their manufacturing operations. In other words, many companies realized that they needed to look beyond the four walls of the factory in order to advance to higher levels of Lean and explore greater benefits. At the same time, outsourcing and rapid globalization began to take place, and before long, many manufacturing companies were facing significantly expanded and deeper supply chains, especially for their inbound parts and supplies. As a result of the above two developments, supply chain management and design (SCMD) emerged as a “hot topic” both for academia and practitioners, and naturally, many manufacturing professionals and educators/researchers started working on applying Lean in the supply chain; see [2], [8], [14], [17], [19], [20], [25], [26], [27],
[30], [32], [33], and [35], among others, as examples of scholarly publications and books that focus on applying Lean in the supply chain.

Compared to SCMD, the number of publications/resources that focus on how to apply Lean in logistics is quite small. (Due to limited space and scope, we will not present a discussion on SCMD versus logistics. A recent and informative article on the subject is presented in [18].) In [10, p. 5], logistics is defined as “the flow of material, information and money between consumers and suppliers.” However, according to [4], the above definition is too broad (as it appears to encompass production itself) and that “consumers” should be replaced by “customers” since reference to consumers “restricts the discussion to consumer goods, to the exclusion of capital goods, whose end users, by definition, are not consumers.” Recognizing the boundary between logistics and production, in [4] the author argues that “logistics is comprised of all the operations needed to deliver goods or services, except making the goods or performing the services.” We generally agree with the modified definition of logistics provided by [4], although we note that there are numerous instances when the core service performed involves logistics operations and, therefore, one may not always find a dividing line between logistics and the service performed.

While there are alternative definitions of logistics, and various attempts to clarify the relationship between SCMD and logistics, the fact is that some ambiguity or gray area will remain, which is not as undesirable as it may first seem since trying to draw a clear or rigid boundary between these two subjects will probably reduce the beneficial interaction and synergistic gains between the two. Hence, we adopt a plain view for the purposes of the report, and simply state that a Lean supply chain and a Lean logistics system are both essential for long-term success. That is, having Lean factories alone is not adequate. Rather, the full benefits of Lean are often achieved when Lean factories are integrated into a Lean supply chain that operates as a Lean logistics system, which brings us to one of the key, non-manufacturing facilities found in most supply chains, namely, the warehouse or the distribution center (DC) as depicted in Figure 1. (Figure 1 is based on a study of Toyota’s US parts distribution system presented by [34].)

![Figure 1](image.png)

**Figure 1.** Lean Warehousing as a key component of Lean logistics. Taken from [16].
According to [11], “warehouses play vital roles in the supply chain.” Yet, compared to the collective body of information and knowledge available on Lean manufacturing, Lean supply chain, and Lean logistics (in decreasing order of prevalence), there is very little information on Lean warehousing. Although some resources in Lean supply chain/logistics devote some attention to Lean warehousing (see, for example, Chapter 4-5 in [4], and Chapter 8 in [19]), and a number of high-quality texts are available for improving warehouse productivity through traditional means (see, for example, [11]), the subject of Lean warehousing remains largely unexplored and largely undocumented, especially in the academic community.

In the industrial community, on the other hand, some companies such as Menlo Worldwide Logistics, an operating unit of Con-way Inc., have embarked on Lean warehousing at least seven years ago. In fact, on Menlo’s web site (Figure 2), the company states that the:

“… Lean warehousing philosophy ensures continual operational improvements, waste elimination and high ongoing operating efficiencies. There is a sharp focus on labor productivity, enabled by optimized layout, system-directed putaway and task interleaving. In addition to operating efficiencies, Lean warehouse operations mean fewer errors, faster turnaround times and process standardization across facilities. Menlo Worldwide Logistics’ Lean facilities utilize Six Sigma, statistical process control and ISO processes to create a mistake-proof operating environment.”

A number of articles that describe Menlo’s impressive accomplishments in this area have been published by prominent organizations (see, for example, [3], [5], and [9]). In fact, according to [5], Menlo Worldwide “reports that warehouse productivity improved 32 percent …, measured by gains in lines per hour. Defects, measured as the error rate, dropped by a whopping 44 percent. The on-time percentage for shipments was north of 99 percent …, hitting 100 percent in eight of 11 months.” Such numbers make it clear that Menlo Worldwide made significant progress in improving their operations using Lean warehousing. However, particulars of the Lean tools and techniques used by Menlo are, by and large, unique to Menlo’s operations, and the applications at least so far have been limited to Menlo warehouses. That is, a Lean warehousing know-how or community has not formed yet around Menlo’s accomplishments.

Another third-party logistics provider that appears to have embarked on Lean to improve their logistics and warehousing services is STL Warehousing in Australia (see Figure 3). The company works “with small to medium sized pharmaceutical, healthcare and medical device companies that have a need for sophisticated warehousing and distribution services,” and according to their web site, they “base (their) strategies on lean thinking practical solutions.”

Another resource for Lean warehousing in the industrial community is a book authored by a long-time practitioner in the field (see [1]). Although the book reflects years of experience and warehousing know-how, and the author gives time-tested, common-sense advice while drawing much-needed attention to the subject of Lean warehousing, most of the topics are discussed only in general terms, and little or no basic Lean tools (such as value stream mapping for the warehouse, or establishing takt time for the order pickers) are presented in the book with sufficient detail. (There are also a number of consultants or consulting-based resources available for Lean warehousing. We intentionally left out the consulting sector from our review. The reader may refer to [29] for an informative article on Lean warehousing written from an industrial perspective.)

As we remarked earlier, the subject of Lean warehousing remains largely unexplored and largely undocumented in the academic community. Of course, warehousing and certain operations associated with it (such as picking and sorting) have been the subject of much academic research as evidenced by the extensive survey papers presented, for example, by [22] and [15] for warehouse design, control, and operations, by [7] for order picking, and by [21] for Automated Storage/Retrieval Systems (which attracted significant interest from the academic community).

Although one can argue that certain links can be established between Lean warehousing and some of the techniques developed/studied in the papers described in the above survey articles, none of the papers published in warehousing focus directly on Lean warehousing, and more importantly, the techniques and metrics used in the papers published to date are more often aligned with conventional warehousing, such as minimizing picker times/distances for order
picking as opposed to considering order due dates, takt times, and planned cycle times for the pickers. To the best of our knowledge, as of the publication date of this report, there are no scholarly, refereed published papers that focus on the subject of Lean warehousing.

There are, however, two Master’s theses and a Ph.D. dissertation on the subject. Interestingly, both of the M.S. theses are out Europe. The first study [13] is concerned with applying 5S at a raw materials and components (plus tools) warehouse used by a shipbuilding company in Norway (Ulstein Verft AS). According to the author, the company was focused on Lean shipbuilding, and “subsequently, the scope of implementation of Lean (was) extended to other departments and in search for performance improvement and value creation to the processes, the shipyard … started the deployment of Lean 5S in the warehouse.” At the time the study was concluded, the implementation of 5S in the warehouse was still in process. Therefore, the author does not provide a complete description of the process or a follow-up, and “the scope of (the study shifted) to a description of the problem areas in the warehouse (receiving, storage, picking, and shipping) which led to the need of the implementation of 5S.” The study was conducted “to investigate the implementation of Lean 5S in the warehouse,” and the expected outcome was “to get an overview over how the processes are/were rolled out and what are/were the possible implications connected to the deployment of (5S).” Implementation concerns such as cultural transformation, resistance to change, and personnel involvement in 5S are also addressed. As indicated by the title, the scope and focus of the study is limited to 5S. Other Lean considerations, such as value streams, flow, pull, and takt times, are not addressed.

The second M.S. thesis [28] is based on examining, comparing, and discussing potential Lean applications in the warehouses of three companies selected for the study. The authors present a fairly thorough comparison of the three warehouses, and they discuss the application of (or lack of) Lean implementation in the three facilities. While the study provides helpful insights into Lean warehousing, it is primarily a qualitative study. Furthermore, subjects such as picker routing are addressed in a traditional fashion based on distance minimization using the Traveling Salesman Problem (which has been addressed by previous studies concerned with picker routing)—although the authors do emphasize the importance of leveling the workload in the picking process through the use of the heijunka Lean principle. The study also considers ABC analysis and slotting, which is again a subject explored extensively by previous publications. The authors conclude that tools for further leveraging Lean in warehousing should “… be tools that primarily improve the flow and increase the visibility; (used) together with efforts for avoiding (non-value-adding) processes and wastes.”

The third academic study on Lean warehousing [24] is concerned with developing a model/tool to perform a formal and comprehensive Lean implementation assessment in a warehouse. According to the author, the assessment tool “provides specific, actionable items that can be used in practice to further implement lean production and provide useful information to monitor the initiative’s progress and make better resource decisions.” To validate the assessment tool,
twenty-eight assessments were performed at twenty-five facilities. The assessment is performed along the following dimensions or Lean constructs: 1. Standardized Processes, 2. People, 3. Quality Assurance, 4. Visual Management, 5. Workplace Organization, 6. Lot Sizing, 7. Material Flow, and 8. Continuous Improvement. Subcategories are established for each dimension. For example, material flow is assessed in terms of the presence (or effectiveness) of pull systems, leveled flow and work, first-in-first-out (FIFO), layout and zones, velocity and slotting, travel distance, cellular structure, and demand stabilization, and cross-docking. The author provides justifications, explanations, and assessment assistance for each construct.

We note that the above assessment tool was used as part of the MHIA project at the Las Vegas PDC of Navistar. Becoming familiar with the tool and using it to assess a real-life warehouse was very helpful for the project PI, Prof. Bozer. However, the results of the assessment are not included in this report since it contains private information for Navistar.

In summary, there is no doubt that Lean warehousing is gaining momentum both in terms of academic research and industrial applications. However, available resources and information on Lean warehousing is limited compared to well-established areas such as Lean manufacturing and emerging areas such as Lean healthcare.

### 2.2. Types of Warehouses

For the casual observer, or to someone who is not directly involved in warehousing, all warehouses may appear to be the same—just a big building with large storage racks, fork lifts running around, some conveyors, with inbound trucks being unloaded at one end, and outbound trucks being loaded at the other. In reality, warehousing professionals understand that not all warehouses are created equal, and different types of warehouses exist to fill different roles and provide certain functions. To implement Lean warehousing successfully, we believe that the discussion needs to start with understanding the various types of warehouses that are in use. Of course, the principles of Lean warehousing do not change by the type of warehouse but how those principles are interpreted and implemented are impacted by the type of warehouse one is dealing with.

Numerous studies and publications provide us with various ways to classify and categorize warehouses. For example, in [11], seven types of warehouses are identified, which are described below with minor changes in wording:

1. *Raw-material and component warehouses* (to hold raw materials at or near the point of induction into a manufacturing process).
2. *Work-in-process warehouses* (to hold partially completed parts/assemblies while they are going through the manufacturing operations).
3. Finished good warehouses (to hold inventory to buffer against variations in customer demand).
4. Distribution warehouses (to accumulate and consolidate products from various sources for combined shipment to various customers).
5. Fulfillment warehouses (to receive, pick, and ship small orders for individual customers, that often represent consumers).
6. Local (or regional) warehouses (distributed in the field in order to shorten transportation distances to permit rapid response to customer demand; frequently, single items are picked, and multiple shipments may occur in one day).
7. Value-added service warehouses (to perform services such as labeling, light assembly, and kitting).

According to [23], on the other hand, warehouses can be classified by (also see [13]):

- Their stage in the supply chain (raw materials, work-in-process, or finished goods).
- The geographic area they serve (national, local, regional, or international).
- The type of products they store (for example, small parts, large assemblies, frozen food, perishable items, hazardous goods, and so on).
- Ownership (user-owned, third-party, public warehouse, and so on).
- Usage (for example, a warehouse dedicated to one company versus a warehouse shared by multiple companies).
- Their dimensions and area (classification according to the storage dimensions/area).
- Their storage height (such as low-bay or high-bay warehouses).
- The type of equipment they use (ranging from mostly manual operations to highly automated equipment).

Yet another classification scheme is provided by [31] as follows:

1. Distribution warehouses—products are collected (sometimes also assembled) from different suppliers and subsequently redirected or sorted to individual customers.
2. Production warehouses—storage of raw, WIP, and finished goods in a production facility.
3. Contract warehouses—facility providing warehouse services to one or more customers.

We agree with the above classification schemes; they each serve a useful purpose. However, we note that, according to The Lean Enterprise Institute (LEI) ([www.lean.org](http://www.lean.org); see “Principles of Lean”), the first step in the “five-step thought process for guiding the implementation of lean techniques” is to “specify value from the standpoint of the end customer by product family.” That is, the starting point and focus in Lean is the “customer.” Understanding the customer, recognizing his/her needs, and knowing what constitutes value for the customer are essential for grasping and implementing Lean. (We will later return to the five steps.)
Hence, for the purposes of this study, the project team identified the following warehouse types, which is similar to the list provided in [11] except that each warehouse is classified only according to the “customer” it serves, which also corresponds to the function performed by the warehouse:

1. Raw Materials and Components Warehouse: Its primary role is to support a manufacturing customer. It holds raw materials, components, and/or kits for production, and it is typically located close to a manufacturing plant (usually within 3-5 miles) or sometimes right next to a manufacturing plant. Depending on the specific type of application and the organization, such warehouses are also known as a “logistics center,” “manufacturing support center,” or “manufacturing material flow center.” Such warehouses act as a consolidation point for the manufacturing plant they support, but they also often perform value-add operations such as light sub-assembly, kitting, sequencing, kanban picking, etc. In some cases, these warehouses become an extension of the assembly line, allowing for only 1 to 4 hours of line-side inventory, and they act as a “supermarket” for suppliers that are not local.

2. Finished Goods Warehouse: Its primary role is to store the output of a manufacturing firm in order to meet the demand from the customer of the manufacturing firm. Typically it is located close to the manufacturing plant. It is often used to address demand-supply balance issues and lead time concerns. A finished goods warehouse becomes necessary when a manufacturing firm, for various reasons, uses a “make-to-stock” approach.

3. Distribution Warehouse: Also known as a distribution center, a distribution warehouse functions essentially like a junction box in a supply chain; that is, goods are received from multiple points and they are shipped to multiple points which represent individual customers. Typically, incoming goods are sorted into outgoing shipments, with minimum storage within the facility.

4. Retail Warehouse: Its primary function is storage of goods and picking of customer orders. Such warehouses are used by e-tailers like Amazon.com and retailers like OfficeMax.com. The customer is often an individual consumer. Retail warehouses are often characterized by a wide range of SKUs, and small orders (that is, few line items per order) placed by retail consumers. They are typically located close to customer demand points or major logistics hubs. Another type of retail warehouse is a warehouse that holds goods for multiple retail stores. For example, a furniture retailer like Art Van Furniture relies on a central (retail) warehouse to hold goods and ship them to a store or to an individual customer when an order is placed. In fact, in some cases, the customers travel to the central (retail) warehouse to pick up their order.
5. Service parts (or spare parts) warehouse: This type of warehouse is similar to a retail warehouse but it is often associated with a manufacturing firm. The customers are either individual consumers or the dealers who service the products made by the manufacturing firm. The order size may range from small to large, and the customer base may include commercial customers and businesses as opposed to just consumers, which is typically found in the customer base of a retail warehouse.

6. Consolidation/Deconsolidation (Con/Decon) Warehouse: Such warehouses are often found close to coastal cities or container terminals. It is used typically to break down large incoming shipments (say, from a container ship) into smaller quantities prior to land transportation, or the opposite (that is, accumulating smaller incoming shipments into large shipments destined for container ships). A con/decon warehouse (or a “break bulk” warehouse) can also be found in facilities such as hospitals, where medical supplies shipped in bulk form from the distributor are broken down into smaller quantities required for delivery to the point-of-use within the hospital. A variety of customers are served through con/decon warehouses, ranging from shipping lines to container terminals, trucking companies, and logistics service providers.

As we remarked earlier, Lean warehousing principles do not change by the type of warehouse. Thus, our intent is to keep the results of the study applicable to all warehouse types as much as possible. However, for the purposes of providing examples, and the technical “deep dive” in section 4, we focused on warehouse type 5, that is, a service parts warehouse, which is also the type of warehouse operated by Navistar Parts, including their Las Vegas PDC.

2.3 House of Lean Warehousing

Under “principles of lean,” the Lean Enterprise Institute (LEI) outlines a “five-step thought process for guiding the implementation of lean techniques” as follows (see also Figure 4):

1. Specify value from the standpoint of the end customer by product family.
2. Identify all the steps in the value stream for each product family, eliminating whenever possible those steps that do not create value.
3. Make the value-creating steps occur in tight sequence so the product will flow smoothly toward the customer.
4. As flow is introduced, let customers pull value from the next upstream activity.
5. As value is specified, value streams are identified, wasted steps are removed, and flow and pull are introduced, begin the process again and continue it until a state of perfection is reached in which perfect value is created with no waste.

The above steps capture some of the key components of Lean but the “principles” seem to be blended with “implementation.” Furthermore, “flow” is mentioned explicitly but “quality” is
not. (“Perfection” would imply perfect quality of course but we believe “quality” merits explicit mention just like “flow.”)

![Figure 4. Principles of Lean. (July 7, 2012).](http://www.lean.org/WhatsLean/Principles.cfm)

Screen shot copyright is held by the Lean Enterprise Institute, Inc.

Using the above 5-step process from LEI as a framework, in [28] the authors discuss the principles of Lean warehousing. However, they preface the principles with the following statement:

“There is a contradiction between Lean Thinking and Warehousing practice today, since lean strive at being just in time with a pull flow with no batching production and with preferably no inventory kept between the different processes. This is an ideal scenario. In real life there exist variation in demand, uncertainty in lead time and long lead times that cannot be fully predicted. This makes a warehouse necessary to provide items to the production, assembling or customer in time.”

The above wording suggests that the authors consider warehousing only in the context of manufacturing. That is, warehousing is basically defined as a non-value-add but necessary waste, which is probably a fair description for warehouse types 1 and 2 but certainly not the case for other types of warehouses such as warehouse types 4 and 5 in our list. We will return to the question of waste versus value-add but we already see how the type of warehouse being considered can play a big role in framing the discussion on waste versus value-add.

Perhaps an alternative approach to describe the principles of Lean is to consider the “House of Lean” or the “Toyota House,” which appears in slightly different forms in various Lean manufacturing texts. The one shown in Figure 5 is the “Toyota House” we have been using in the University of Michigan Lean Manufacturing Certificate Program (which is one of the longest-running and heavily-attended university-based Lean manufacturing training programs in the world). Since a foundation is needed to properly support a house, the components listed under “operational stability” in Figure 5 are key ingredients needed to achieve Lean flow (left-
hand side column) and high quality (right-hand side column). In some Lean texts, other Lean components (such as 5S) are also included in the foundation.

Figure 5. The “House of Lean” as shown in the University of Michigan Lean Manufacturing Certificate Program.

In the “flow column,” one of the key components is “continuous flow,” which is also known as “one-piece flow.” Very briefly, continuous flow refers to the make-one, move-one principle in Lean manufacturing, where parts are made in batch sizes of one, and moved to the next process in batch sizes of one, thus avoiding excess inventories and unnecessary delays caused by large production lot sizes and/or large transfer (i.e., material handling) lot sizes. Benefits of one-piece flow are well-understood and widely documented in Lean manufacturing.

The components shown in the “quality column” are generally aimed at building quality into the product by practicing “quality at the source,” and at the same time, allowing the operators to perform value-add work while automatic-cycle machines are monitored not by people but by sensors (that stop the machine and alert the operator if an abnormal condition is detected). Also, visual controls are used to help operators, team leaders, and anyone else on the shop floor to quickly distinguish normal from abnormal, and to easily determine whether or not a process is under control/on track, without consulting a computer terminal or looking through reams of data.

Last, the roof of the house represents the desired outcomes (higher quality, lower cost, and shorter delivery times), while the occupants of the house are of course the hourly operators, team
leaders, group leaders, and management, all of whom are focused on eliminating waste and delivering value to the customer through continuous improvement.

Given the observation we made earlier, that is, Lean manufacturing started on the factory floor but soon moved to supply chain/logistics, a number of individuals have developed the “Toyota House” for supply chain/logistics; for example, see [6, p. 55], among others, which is shown below as Figure 6.

![Figure 6](image.png)

**Figure 6.** The “House of Lean” for Supply chain/Logistics.” (Taken from [6].)

Before we present the House of Lean for Warehousing, it would be desirable to present the principal operations performed in a warehouse, which has been depicted before in various texts. Although each text varies slightly, we believe the operations shown in Figure 7 cover most of the warehouse types we discussed earlier.

![Figure 7](image.png)

**Figure 7.** Principal Operations in a Warehouse.
The operations shown in Figure 7 are self-explanatory and well-understood by those who are familiar with warehousing. We, therefore, will not provide an explanation for each operation. (For a quick primer on warehousing, the reader may refer to the introductory chapters in texts such as [11], among others.) However, we do wish to comment on the “alternative paths” shown in Figure 7. For example, the reader may note that there are two alternative paths from “main storage” to “loading/shipping.” One of the paths involves sorting, the other path does not. (In some warehouses, the main storage area is used only to replenish the forward picking area. In such cases, one would remove the direct path from main storage to loading/shipping.) There are also alternative paths from “forward picking” to “loading/shipping.” The above alternative paths imply that the operation in question is optional, it may or may not take place. That is, items pulled out of the forward picking area may or may not need sorting, which often depends on how the items are picked. Also: 1. One may add a “packing” and/or “check/verify” operation to Figure 7, prior to “loading/shipping,” which would be appropriate for many warehouses but we left it out to keep the Figure simple; and 2. We assumed that cross-docked items would need to be sorted since the sequence/timing of how cross-docked items are received does not in general match the sequence/timing of how the cross-docked items are loaded onto outbound trailers. Last, some of the operations depicted in Figure 7 involve “staging,” although we did not show staging as a separate operation.

Given the warehouse operations shown in Figure 7, we developed the Lean house of Warehousing shown in Figure 8. The components for the Lean house of Warehousing are remarkably similar to those shown earlier for the House of Lean for Manufacturing. However, as we explain below, the role, impact, and interpretation of the components must be done within the framework of warehousing in order to understand and implement them successfully.

![Figure 8. The “House of Lean” for Warehousing.](image)
Consider first the components in the foundation. Standardized Work, which is fairly well-known and practiced in manufacturing (although it continues to present a challenge for some companies), is a relatively new concept for warehousing. We note that “standardized work” is not the same as “standardization.” That is, various equipment standards developed for pallets, storage racks, conveyors, dock doors, etc. is not what is meant by standardized work, although such standards can be used to support standardized work. Rather, standardized work focuses on how work is performed by people, and it aims to establish best methods for each job type by developing standard methods, standard process/batch sizes, and standard times for key functions including unloading, put-away, picking, packing/sorting, and shipping.

Preventive maintenance (PM) is concerned with ensuring that all the equipment used in the warehouse is maintained properly to provide around-the-clock uptime. The lessons learned from manufacturing in PM apply to warehousing as well; that is, we cannot become Lean with poor equipment uptime. Hence, ensuring that the dock equipment, the pallet jacks, the fork lifts, the order picker trucks, the pick carts, the packing stations, and so on are up-and-running is a key component for Lean warehousing.

Robust processes generally means having processes that perform what is needed in a way that is consistently repeatable and effective. It also means having processes that can accommodate a wide range of operating conditions and can deal with variations in those conditions. For example, certain automated picking systems may lack robustness since the automation may be inflexible relative to the characteristics of the items being picked and/or the required throughput capacity of the system. Certain manual picking systems may also lack robustness since they may involve excessive walking for the pickers.

Supplier integration in Lean manufacturing plays a key role both in terms of achieving just-in-time deliveries and in terms of ensuring the availability of high-quality components at competitive prices. Lean companies seek to establish long-term partnerships with their suppliers to achieve the above goals. For Lean warehousing, the role and impact of supplier integration depends on the type of warehouse. Clearly, for warehouse type 1 (raw materials and components), supplier integration plays the same role it does in Lean manufacturing. For warehouse type 2 (finished goods), however, we note that the “supplier” to the warehouse is the manufacturing system which makes the goods. In order for the finished goods warehouse to serve its customers better, the manufacturing system(s) that supply the warehouse must be able to supply on a continuous and reliable basis with short lead times. Otherwise, one would find excess inventories in the finished goods warehouse, which would obviously be a source of waste.

For warehouse type 5 (service parts), on the other hand, supplier integration is also a key component of Lean since the core service such a warehouse provides to its customers is the availability of the service parts when the customers need them. In many cases, customers of
such warehouses are either dealers or individual customers (which may be an industrial customer or a consumer). The dealers order the parts either as a stock item or because they have an immediate customer waiting for the part. Whether it’s a consumer with a broken home appliance, or an industrial customer with an expensive machine or heavy equipment that broke down, service parts warehouses play a key role by making sure the parts needed for repair are available with short notice. However, filling such a role may lead to excessive inventories in the warehouse, especially when one considers the fact that such warehouses are called on to support an ever-expanding array of products and customers. Hence, ensuring a steady and reliable supply of parts from the suppliers to the service parts warehouse is essential to avoid excess inventories. Otherwise, most service parts warehouses compensate by carrying excess inventories since shortage of a part represents a failure in the core mission of such a warehouse. Two other challenges related to excess inventories in service parts warehouses are very low turnover parts and obsolete inventory.

The two columns of the Lean house are “flow” and “quality.” In Lean manufacturing, the flow column is essentially “one-piece flow” also referred to as “$1 \times 1$ flow” (or ” make one, move one”). It is concerned basically with reducing the production batch sizes as well as the material handling batch sizes. As is well-known in Lean manufacturing, the production batch size is reduced by reducing or eliminating machine set-up. The material handling batch size, on the other hand, is reduced by reducing the material handling distances via one-piece flow manufacturing cells and internal milk runs that supply those cells.

Compared to manufacturing, unless light assembly or kitting is performed, no “production” takes place in a warehouse. However, work (often in the form of unit loads and/or containers) is “generated” during various processes in a warehouse, such as receiving, replenishing the forward area, and picking the orders. Hence, small “production” lot sizes means performing the above processes in small batches. In some cases, this would be difficult to achieve. For example, material often arrives at receiving in large batches such as truck loads, which is undesirable in terms of Lean. (External milk runs can be used to reduce the batch size of individual part numbers on the truck but nonetheless, the arrival of a full truck means the process to be performed, i.e., unloading, starts with a large batch size.) In the process of unloading the truck, incoming large batches are often broken down into smaller lots for subsequent processes such as put-away, which often means the incoming parts must be staged at receiving.

Likewise, work is generated when order picking is performed. Picking the orders in large batches (such as “wave picking” and “batch picking” multiple orders at a time) is contrary to one-piece flow. In fact, for order picking, one-piece flow means the orders must be processed (i.e., picked, verified, and packed) one order at a time, which we will refer to as one-piece order processing (or “$1$-OP”) in this report. Although verification and packing are often performed one order at a time, the primary reason orders are not picked one order at a time in many
warehouses is due to long “set-up” times, which takes different forms depending on the type of order picking system used.

Consider a picker-to-part order picking system, which is also known as in-the-aisle order picking. A common approach used for such picking systems is the walk-and-pick system or its slightly modified version known as pick-to-belt or pick-to-conveyor systems. (The reader may refer to [11], among many others, for information on order picking systems.) In such a picking system, set-up occurs in two forms: 1. The “dwell time” spent by the picker at the start and end of pick trip; it usually accounts for tasks such as picking up empty containers and the pick list at the start of a pick trip, and discharging the picked items at the end of a trip; and 2. The walk time from one pick location to the next pick location. (Strictly speaking, the picker’s walk time can be interpreted as the load/unload time in manufacturing because walking occurs for each pick the same way load/unload times occur for each part processed in a manufacturing system.) Due to the dwell time and the walk times, in most walk-and-pick systems, multiple orders are batched into one pick trip. In other words, based on the same justification used in pre-Lean manufacturing systems (i.e., a large batch size is thought to be justified because it compensates for the long set-up times), multiple orders are batched into one trip to compensate for the walk times.

As set-up time reduction in manufacturing helps eliminate large production batch sizes, eliminating the picker walk time would allow 1-OP in the warehouse. Readers familiar with order picking would recognize that one way to eliminate picker walking is to use an opposite approach, namely, a part-to-picker system (also known as end-of-aisle order picking). With such order picking systems, the containers are retrieved (one at a time or in small groups) and brought to one or more pick stations where the picker performs the picks. After the picks are performed, the containers are returned to the forward (or storage) area.

While it eliminates picker walking, a part-to-picker system does not necessarily support 1-OP. This is primarily because a part-to-picker system does not eliminate the “set-up time.” Rather, it transfers the set-up time from the picker to the material handling system which must move the containers between the storage area and the pick stations. Since the time to move a container (or group of containers) is non-negligible, orders are often picked in batches because when a container (or group of containers) is/are retrieved, a “set-up” has been incurred and, therefore, multiple picks are made from each container to fill multiple orders at the same time. This is true even for more recent and automated applications of part-to-picker systems such as the Kiva system, where unit load AGVs, called “bots” by the vendor, bring multiple containers, placed in small racks, to the picking stations. In one Kiva application, for example, orders are reported to be picked 16 orders at a time. Once an AGV picks up a container and moves it to the picking station, multiple orders are picked to compensate for the container retrieval and subsequent storage time. Whether it’s a Kiva system, or a more traditional part-to-picker system (such as
picking from carousels or a miniload AS/RS), implementing 1-OP with a part-to-picker system would significantly increase the workload on the material handling system because the same container would have to be retrieved multiple times to fill different orders.

Our conclusion is that, using known methods for order picking, unless a new, paradigm-shifting technology is introduced, whether it’s a picker-to-part system or a part-to-picker system, there is no obvious way to eliminate set-up times and implement 1-OP. Hence, we believe the focus will be on set-up reduction, which means reducing the picker walk times (or container storage/retrieval times) by using better slotting techniques, ABC analysis, order profiling, and better picker routing techniques, which are not new to warehousing. (We note that exceptions to the above conclusion may occur. For example, when picking customer orders from a carousel at a dry cleaner, it is possible to practice 1-OP due to the low throughput volume, and the fact that customers join the queue and are served one at a time. Another exception is automated order picking systems such as the A-frame, where small to medium-sized items that belong to the same order are automatically dropped onto a belt conveyor. Since there is no picker, and no container storage/retrieval, such systems can achieve 1-OP. However, in typical applications, multiple orders re dropped onto the belt as separate clusters because the items that are picked must travel on the belt to a packing station. Also, A-frame based automated pick systems create a significant replenishment workload since the items are replenished by hand, one item at a time, from the backside of the A-frame, which is typically based on a flow rack.)

The second column in the Lean house is the quality column since one-piece flow with poor quality would be far from ideal. The primary principal for quality in Lean manufacturing is “quality at the source” as opposed to inspecting quality into the product. That is, errors and quality problems must be addressed at the source, and no defective products should be passed to a downstream operation. In warehousing, a “defect” could be generated in a number of ways. Some common sources of defects are: 1. During putaway, an SKU is stored in the wrong location; 2. During picking, the picker picks the wrong SKU, or he/she picks the wrong quantity; 3. The right SKU and the right quantity are picked but during picking or sorting, the picked items are merged with or packed with the wrong order. Of course, other errors such as errors in the customer’s billing address or shipping address can also occur but such errors are often information-related errors as opposed to operations-related errors on the warehouse floor.

Numerous techniques, most of them involving bar code scans or RFID tags, have been developed in warehousing to reduce or eliminate putaway and picking errors. Most of these techniques pre-date Lean warehousing. For example, as barcodes and hand-held laser scanners became prevalent, workers were instructed to scan both the barcode on a unit load (or container) and the barcoded address of a rack opening to ensure that the unit load was placed in the correct storage location. Light-directed picking and subsequently voice-directed picking were introduced to reduce errors and increase the pick rates through “paperless picking” and “hands-free picking.”
However, despite such advances, many order picking systems inspect and verify the picks before packing and shipping them since the cost of errors is very high once they reach the customer.

Remarkable advances were made both in “flow” and “quality” in warehousing, and most would agree that these advances were made prior to Lean thinking applied to warehousing. However, as shown in Figure 8, the flow column in the house of Lean is also concerned with “pull systems” and “level flow” (or level loading), which, in general, are not practiced in warehousing. Many warehouses operate on the “push” principle, and level-loading is generally not practiced. In fact, developing and implementing pull systems and level-flow continues to be a challenge even in the manufacturing sector. Another Lean tool which was not practiced in warehousing is 5S and visual management, although a number of applications emphasized “good housekeeping.”

2.4 Sources of Waste and Principles of Lean Warehousing

We conclude section 2 with a review of “sources of waste” in warehousing, and the “principles of Lean warehousing.” The sources of waste is important to understand because one of the key premises of Lean is to expose and eliminate waste, which is defined of course as any task or activity that does not add value. What the “customer” is willing to pay for is defined as “value-add;” all else is waste, which is classified as either “pure waste” or “necessary waste,” where the latter is a task that does not add value but is necessary to enable or sustain value add activities. For example, if there are separate main storage and forward pick areas, one must replenish the forward area by periodically moving stock from the main storage area to the forward pick area. If replenishment is not performed as needed, the forward area would run out of stock and we would not be able to pick the orders. Therefore, replenishment is a necessary activity, but the customer is not paying the warehouse for replenishing the forward area; rather, he/she is paying the warehouse to retrieve (that is, pick) the right items and ship them. Hence, picking would be a value-add activity, while replenishment would be classified as necessary waste.

However, if a walk-and-pick system is used, for example, the walk time itself would be considered necessary waste, while the action of removing the right item from the right container in the forward area, and dropping it into the pick cart (or into the appropriate container in the pick cart) would be considered value-add. We note that our interpretation of walk time is consistent with Lean manufacturing, where machine set-up is generally considered a necessary waste. We also stress that whether waste is “necessary” or “pure,” Lean is aimed at reducing and ultimately eliminating all forms of waste.
The following eight sources of waste are identified in Lean manufacturing:

1. Overproduction
2. Transportation and Material Handling
3. Waiting
4. Motion
5. Inventory
6. Over-processing
7. Defects
8. Unused employee creativity, knowledge, and ideas

Although the above wastes are listed in no particular order, overproduction is listed first because in many manufacturing systems, overproduction—that is, making more than what the customer wants, sooner than when the customer wants—is often the primary source of waste in manufacturing systems. Overproduction is often a result of “push” flow, and its primary symptom is excess inventories, which itself becomes a source of waste as the above list indicates.

As reviewed in [13], the sources of waste in warehousing given in [1] echoes the sources of waste given for manufacturing:

1. Overproduction—excess inventory in the warehouse.
2. Transportation—unnecessary movement of cargo is a major source of waste in material handling processes.
3. Waiting—waiting is a waste of time. This is as true in warehouse operations, as it is in production.
4. The waste of movement—movement is a waste when it involves fetching tools or stored items, which cannot be located.
5. The waste of inventory—poor inventory control represents waste, particularly when stockouts are frequent. Excess or obsolete inventories as well as lack of inventory visibility and control in the warehouse represents waste.
6. The waste of extra processing—in the warehousing context, this waste occurs as over-checking.
7. The waste of defects—in warehousing, errors result in waste.
8. The waste of creativity—when the employees’ creativity is not used, it represents a waste of human resources.
The 7 wastes found in warehousing, along with examples found in the three companies selected for the study, are given in [28] as follows. (We slightly reworded the material to improve clarity, and when needed, we inserted parenthetical remarks. Also, some publications in Lean refer to the 7 wastes, which refer to the first seven sources of waste listed earlier. The waste of creativity was added later.)

**Overproduction**
Since warehouses do not generally have production processes, overproduction cannot be defined for a warehouse. However, for warehouses with production processes like Company C, the overproduction waste is incurred when making more than what the market demands, and storing the excess inventory until demand occurs.

**Transportation**
Unnecessary travel, for example, during the picking process. (The authors propose batching of orders to reduce the walking waste.) In the picking area, the transport waste occurred in Company A due to excess inventories and the fact that the items were not organized in a manner to minimize the travel distances but only to minimize the motion waste. Company B placed similar items together but it created the transport waste because the items were not placed to reduce travel distances. Company C had the transport waste when the work performed by two workers, going in the opposite direction and back, could have been performed by one worker.

**Waiting**
Waiting waste occurs, for example, if the items required for an order are not in the picking area, and the picker has to wait until the picking area is replenished from the bulk area. Waiting also occurs when there is shortage of equipment, and the workers are delayed until the resources become available. Company A had waiting waste at receiving, waiting for the unpacking/sorting station to be able to process incoming items. Company B had waiting waste at the packing station when placing item on the conveyor and waiting for the packing staff to be able to start on the next order. Company C had the waiting waste for the boxes before each process, where they waited to be processed. There was also waiting waste when waiting for the humidity test and certification by an outside party.

**Motion**
Motion waste in the warehouse occurs, for example, when items are not placed within the picking height and the picker has to reach or bend to pick the items. Company A reduced this waste by placing hand-picked items in the picking height and larger items farther up. (It is not clear how this would reduce the motion waste; placing large items farther up may make matters worse.) Company B had significant motion waste in the bulk area because when retrieving an item, the worker would sometimes move other items, or stretch/bend when searching for it. Company C experienced the motion waste when retrieving a box for a process, and not knowing where in a zone it was located, the worker had to move other boxes around to find the correct box.
Inventory
Inventory waste occurs when there is an excess or shortage of inventories. It is also considered a waste to store the wrong items. Company A had excess inventories because they purchased large amounts of inventory and frequently. Company B had large inventory waste because of the uncertainty of the market and long lead times from their suppliers. The company had either not enough or too many items. Company C experienced the inventory waste because of the internal flow of the material in the warehouse and the lack of their ability to track the items.

Over-processing
Examples include re-entering information or data into a system multiple times, or using equipment which offers more capacity than what is needed. (All three companies had over-processing waste in terms of how information was entered into the system, or how the information was used by different parties in the system to make decisions. One example cited, that is, Company A, involved returned items, which presents a challenge for many warehouses.)

Defects
This type of waste occurs when an item is damaged within the warehouse, when the wrong items are picked, and when the wrong quantities of an item is picked. Company A had returns caused by picking errors or damaged items. Company B hired temporary workers during the high season to cope with the high demand. Due to lack of experience, the temporary workers would sometimes pick the wrong items. (This particular example is striking in that it underlines the significance of standardized work, which would have facilitated the proper training and engagement of the temporary workers in the picking process in Company B. Lean companies such as Toyota also use temporary workers but they don’t let that diminish their product quality.) Company C would have a defect waste if the items did not pass the certification test, which forced the reprocessing of the items.

The above sources of waste and their definitions, along with the examples provided, are indeed helpful. However, we would like to comment further on the overproduction waste. Excess inventory in the warehouse as a whole is cited as a source of the overproduction waste, and we agree with that assessment. However, if we consider “overproduction” in a context larger than just manufacturing, we will recognize that it occurs when a process (even if it’s value-add process) is performed sooner than its needed or in quantities larger than needed. Clearly, in manufacturing, this occurs when a product is made ahead of time or in excess quantities, which results in excess finished goods. For a warehouse, can we perform a process before it is needed or in quantities that exceeds demand?

To address this question, consider the order picking function. Would a warehouse pick orders before the orders are placed and hold them as “finished goods?” It seems the answer is a decisive “no,” since virtually all warehouses wait for orders to be placed before picking them; that is, most warehouses operate on a “make to order” basis as opposed to a “make to stock.”
(Of course, an order could be placed by a dealer who is “anticipating” the demand but from the warehouse’s point of view, demand occurs when the order is placed by the dealer.) One exception we know is a primary medical supplies distributor that makes daily shipments during the week to a major medical complex with multiple hospitals. Since the distributor does not pick orders during the weekends, but the customer needs daily shipments, instead of making large shipments on Fridays (which would drive up inventories at the customer), the distributor picks the orders on Friday (based on anticipated demand), and the items are later shipped to the medical complex over the weekend. Hence, technically, the distributor builds a small supply of “finished goods” (that is, picked and packed orders, ready to be shipped) to meet the customer’s demand over the weekend.

Except for examples such as the one above and others that involve kitting (where kits are assembled/picked ahead of time and stored), it’s very rare for a warehouse to pick orders ahead of time based on anticipated demand. However, this does not mean that the “overproduction” waste, defined in the larger context, cannot occur in a warehouse. Consider, for example, the case where an order (that already has been placed) is picked too far in advance of its due date (which generally corresponds to the outbound trailer departure time for that order). Such an order leads to the overproduction waste, which leads to unnecessary congestion and increased levels of work-in-process (WIP) in the packing and shipping areas, where the orders takes up space and resources until it is packed and shipped later. Picking the orders too far in advance can also lead to uneven flow from the picking area to the packing/shipping area. To avoid the overproduction waste, the problem we consider in section 4 takes the order due dates into account while trying to minimize the picker walk times, which represents a significant deviation from the traditional literature where the majority of the order picking papers neglect the order due dates and instead focus only on minimizing the picker walk times.

Another example of the overproduction waste may occur due to the replenishment operation. If items from the main storage area are replenished too soon or in quantities that are too large, then it would lead to “overproduction” since it would unnecessarily increase the inventory levels in the forward picking area, which potentially increases the pick times (and/or the walk times) in the forward picking area.

Hence, to avoid the overproduction waste in a warehouse, in addition to lowering the overall inventory level in the warehouse, we need to use pull systems so that the appropriate amount of items are pulled at the appropriate time from the main storage area to the forward picking area, and from the forward picking area to the packing/shipping area. In other words, the pull signals should travel upstream from shipping to packing, from packing to picking, and so on as shown in Figure 9. Most warehouses perform the pull from forward picking to the main storage area reasonably well (although the replenishment cycles and the replenishment quantities are not necessarily optimized) while many of them use the “push” system from forward picking to packing and shipping.
We summarize the principles of Lean warehousing as follows:

- Use 5S, visual management, problem-solving, and kaizen.
- Use status at a glance boards and scoreboards—Is the system on track or behind? Are we winning or losing? Can we go on a self-guided tour of the site? Use standard signage throughout the facility.
- Use standardized work, and standardized equipment by zone/area of warehouse.
- Establish one-piece flow in receiving, put-away, picking, packing, and loading.
- Level the flow throughout the facility; reduce unevenness or overburdening.
- Implement pull system based on order due dates.
- Minimize or eliminate staging locations in receiving, put away, and shipping.
- Eliminate or reduce “touch points” or “hand-offs” between process steps.
- Establish pacemakers. How is work dispatched to the floor?
- Schedule inbound/outbound shipments by time windows.
- Eliminate all excess inventories.
- Use Lean storage—commodity code slotting and velocity slotting.
- Measure, improve, and justify cubic and square-feet storage density with the intent to improve storage as well as travel times.
- Use small-lot packaging, pre-sorted by commodity inbound from suppliers.
- Perform smaller, more frequent replenishments.
- Pick to shipping container without handing over to another person or department.
- Promote continuous improvement and learning.
- Train local leadership on Lean principles, and identify a pilot facility for Lean.
- Perform shift start meetings, and identify/track progress on current challenges.
3.0 VALUE STREAM MAPPING

Value stream mapping (VSM) is a key Lean tool that has been used successfully in manufacturing and other sectors such as healthcare. Rather than review the basics of VSM (there are many resources in the Lean literature for that), we will discuss the application of VSM in warehousing. One of the key considerations in VSM is the level or scope of the map. In most cases, the appropriate level to start would be a door-to-door value stream map for the warehouse. However, in most warehouses, there are three interrelated but distinct processes; namely, put-away, replenishment, and picking. We envision that as Lean implementation is rolled out in the warehouse, a second-tier value stream map will be prepared for each one of these three processes, with the door-to-door map providing the high level view, showing the interactions or touch points between the above three processes.

The other key consideration in VSM is the identification of the “process boxes” and the “data box” attached to each process box. When value stream mapping a manufacturing system, each process box (which corresponds to a manufacturing operation or group of operations) is classified as a *value-add step* in almost all cases. In warehousing, however, while put-away, for example, would definitely be shown as a process box in the value stream map, one cannot argue that put-away is a value-add process in the door-to-door value stream map. Rather, as we discussed earlier, put-away would be classified as a non-value-add but necessary type of waste. Hence, a key difference between manufacturing versus warehousing VSM is that virtually process boxes in manufacturing are classified as value-add while many process boxes in warehousing would be classified as non-value-add. (It’s instructive to note that, if a second-tier value stream map is prepared for the put-away process, then some of the tasks performed as part of put-away will be shown as value-add steps. Note that for such a map, the “customer” is the forward picking area, and the customer is “paying” the main storage area to replenish the forward picking area, although we are not of course referring to money actually changing hands.)

A simplified (or high-level) warehouse value stream map, taken from [12], is shown in Figure 10. As the value stream map suggests, the type of warehouse considered in this particular map is warehouse type 2 (that is, a finished goods warehouse). For the same type of warehouse, the author also shows the current state map (Figure 11) and the future state map (Figure 12). The process boxes “palletizing & storage” and “order picking” are classified as value-add processes while the “off-site freezer storage” and the “rack storage” are classified as non-value-add. We agree with the author’s classification, except that in certain other types of warehouses (such as service parts warehouse, type 5), not all inventory can be classified as non-value adding waste since the core mission of the warehouse is to stock the parts so that they are available for repairs when customers need them. In such cases, a company must first develop a strategically appropriate, minimum level of on-hand inventory for each family of SKUs. Inventories in excess of the minimum levels would then be classified as waste.
Figure 10. Simplified Warehouse Value Stream Map [12].

Figure 11. Warehouse: Current State Map [12].
4.0 ORDER PICKING

It is generally agreed that order picking is one of the most costly activities in a warehouse. For example, according to [31], as shown in Figure 13, order picking accounts for the largest percent of warehouse costs. Also, according to [13], who also cites [31], order picking accounts for 65% of the total cost, and 50% of the workforce in a warehouse. Yet another source [11] confirms that 50% of the total operational costs in a warehouse are due to order picking; see Figure 14. Therefore, for the “technical deep dive” we selected the order picking operation and we developed a new order batching heuristic to batch the orders and route the pickers with “pick windows” and order “due dates” in mind.

**Figure 12.** Warehouse: Future State Map [12].

**IMPORTANT NOTE:** The project team also developed the current state map for Navistar’s Las Vegas PDC. That map will be appended to the report if/when permission is obtained from Navistar.
Figure 13. Cost of Order Picking in a Warehouse [31].

Operation cost distribution in a typical warehouse

Figure 14. Percent Share of Order Picking Cost in a Warehouse; taken from [28].
Suppose the order due dates fall into four groups, which correspond to four 2-hour increments. For example, if the shift starts at 8am, there is a 10am due date for group 1 orders, 12-noon due date for group 2 orders, 2pm due date for group 3 orders, and 4pm due date for group 4 orders. Of course, the heuristic is designed to work with any reasonable number of groups (or due dates) specified for a shift; we picked the above due dates to motivate the heuristic. Also, the due dates would normally correspond to outbound truck departure or ready times, which is consistent with how outbound milk runs would be set up in a Lean logistics system so that the service parts picked by the warehouse are delivered to the dealers or customers on a timely basis and in small lots.

Further suppose that there are 40 orders in each group, resulting in 120 orders per shift. If there are, on average, 20 line items per order, then 40 orders would represent 800 lines per 2-hour window (or 120 mins). Hence, the takt time would be equal to $120/800 = 0.15$ mins or 9 secs per line item, or $120/40 = 3$ mins per order. To regulate the flow, we need two parameters: 1. A pick window, which is the time each pick trip should be completed, and 2. The maximum number of “open” orders at any given time. An order is considered “open” until all the line items of that order have been picked. Once all the line items are picked, the order is “closed,” packed, and then moved to shipping. The two parameter values should be selected in conjunction with another. For the example, we picked a 20-minute time window, and at most 6 open orders. The first parameter ensures that the pick trips are regulated and completed as required; if a picker is behind, it will be made obvious through the use of visuals and status at a glance board. The second parameter avoids congestion in the packing area, and ensures that orders are picked in small lots. Picker walk time is minimized subject to the above two parameters.

Note that, constraining the problem by the above two parameters would, in general, increase the walk time per pick (compared to ignoring the two parameters, and batching the orders just to minimize the picker’s walk time) but the two parameters are critical in terms of regulating the flow from the forward picking area to packing and shipping. Both parameter values may require trial-and-error to set their appropriate values. The goal is to minimize tardy orders. The number of pickers to provide is a decision variable.

The assumptions and the greedy batching heuristics are summarized as follows, where an “item” corresponds to a “line item”:

Orders

120 orders / shift.

Each order is specific to one dealer (all orders placed by each dealer for a given day are consolidated into a single order).
Orders are given (known) at the beginning of the shift.

Each order has multiple line items. The number of items per order follow U~ (6,34).

Orders have 4 due dates (the first 30 orders have due date 1, the second 30 have due date 2, and so on). Due dates are based on the departure times for the 4 trucks with one leaving every 2 hours. Therefore, all orders with due date 1 must be ready for the first truck 2 hours into the shift, due date 2 must be ready for the second truck 4 hours into the shift, etc.

Layout

Layout consists of 10 aisles, 3 cross-aisles (at front, middle, and back), and 20 bay locations per aisle. (Bay locations are numbered 1 through 10 before the middle cross-aisle, and 12 through 21 after the middle cross-aisle.)

For each aisle, 3 “nodes” are defined (one in each cross-aisle): front, middle, and back.

Item locations will indicate if the item is on the left or right side of the aisle. (This information was not used in the heuristic as the distance is the same for an item in a bay on either side of the aisle.)

Each bay is represented by a $2 \times 2$ grid.

Cross-aisle Distance between adjacent aisles is 8 ft.

It takes 2 seconds to move horizontally per grid.

It takes 2 seconds to move vertically per grid.

Average walking speed for a picker is 2 ft/sec (120ft/min). **Based on .6m/s avg picker walking speed given by Roodbergen, Koster, EJOR Vol 1, p32-43.

Orders are sorted by due date, aisle #, bay #, and then order #.

Pick Window

A pick window is the unit of work (represented by a fixed period of time) where an order picker will get a new work assignment, and then starting at the I/O point will walk to the next item on the pick list, pick the item, repeating until time expires or the list is complete, then returns to the I/O point to stage the orders.

A pick trip is the route or path that the picker takes for a given pick window.

Staging consists of moving each order from the cart location (A, B, C, etc) to the corresponding staging container (A, B, C, etc).

The picker will use a cart which is divided into 6 compartments. The staging area set up with containers corresponding to each of the compartments.

All pick windows are the same fixed duration of 20 minutes. A picker can complete a pick trip early, however, a pick trip can NOT exceed this time duration. If prior window is completed early the next pick window will not begin until the designated start time.

Pick windows are numbered sequentially.
Pick windows were initially designed to be consecutive with no overlap, meaning that one picker could complete pick window 1, then complete pick window 2, etc. The analysis was modified to include additional scenarios: 2 pickers with a 10 minute staggered and 3 pickers with a 6.67 min staggered window.

Each pick window contains fixed and variable dwell time.

- Fixed dwell time at the beginning of pick window for pick trip initialization (get pick list, set up cart, etc): 30 seconds
- Fixed dwell time at the end of the pick window for staging (moving items from cart to staging containers): 60 seconds
- Variable dwell time at the end of the pick window for order finalization each order “closed” (to close/label/move container as well as set up new container): 45 seconds

Each item picked takes 15 seconds.

Each pick window will have a maximum of 6 “open” orders which will be used to generate the pick list. Only items from these 6 orders can be picked with this pick window.

The initial 6 orders will be “opened” based on their proximity to the lower leftmost bay of the layout meaning the first 6 orders on the order list (sorted as mentioned above). In other words, starting at Aisle 1 and Bay 1, the first 6 items found in unique order numbers will determine which orders are the first 6 orders to be “opened”.

All orders from due date 1 must be “opened” before orders from due date 2 which must be opened before due date 3, etc.

Orders can be picked across multiple pick windows as long as the windows are consecutive (meaning that once an order is “opened” it remains “open” as one of the 6 orders for the pick window until all items have been picked for that order and the order is “closed”). An order may be “open” yet not be picked in a given pick window – this will not violate the consecutive window constraint.

After the picker picks an item, the “next” item is determined as follows:

- If there are more items in the same aisle:
  - The “next” item is the item from the pick list in this aisle closest to the picker’s current position.

- If there are no more items in the aisle
  - Move to the closest node
    - If current location is bay 1-5, move to front node (row 0)
    - If current location is bay 6-10 or 12-16, move to middle node (row 11)
    - If current location is bay 17-21, move to back node (row 22).
  - Check next aisle (repeat until we find an aisle with an item or we reach aisle 10)
If at front or back node (row 0 or 22), the “next” item is the closest item to node location in this aisle.

If at middle node (row 11), check if items on both side of node.

   If so, determine the farthest item on each side of the aisle and the “next” item is the closer of the two.

   If not, the “next” item is the closest item to the node in this aisle.

If we reached aisle 10, go back to the initial aisle for this pick window, and go backwards one aisle (repeat until we find an aisle with an item or reach aisle 1).

The picker will check if there is time to pick the “next” item. If so, the picker moves to the item, picks it, and then checks the “next”. If out of time, the picker returns to the I/O point and stages items by moving them into the appropriate shipping containers.

Orders are “closed” or ready for the truck when all items have been picked, placed in the corresponding container in the staging area, and the container is complete.

All metrics involving time of a closed window will be given in terms of pick window end time not time picking last item of an order or actual time returned to the staging area.

Using the above greedy batching heuristic, multiple numeric runs were made using the 10-aisle layout and group of 4 due dates. The details of the results, along with an alternative heuristic (that may perform better than the greedy heuristic) will be presented in a technical report prepared to be submitted to a refereed journal.

Also, the results contained in this report, including the house of Lean warehousing, Lean warehousing principles, and value stream mapping for warehousing will be prepared as a powerpoint slide deck.
REFERENCES


12. F. C. Garcia, Applying Lean Concepts in a Warehouse Operation, Bristol, PA, USA.


