Manufacturing and Design of Low Cost Stackable Drawer for Mass Production

by

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B.S. Mechanical Engineering
Massachusetts Institute of Technology, 2015

Submitted to the Department of Mechanical Engineering on in Partial Fulfillment of the Requirements for the Degree of

MASTER OF ENGINEERING IN MANUFACTURING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SEPTEMBER 2017

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Abstract

This thesis explores a next generation storage unit design for warehouses that increases stiffness, decreases assembly time, maintains or improves gross cubic utilization (GCU) – the amount of total available space that is actually utilized by product within the unit—while minimizing costs related to onsite assembly, shipping, packaging and manufacturing. This work focuses specifically on a stackable based storage solution in which machinery could stack and unstack different totes to stow and retrieve product. This is a descriptive thesis of the engineering design process – problem and goal identification, background research, functional requirements, creative idea generation and analysis, concept selection and iteration, design verification, and implementation – is used to propose a solution. Concept designs are primarily explored in CAD models. Designs are verified and analyzed for mechanical integrity through finite element analysis and manufacturing, packaging and assembly costs are analyzed to ensure feasible implementation. The proposed design weighed 370lb, had 82.5% GCU and took about 17.2 minutes to assemble. The manufacturing costs were $376.52; the packaging and logistics costs were $24.98 and $15.72 respectively; the onsite assembly costs resulted in $11.70. These costs totaled up to $429.52 for a stackable pod.
Acknowledgements

In addition to my family, I thank many people at MIT for their contributions, whether directly or indirectly to this thesis. I would like to thank my mom, Amy, for her continuous support in every one of my endeavors and constant care, even remotely. I thank my dad, Peter, for always being there for me as well as sharing immense amounts of technical wisdom and life experiences to aid my personal development. I thank my older sister, Cindy, for paving and steering me on to this path which has lead me to write this thesis at MIT. She helped me study for SATs and edit my college applications, which I thank her greatly for.

I also extend thanks to my team mates on this project, Youngjun Joh, Barbara Lima and Ben Schilling. We spent a lot of time together in Sid Pac, Google Hangouts, and the car brainstorming and generating concepts that lead to the final design. Their ideas, concept designs and hard work were essential in writing this thesis. This final semester and summer was also a particularly busy and hectic time for me. I particularly thank them for not only being reliable team mates with great knowledge and work ethic, but also friends who were always there for me.

From MIT staff, I thank Jose Pacheco and Prof. David Hart for running the M.Eng in Manufacturing program at MIT and making it the year I have grown the most in. I wanted to come back to MIT to dive into advanced manufacturing (e.g. statistical process control, design for manufacturing, manufacturing of robotics) and learn more about the entrepreneurial ecosystem at MIT. I fulfilled everything I wanted to get out of this year being in the program. I also thank Prof. Maria Yang, my thesis advisor, as she has shared many useful design for manufacturing tools as well as spent many hours editing to make this thesis possible.
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1. Introduction

This research utilizes a 7 step engineering design process to develop a concept for a next generation storage units, called “pods” for warehouses or fulfillment centers. The concept of focus is stackable based and aimed to be produced in quantities of millions per year. An iterative design process was used to develop a final concept. Additionally, manufacturing, packaging and shipping costs are considered to evaluate scalability.

The Pods

<table>
<thead>
<tr>
<th>Pod</th>
<th>A storage unit housing inventory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>Foundation of a pod</td>
</tr>
<tr>
<td>Pod Face</td>
<td>A vertical plane defined as being parallel and flush to an outside face of a pod base. There are 4 faces per pod, A, B, C, D, set counterclockwise (from above) about the base.</td>
</tr>
<tr>
<td>Tote</td>
<td>A removable storage container within a pod</td>
</tr>
</tbody>
</table>

Table 1. Pod Terminology

The pods are designed with optimizing the gross cube utilization (GCU). The greater the percentage of space within a pod that is dedicated to product, the greater the space efficiency of the pod. Considering yearly fixed operational costs and building capital depreciation life, every percent change in GCU, translates to millions of dollars in fulfillment center cost. As a result, space efficiency is critical for pod designers and engineers to consider.

2. Problem Statement

As product demand increases, the need for scaling pod production and maximizing product space in a fulfillment center is increasingly critical. A new generation pod design is needed to minimize assembly time, minimize sway, and maintain or improve gross cubic utilization within the walls of the pod while optimizing costs related to onsite assembly, shipping, packaging and manufacturing for scalability.

Sway refers to the side to side and front to back deflection of the pod. The sway is important to minimize because it translates directly to how many pods can be in a fulfillment center. If the pods sway too much when being moved around, more clearance space is needed around each pod, which means overall less pods in a warehouse. The
stiffness is also important to ensure robustness of the pod. For assembly, the pod must be easy and fast to put together to meet high demands and volumes. A next generation pod that can meet production at 1 million pods per year is needed.

The greater the supply, the more product is needed to hold in order to maintain their well-known quick delivery time. A million pods per year is the volume target used for the designs developed. As such, the pod must be very scalable from a manufacturing, packaging, shipping and onsite assembly costs perspective.

<table>
<thead>
<tr>
<th>Size</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>XS</td>
<td>6</td>
</tr>
<tr>
<td>S</td>
<td>6</td>
</tr>
<tr>
<td>M</td>
<td>5</td>
</tr>
<tr>
<td>L</td>
<td>3</td>
</tr>
<tr>
<td>XL</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>21</td>
</tr>
</tbody>
</table>

Table 2. Tote Size Distribution

The stackable concept explored has totes of different heights stacked on top of each other – in particular, a total of 21 totes of 5 different sizes. These totes could all be filled with product to maximize gross cubic utilization and a custom forklift would be able to interface with the pod to select and remove the desired tote within a pod.

Primary Goals

The primary goals of this work is towards developing a stiff and easy to assemble onsite pod, while optimizing cost and gross cubic utilization. The pods experience a significant amount of front to back and side to side loads. With inertia, pods will very likely sway front to back or side to side, which poses a risk for collision. More pod sway requires the clearance for pods to travel past each other to increase. Any increase in clearance has a dramatic effect on reducing the pod capacity in a fulfillment center as the extra clearance would be aggregated across the entire floor of a fulfillment center. Reducing assembly time is also necessary to be able to meet projected demand.
Understanding the mechanism by which the totes would mate and stack with each other and how reliable and easy that was to do for a machine, such as a forklift is also a primary area for improvement.

3. Functional Requirements

Assembly Requirements

Minimizing the assembly time on the next generation pod is a priority. Moving assembly from offsite to the supplier will increase yield rate as well as reduce labor cost. The design is aimed to meet a production rate of over a thousand pods per day in total. Accounting yield loss due to manufacturing defects as well as human inefficiencies, a 1.5 safety factor should be taken into account for assembly times.

Pod Life Requirements

In this design study, consideration for tote removal and insertion cycles on the order of thousands were kept in mind for materials selection. However, life time wear and tear and fatigue was not meticulously analyzed. Additionally a standard 7 year life without maintenance was considered.

Forklift Requirements

One or two forklift like machines or tote handlers will need to interface with the stackable pods so that product can be accessed. The steps for the forklift system to approach the pod, find the desired tote, hold up unwanted totes above the desired tote and take out the desired tote should be performed quickly. As the forklift system must hold the tote, features on the tote should be integrated so that it can be held up.

Cost Requirements

Costs include manufacturing, packaging, shipping, and onsite assembly costs. The solution proposed was aimed to be below $500.

Loading Requirements

Pod sway should be minimized in front to back and side to side directions. A goal of 25 mm is desired for this study. Each tote must also be able to sustain the weight of the heaviest product that could go inside the tote.
4. Creative Idea Generation and Analysis

The creative idea generation phase consisted of a lot of research on existing stackable products and related mechanisms, as well as sketching and modeling many low fidelity, high level concepts quickly. The concepts are split into 5 categories to ensure the pods had a means of being shipped, a plan of how parts would be assembled on site, a way of being stacked together, a locking mechanisms, and method by which product can be accessed. Table 3 highlights concepts explored in the following sections for each of these categories.

<table>
<thead>
<tr>
<th>How will robot access product?</th>
<th>How will it be shipped?</th>
<th>How will totes be assembled onsite?</th>
<th>How will it be stacked?</th>
<th>How are totes locked?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift, Lift &amp; Shift Shift:</td>
<td>Full size</td>
<td>No assembly (just stacked)</td>
<td>Insertion</td>
<td>Wall Geometry (Legos)</td>
</tr>
<tr>
<td>Hold &amp; Slide</td>
<td>Nestable via draft angle</td>
<td>Spot weld</td>
<td>Asymmetric Design</td>
<td>Turn key</td>
</tr>
<tr>
<td>Rotation</td>
<td>Collapsible via hinges</td>
<td>Rivets / bolted joints</td>
<td>Shifted/Periodic Design</td>
<td>Detents (mechanical or magnetic)</td>
</tr>
<tr>
<td>Lift in frame and slide between totes</td>
<td>Modular sides &amp; bottom</td>
<td>Keyhole Slots</td>
<td>Rail / bar / platform</td>
<td>Cam mechanism</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Press-fit / Snap fit</td>
<td>Stack in frame</td>
<td>Actuated pin in slot</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Locking Pin</td>
</tr>
</tbody>
</table>

Table 3. Concept Generation Categories

Concepts for How Product is Accessed

One of the major questions related with stackable pods is: *how can product be taken out of a tote?* The following section provides 4 different concepts for how product can be accessed: Lift, lift, & shift, shift, Hold & Slide, Rotation, and Lift &
Slide between. The disadvantages and advantages, potential risks, additional equipment needed and other related considerations are discussed for each concept.

Lift, Lift & Shift, Shift

Two simple fork lifts or one complex forklift can interact with the stackable pod. One forklift is responsible for lifting totes above the target tote and the other forklift lifts the target tote, shifts it out and then shifts it to the robot picker.

The “Lift, Lift & Shift, Shift” method is intuitive and relatively easy to program for the software team. However, the multi-steps of needing to lift, lift, shift and shift takes up more time. While one complex custom forklift can be engineered to complete all the steps, a simple version displayed here uses 2 forklifts. In Figure 1, Fork lift A lift and holds totes, and forklift B is used for the lifting and shifting the target tote Figure 1. The two lifting steps also take up some vertical clearance which eats up GCU.
The hold & slide concept is meant to reduce time for picking a product. With the lift, lift & shift, shift, method, 4 steps are necessary in order to take out a tote. With this concept, only 2 steps are necessary. The above totes would be held up and the desired totes would be slid out directly. The advantages of this concept are that product can be accessed quickly which enables faster cycle time. There is also an easier likelihood that 1 machine or forklift is necessary to take the totes out. Some considerations were wear by sliding and the need for some locking mechanism to prevent drawers from sliding out when being moved around. Any existing work on the tray based pod could also be potentially reused as this concept is essentially a tray based pod without the exoskeleton or frame.
The rotation concept is primarily a creative thought provoking concept. Totes are individually rotated around a corner to expose the contents. The usability is intuitive and simple. The aesthetics are interesting and can be used for branding. The forklift may not be needed as only a machine too rotate out the tote is necessary. A motor could also be used directly at the hinge to rotate a tote. Multiple motors could be used at each hinge or one motor with a mechanism that could select the right tote could be used to open totes one at a time. The product is quick to access and no critical alignments due to tolerances are needed. From a mechanical perspective, there are many risks with this concept. All the weight is in one corner and the tote may not be stable when a tote full of product is swung out. More space is also needed in terms of floor space, in order to rotate a tote instead of slide out a tote. This concept also does not allow totes to different positions, leaving less room for modularity in the future. Instability is also a large area for concern as the uneven stiffness and moments could lead to bending and toppling.
In the lift & slide concept, totes above the target tote are lifted by the same machine that then reaches in through the space between to remove the product. This method of accessing product is beneficial because the lifting and picking of product are all done in one step, which decreases cycle time. The concept also has fewer degrees of freedom which make less alignment work necessary. The disadvantage is that the machine that interfaces with the pod does not have a lot of space to manipulate product. The need to push all for the machine to pick the product means that a lot of vertical clearance would be required. This means the height of the pod would be limited which takes a way product space, which is gross cubic utilization of the plant. A particular risk with this concept is the inaccuracy in the cantilever arm picker and complexity of what this machine would need to do and look like.

Concepts for How Pods are Shipped

The following section provides 4 different concepts for how pods can be shipped: full size, nestable by draft angle, collapsible with hinges, and modular walls. The disadvantages and advantages, potential risks, additional equipment needed and other related considerations are discussed for each concept.
The most simple solution would be shipping the entire full size pods to the fulfillment centers. The pods would require no need for on-site assembly, reducing labor costs and reducing setup time. Additionally no part ratio management would be needed as all parts come fully assembled. Transportation costs, however will be high due to low space use efficiency in a shipping container. In other words, a lot of air will be shipped and this low packing density translates to higher costs for transporting pods to the fulfillment centers. As such to make this solution work, many large transportation trucks would be needed. For this option, a shipping method that charged or stacked up costs by weight rather than volume would be ideal. In general, shipping full sized pods is a last resort; the significant amount of additional transportation costs make the option currently infeasible.

Nestable by Draft Angle

Pods can be designed with a draft angle on the side walls so that they can stack vertically on each other during shipping. Reduced space during shipping, no assembly needed for each tote, and ease of manufacturing are potential benefits for this method. The draft angle, however does eat up some space, which would otherwise be used for storing product. Considering the sensitivity of cost with gross cubic utilization, the reduction of the gross cubic utilization could translate to significant costs. Effectively, depending on the expected lifetime of each bin, the cost of the gross cubic utilization loss has to be balanced with the reduced transportation costs. Potential risks include...
jamming or wedging in the nested form when being shipped. There could also a possibility of less stability when totes are stacked. For this stacked form, additional thought will be needed to identify a mechanism by which totes can be stacked without nesting.

**Collapsible with Hinges**

An overview of existing collapsible baskets, totes, and containers was conducted for design inspiration. Foldable plastic distribution containers are a standard for shipping goods where cardboard was widely used. For the stackable pods, hinges would need to be placed in strategic locations on the totes to allow for collapsing into a smaller format during transportation to a fulfillment center. The foldable design saves valuable space during shipping while having nearly no loss in gross cubic utilization when totes are constructed. Collapsible totes would most likely require no or little additional equipment and could utilize one way locking mechanisms which would facilitate the on-site assembly process. Costs however will be moved to having some more on-site assembly time and labor. The hinges may also pose a risk for structural weak points and the clearance needed for hinging could reduce pod stiffness. The increased number of parts could mean increased part costs as well as assembly costs not only on site but also at the supplier. The ideal design would likely minimize number of hinges while maximizing gross cubic utilization and stiffness.
Modular Walls

The 4 side walls and bottom plate could be manufactured individually. The totes could be assembled on site in a way similar to how puzzle piece foam flooring or laser cut acrylic pieces come together. The compact form and reduced spaced during shipping is the primary benefit with this concept. Additionally repair costs could be decreased as any wall that is damaged or defected could be swapped out for a new wall during assembly or sometime after usage. The modular walls concept should theoretically have minimal loss in gross cubic utilization for the features that connect the walls together. Similar to the collapsible hinged wall concept, low stability and stiffness for a fully assembled pod is a risk. While walls could be fit connected together by hand, depending on connection features, additional assembly equipment may be needed.

Concepts for How Pods are Joined and Assembled Onsite

With regards to assembly, pod parts can be assembled at the supplier or on site at the fiducial center. From a deployment and yield rate perspective, as much assembly should be done at the supplier. However as shipping full size pods is likely infeasible, collapsible wall concepts are very attractive. For such concepts, totes and pods must be joined and assembled on site to some degree. The following section provides 8 different
mechanisms for how walls could be assembled together onsite: rivets, clinching, spot welds, living hinge, detachable hinge, key hole, snap fit, dovetail. How walls would assemble together and the how pod builders would interact with the tote is important for analyzing each concept. The disadvantages and advantages, potential risks, equipment needed and other related considerations are also discussed for each concept.

*Rivets*

![Rivets in Sheet Metal](image)

Riveting is a manufacturing method by which metal pieces are joined together with a rivet. The rivet, a metal fastener that has a cylindrical post with a head is placed into hole. A rivet gun deforms and expands the cylindrical post which holds the pieces of metal together with the rivet [7]. Riveting is the status quo of how the metal members are assembled today. For stackable pods, walls and the bottom wall would be shipped in a flat package and riveted on site, which would save on transportation and shipping costs. Compared to other methods of joining metal without welding, such as with screws, bolts, brazing, soldering and adhesive, rivets are relatively fast and easy with the rivet gun. Still, the need for a rivet gun, electricity, air compressor and many rivets on site would require a skilled laborer and regulation checks. Additionally, a riveted joint is relatively weak. Engineers typically have many rivets on a part to attain desired structural stiffness. A stackable pod is projected to have a number of rivets in the high hundreds and each rivet has an associated per unit cost. Holes are generally predrilled into the metal members but accounting for misalignment would need to be consider for riveting.
Using only a single stroke, a depression is made between 2 sheets of metal, which joins them together. Various shapes and the number of clinches change for different metal, coating, loading, fatigue life, and size applications. Similar to riveting and spot welding, the flat walls would be assembled and clinched together onsite. The major advantage of clinching over riveting is not needing to pay for each additional rivet. Given that pods are produced at a million per year, not having a variable cost could be huge savings in the long run. Additionally, issues from aligning holes when riveting is not a concern with clinching. On the contrary, without holes as mechanical alignment features, members could move or be secured in the wrong place during clinching. Fixing an error in clinching is not time effective and the part will most likely need to just be tossed out. While electricity and an air compressor is also needed, relatively specialized equipment is needed for clinching and speed of joining is reduced, compared to riveting.

Spot Welding
Spot welding is a process in metal pieces are held together under pressure and are joined by heat generated from resistance to electric current. The process has two copper alloy electrodes that concentrate welding onto a small spot while the work pieces are clamped together [10]. If walls are sheet metal, they can be shipped in flat packages and then spot welded on site. Spot welding minimizes design features needed for connecting walls together and keeps the parts very flat for very high packing densities when shipping. Spot welding will also provide relatively stiff connections. The primary disadvantage to spot welding is the need for welding cells needed site and likely need for 240V supply. Labor will need to be more skilled and therefore greater in costs. Additional regulations may also need to be factored in if spot welding were brought into the onsite assembly process. Eye damage and burns would be potential health effects. In addition, weld analysis will be necessary to ensure the correct parameters including electrode force, diameter electrode contact surface, squeeze time, weld time, cooling time, and weld current are selected so that changes in material properties are accounted for in ensuring structural integrity.

Living Hinge

![Living Hinge Example](image)

Figure 11. Food Container: A Living Hinge Example [11]

A living hinge is a mechanism for parts that require a flexible connector or hinge. The living hinge has a unique material property or geometry that is designed into a part allowing it to bend along the line of the hinge. Low stiffness materials like cloth, leather, and rubber can be readily used as living hinges. Other stiffer materials like plastics or even wood can be made into living hinges by changing the geometry or cutting away
material at the hinge. Tupperware lids and shower bottle caps are common examples of parts with living hinges. The ability to make living hinges with plastic means that they can be injection molded for scalability. Injection moldable living hinge design is a method that replaces conventional hinge design with a flexible thin web of plastic, which ultimately reduces number of parts and cost.

![Living Hinge CAD Concept](image)

**Figure 12. Living Hinge CAD Concept**

Given enough stiffness, the side walls could be injection molded in one piece with 3 living hinges as seen in Figure 12. The start and ends of the walls would need to come together with some method of joining or snapping action. The uni-body design eliminates small hinge parts and streamlines the bill of materials. As the living hinges require no extra tools or parts to fold the sides, assembly is relatively quick, easy and low cost compared to conventional hinging methods and metal joining methods. While the failure mode of living hinges is in torsional ripping action, a living hinge designed and implemented properly should be able to last well over a million cycles in flexing [12]. The advantage of the stackable design is that flexing only on the living hinge walls would only happen once during assembly so failure fatigue is low. Nevertheless, loads
coming in unpredictable directions, particularly parallel to the very thin flexible hinges is a high risk. Even finite element analysis could be used for geometry iteration and structural insights, but would not be able to be used for design selection. Physical models with the right material and injection moldable parameters will need to be extensively iterated to ensure the hinge works.

A single mold for each tote size is also a potential benefit, since typically having separate parts require separate cavities, gates and runners which increase tooling cost. However such a long thin mold could require detailed mold flow analysis. A lot of trial and error would be necessary to ensure heat is distributed evenly so that the part does not come out warped. Thus, a living hinge design would require high up front prototyping time and costs.

While the benefits of no fasteners, one part, easy assembly, and low cost are very attractive and have significant advantages, the disadvantages such as limited material selection to primarily polypropylene, limited load bearing, and added development time would make a living hinge concept difficult to advance for stackable pod design.

*Detachable and Modular Hinge*

![Figure 13. Detachable Hinge][13]

A detachable and modular hinge concept is considered to reduce number of parts compared to conventional hinges and to increase robustness compared to living hinges, while enabling full collapsibility for shipping. The modularity means that the walls can be separated and stacked during shipping or also have the capability of being all hinged together and shipped flat. The flexibility in configurations will be beneficial to packaging and shipping. Having individual walls which can separate also allows them to
be easily replaced or swapped out given a defect. Figure 14 shows a modular hinge CAD concept. Strategic design should be used to minimize number of unique walls or parts. Tolerances on the hinge will also need to be tight to minimize rattle and loss in pod stiffness.

Figure 14. Modular Hinge CAD concept

Keyhole

A common mechanism used to assemble furniture, in particular low cost garage racks such as that in Figure 15, are keyholes. A round peg with a head on one wall is inserted into a larger diameter hole on another wall and slid down a slot to secure the connection between two walls. The keyhole concept is very simple and intuitive, requires no complex design features, and cheap to manufacture. The keyhole feature is well suited for a one time assembly and can be very stable and stiff if designed.
appropriately. Keyhole assemblies can be cumbersome to align and assemble. A common issue with keyhole based assemblies is parts coming together crooked. Fixtures may need to be design to ease the assembly process. Additionally, a tradeoff between the stiffness of the joint and ease of insertion need to be considered. A very stiff joint is desired but it may require extra tools like a clamp or hammer to connect the walls together which reduces production time. Making the connection loose is great for assembly but would be at the cost of less pod stiffness and more sway. Additionally, the bottom plate would be connected to the walls and all the load from the product would be applied on the pegs. Under these loading conditions, the peg will need to be stiff and robust enough to resist yielding. Beam bending analysis would be able to mitigate yielding risks and help determine the amount, diameter, and material for the pegs.

Snap Together

Snap joints are a very common, simple, economical and quick way of joining two different parts. Across all types of snap joints, metal or plastic, a protruding part of one component in the form of a hook, stud, dimple, bead or other geometry is briefly deflected and when the two parts are pushed together. The protruding part typically catches an undercut in the other mating part. In designing a snap fit part, stresses need to be heavily analyzed to insure the snap does not fail during insertion and its lifetime. After the two snap fit sides are joined together, the protruding part should return back to a stress free state [14]. The insertion and retaining force can be the same or even significantly different depending on the geometry of the undercut and protruding feature.
For the stackable pod concept, designing a one way snap, one that is easy to insert and difficult to disassemble would be strategic as totes are expected to stay assembled for its entire life time. Two of the most important considerations in designing a snap fit are the mechanical loads during the assembly operation and the required retaining force.

![Snap Together CAD](image1)

**Figure 17. Snap Together CAD**

For the low stiffness, plastics are very suitable materials for snap fits and they can be injection molded directly into the part design. In the CAD concept displayed in Figure 17, the front and back walls have the undercuts and the side walls have the protruding features. This type of snap is a cantilever snap joint, which has mainly a flexural load. The center block is used to help bear the load while the snaps are primarily meant to join the walls. Once snapped in, separating the walls would be difficult.

![Annular Snap Fit Examples](image2)

**Figure 18. Annular Snap Fit Examples** [15]
In steps further in the design process, different geometries and types of snaps should be considered. Annular snap joints, as shown in Figure 18, are rotationally symmetrical. These joints, very common for pen caps, ball and socket joins, and bottle caps, will see stress axially and radially. Hybrids of cantilever and annular snap fits also exist.

The geometry for a snap fit design is critical to its behavior. Typically stiffness grows exponentially with thickness and linearly with width of the protruding part. Identifying all the parameters that could change the behavior of the snap will be necessary to select a final snap design. Additionally, non-linear based finite element analysis will be able to provide insights on the associated forces and stresses.

Overall, designed and applied correctly, snap fits are very easy to assemble, requires no parts and can be injection molded directly into a plastic part. A lot of iteration and development time, similar to the living hinge concept, will be needed to bring a snap fit to fruition. However, prototyping a mockup with similar materials would be much more insightful for a snap fit joint as opposed to a living hinge, for which the material properties play a very significant role. The snap fit joints also tend to have a complex geometry which will add too tooling cost. The biggest risk is the snaps falling off during insertion or failing because it cannot support the load.

*Dove Tail*

![Dove Tail CAD](image)

*Figure 19. Dove Tail CAD*
A dovetail joint is a simple joinery method commonly used in woodworking for furniture and cabinets. Parts can be easily inserted into each other, yet have high resistance from being pulled apart. Figure 19 showcases a dovetail concept CAD. There are two unique parts: the male side walls, and the female front-back walls. The side walls slips right into the front back walls. The tolerance needed for sliding the walls together is expected to increase amount of pod sway. The dovetails could have a taper which allows the walls to be wedged in together. Designed properly, the wedging feature could be finished off with a hammer or clamp to dramatically improve pod stiffness. A high risk would be the top surface not aligning well. If one side of the wall is slightly more depressed into the dovetail joint than the other side wall, and this deviation propagates across all 21 totes, the fully assembled pod could be very skewed. The merit in a dovetail design is not needing any mechanical fasteners. However, this benefit might be balanced out by the need to join the bottom plate to the side walls with fasteners.

Concepts for How Totes are Stacked

The following section provides 5 different concepts for how pods can be stacked: insertion, asymmetric stack and nest, shifted stack and nest, rail and bar stacking, and stacked in frame. The disadvantages and advantages, potential risks, additional equipment needed and other related considerations are discussed for each concept.

Insertion

![Pin and Socket Work Bench](image)

*Figure 20. Pin and Socket Work Bench*
Totes would be stacked by inserting mating features on the bottom of one tote to the top of the other tote. For example the pin and socket is one method used in previous prototypes. Pins on the top side of one tote are into sockets or holes on the bottom of another tote. This means of stacking totes takes up very little space which helps with the gross cubic utilization. Additionally, this method of stacking would be quite stable. Likelihood of toppling would be low as totes are fully constrained by the 4 pins. A design that can fully constrain the system with less pins or geometries would be advantageous in aiding the stacking and unstacking operations. The tight tolerances for a pin and slot require precise alignment, which may be impossible for the forklift to place the tote back in the right place every time. Perhaps performing the forklift operation slowly would help but reducing cycle time is a major disadvantage when the primary objective is to reduce delivery time. Loosening up the tolerance would help with alignment but then translate to low pod stiffness and increased sway. Overall, alignment is the biggest concern with pin and socket insertion strategies. Guiding cones, rails, slots, and chamfering features could help with alignment.

Asymmetric Stack and Nest

Figure 21 displays a clever shipping tote design, which can stack as well as nest. In one orientation the totes will nest to increase packing density when shipping. Rotating the tote 180 degrees will allow the totes to stack. The asymmetric corrugated geometry of the front and back walls allows the totes to be able to sit on each other when not aligned. The design is very simple and easy to mass produce. The geometry and
mechanism by which the totes stack has low risk of alignment issues. The corrugation in the walls can also be utilized to provide structural strength to each tote, but at the cost of taking up gross cubic utilization. However, since the orientation of the tote is so important – literally the difference between stacked and nested – careful attention needs to be paid on ensuring the totes are placed in the right direction. The way that the totes can nest also means that the walls would need to be drafted, which decreases gross cubic utilization. Additionally, toppling and sway when stacking 21 of such totes on top of each other is a concern. Finite element analysis on the assembly would be helpful to model and validate the sway given the mass and accelerations of the pod. However, with such an assembly, actual modeling and prototyping of physical totes would be the best and most reliable way to determine if the sway and toppling would be a concern. An interesting topic for exploration in later design phases if selected would be to analyze how small and thin the corrugation could be to minimize gross cubic utilization loss without risking stability.

*Shifted Stack and Nest*

![Shifted Stack and Nest](image)

Figure 22. Stackable and Nestable Totes [17]

The shifted stack and nest concept is similar to the asymmetric stack and nest concept in that a one-piece construction can nest and stack. The difference in this concept is rather than rotating the tote 180 degrees, shifting the tote forward and backwards enables stacking. The top of the tote has pin like features which are utilized when stacking. To nest, the tote is taken off the pins and slid forward to nest into the
tote below. The pros and cons for this concept are also similar. The design is also simple and capable of being mass produced quite easily. Orientation in this design in terms of which way is front and back does not affect whether it is in stacking and nesting configuration. The linear position is most important. The ribbing of the design will also have losses in gross cubic utilization and similar to the asymmetric stack and nest concept toppling and collapsing due to misalignment is a concern.

**Rail and Bar Stacking**

![Figure 23. Hook on Rail (Left) and Rest on Bar (Right) Nestable Totes](image)

Wire meshed stackable totes seen in Figure 23 inspire the concept of totes with a hook or bar with can be manipulated for stacking purposes. The totes would be shipped in nested form but the hooks on the base of a tote could latch onto the top of a tote below. Another similar idea is having a hinged bar on top of each tote. The bar would be flipped outwards so totes could nest when shipping. At the fulfillment center, the bar would be flipped in for each tote which acts as a platform for a tote above to sit and stack on. Both of these concepts are similar in that there is little risk for alignment issues and maneuverability for the tote is easy. The main issues around concepts that just hook on or sit on top of another tote are the low stability, high potential for toppling, low structural strength, and possible manufacturing complexity. The biggest advantage of
these concepts are the quick transition from nested to stacking configuration, which is not a design priority.

*Stack in Frame*

![Stackable Totes in Frames](image)

One of the main issues with stackable pods is alignment. Loose tolerances make alignment easier but pod stiffness lower. On the contrary, tight tolerances are good for pod stiffness but make alignment difficult. In this concept, totes are within a frame and the totes can slide up and down within the frame. Fixed in linear motion, the totes degrees of freedom are decreased, which could lead to easier handling and stacking alignment. Additionally, this stacking design concept would have stability and structural strength given the frame. However, this concept would require additional assembly steps and parts to make the frame. The sliding mechanism would need to run smoothly to avoid possibility for jamming and a unique and novel method to reach in and access product in totes at all levels would need to be developed.

**Concepts for How Totes Lock**

The following section provides 5 different concepts for how pods can be locked: detents, locking pins, Lego wall geometry, turnkey, actuated spring pin in slot, cam mechanism. The locking refers to any stackable concept that is not constrained from moving side to side or front to back. The disadvantages and advantages, potential risks,
additional equipment needed and other related considerations are discussed for each concept.

Detents

Detents are a common method of resisting motion and can be done mechanically or magnetically. Figure 25 shows the location of where detents could be placed in the pod assembly. A ball spring detent is shown in Figure 26. This assembly involves a ball or pin on a spring which retracts when an object slides over it. The ball or pin would settle in grooves in object to help resist motion. Detents can also be made with just a simple bump in the material, as in no springs involved.
Another method of creating detents is with magnets. Effectively the ball and grooves can be simulated with an array of magnets that alternate the direction of the north and south poles. This arrangement makes magnetic “wells”, where potential energy is decreased and effectively act as grooves where the magnet wants to stay at rest. The advantages of a mechanical detent included easier understanding forces and lower cost. However mechanical detents, particularly ones without a spring, will wear overtime and lead to less retention forces. With the spring, detents have a longer life time but have larger costs associated with it. The lower the retention force, the easier totes slide out when supposedly locked, which would be disastrous. Magnetic detents are primarily beneficial for having no mechanical wear. This gives them a long life time but magnets are generally more expensive and also heavy. There would also be uncertainty with the effects of residual magnetic fields. Another disadvantage with magnetic detents is that modeling the forces would be quite difficult. Magnetic detents are used in industry but the behaviors of them are not well understood. The effects of different design parameters on the feeling and effectiveness of magnetic detents, including gap distance, magnetic thickness, magnet width, magnet length, the geometry differences between North and South Pole facing magnets, magnet configuration and number of magnets are tested highly empirically, which typically translates to high development time and money.

Lego Wall Geometry
Legos provided inspiration for developing mating features in the side walls. These features would allow totes to be stacked and connected together and constrained from moving from side to side. Like Legos, a small amount of force, which would be specified, would be needed to separate the pieces from each other. Such a Lego-like design would be nicely integrated into injection molded walls. Stacking Lego-like walls is intuitive and could be interesting for branding. Wear overtime could lead to a less tight fit. Getting the right geometries and features could also require some up front prototyping and development. Given that injection molded walls needed to be ribbed, extra consideration on how ribs would affect the connecting design would be necessary.

**Actuated Spring Pin in Slot**

![Diagram of actuated spring pin in slot concept](image)

Figure 29. Actuated Spring Pin in Slot Concept

Figure 29 shows a concept of how a pin can be actuated with a button. Unlike a springed detent, the pin is much longer and inserts into a slot. With a springed pin in a slot, forward and backward movement is completely constrained. On the other hand, totes with springed detent can only resist a certain amount of applied load to stay in position. The spring pin in slot concept could be actuated with a button to retract the pin from a tote below. This concept would allow the tote to slide right out without being lifted.
up, if the forklift could push the button and slide at the same time. Alternatively, the pins could be completely static and a forklift would just need to lift the totes a little bit to clear the height of the pin.

*Locking Pin*

![Diagram of Locking Pin Concept](image)

The locking pin concept takes advantage of two different sized pins on and slots on each side of the tote. A large pin would be in the back and a small pin in the front of a tote. Likewise, a large slot would be in the back and a small slot in the front. When a tote slides on top of another, the large pin moves over the small slot and drops in only the back larger slot. The smaller pin then drops into the small slot. In the slots, the totes are constrained in forward and back motion. The forklift would be used to lift the desire tote out of the slot and then slide it out of the pod.
The turn key concept was inspired by the latches typically seen to stow the foldable tables to the back of a seat in airplanes. Figure 31 shows a top and front view diagram of the turn key concept for stackable pods. Latches hold the totes in place and when turned 90 degrees, totes are free to slide out. The latches would stay in unlocked position while the tote was out of the pod so that the tote could be easily stowed when the desired product was taken out. After the tote is placed back into the pod, the latch would need to be turned to lock position again.
Figure 32. Turn Key Zoomed. Locked. Unlocked position (left), Locked position (right)

Figure 32 shows this concept embedded into a quick CAD model of the stackable totes. A latch is pinned and sandwiched in the center of the front wall. When perpendicular to the ground, the latch is in locked position. When parallel, it is in unlocked position. The latches can be rotated with a key in the latch that the forklift mechanism would manipulate. In the model, a hex key would be able to turn the latch, but any shape, such as a Philips, flat, star, or custom head could be used.

The turn key concept is relatively intuitive, simple and reliable. In locked position, the totes would certainly be locked and vice versa. However, the turn key would require more parts and more manipulation with the forklift. Some gap will be needed in order to allow the latch to turn within the walls of the front wall, which requires tolerancing. The wider the tolerance, the smoother the latch can turn, but the lower the stiffness of the pod assembly. All the front to back load contributing to sway would be on the latch.
Hence a very stiff latch would be necessary. Having multiple parts would also add to assembly time.

Cam Mechanism

Figure 33. Cam Locking Mechanism Concept Diagram

The cam locking mechanism is aimed to alleviate tolerance issues. Every mate has a male and female part. In this design the female hole or slot, will be relatively oversized to allow the male pin or rail to easily insert inside. A cam mechanism will enable the slot or hole to tighten or close up as the pin or rail slides inside. This cam mechanism should effectively take out the slop due to tolerancing.

5. Concept Selection & Iteration on Most Critical Modules

In the concept generation phase many ideas were quickly researched, sketched out and then organized into 5 categories. Within each category, tradeoffs for each concept
were considered. Modular or collapsible walls enabled efficient shipping and packaging. Stackable pods that could also be slid out presented itself as a novel means of saving head space and a mechanism to lock the pods from sliding back and forth is needed.

<table>
<thead>
<tr>
<th>Modular Snap Hinge</th>
<th>Sliding Lock</th>
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<tbody>
<tr>
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<td><img src="image2.png" alt="Image" /></td>
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**Selection Decision**

- Shipped flat and easily built on site with little to no extra tools for semi-permanent state
- Simplicity and most robust locking mechanism

Figure 34. Most Critical Modules

Figure 34 highlights the most critical modules for the selected stackable pod design. The most critical modules are features that are absolutely necessary for the full functioning of the concept, and they typically require a good amount of consideration and iteration.

To make the totes modular, detachable hinges and snaps were selected. The main idea is that three walls are hinged together and the start and end are snapped together. This joining mechanism allows the walls to be shipped flat, be easily built on site with little to no extra tools and remain in a semi-permanent assembled state with the snap. The turn key concept for the sliding lock mechanism is also attractive. It is simple and seems to be the most reliable locking mechanism given the concept generation exercise.

In this design phase, no simulations or rigorous calculations are considered. The focus is developing concepts for the most critical modules which answer the questions: *How do the walls hinge together in a modular way? How can a stackable tote slide and lock?* This section first describes the evolution of concepts for the detachable modular snaps. One snap concept is selected and used across all assembly designs that explore how totes can slide and be locked with one another without being lifted. The concept design that resulted from this phase entered into the next design phase for finite element analysis.
Figure 35. Snap Hinge Design Evolution

Figure 35 highlights 3 iterations of the snap fit hinge. In the first iteration, to install a wall, the worker would have a wall flat on a floor. Another wall would be pressed into the hinge and then pulled to secure the two sides of the annular hinge. All 4 walls would be hinged together and then rotated to form the tote. This starting hinge design allows the walls to be modular and thus compact in shipping size. The assembly is relatively easy compared to the existing pods. No additional fasteners are needed and only 2 unique molds are needed for a tote. The issue with the first iteration is the expected rigidity once assembled and the retention force of the hinge design. The final ball snap and rotate to lock concept satisfied all the requirements.
Figure 36 shows two walls would be installed together. In this hinge design, the initial insertion is very smooth and easy. The slot is large allowing the ball snap of the other wall to easily slip right in. By rotating the wall 270 degrees, the walls are strategically locked into place, resisting any directions of forces expected when in tote formation.
Figure 37 shows the final step of the tote assembly. After all four walls are inserted together and wrapped around an aluminum plate, the first and last wall must be snapped in together. Finite element analysis is needed to determine the final geometry to ensure the wall can easily be relatively easy to snap together. After snapped in, the wall needs to have high retention force.
Given the symmetrical geometry of the ball snap and slot, the insertion and retention force should be the same. In effort to make the insertion and retention forces different, the ball snap was modified to a peg which would be inserted into a chamfered slot on the other wall. The chamfer would help guide the peg into position. Once in position, the peg would have more difficulty coming out. This improved rotate to lock hinge is shown in Figure 38 and finite element analysis was used to verify if the concept was valid.

Sliding and Locking Method

One of the main concerns for the stackable sliding concept is how the totes would slide with each other and also be able to lock in place when stowed. With no exoskeleton or frame, only the walls of the totes would be mated with each other to give the structure of the pod. This sections explores various methods and features in effort to combat issues with sliding and locking for a stackable pod. For locking, the turn key method was heavily investigated given its expected reliability and simplicity compared to other locking methods.
Version 1

Figure 39. Version 1: Assembly CAD (Left) with Exploded View of Tote (Right)

Figure 39. Version 1: Assembly CAD (Left) with Exploded View of Tote (Right) shows the exploded view of the first full tote assembly design which served as a baseline for the sliding and locking mechanism development. The design comprised of 3 unique injection molded walls. The front and back walls are similar except some features. In the back wall, a protruding feature acts as a stop so that the totes cannot be pushed too far back. In the front wall, there are features for the turn key mechanism and cut outs to allow the back stop of above tote to slide pass. The two side walls are identical with a cut out allowing extruded aluminum to be inserted into.

Figure 40. Version 1: Locking Latch

Figure 40 shows a zoomed up snapshot of the locking latch in this version 1 assembly. The latch was designed to be made in two pieces which would sandwich the front wall and press fit together. A hex key would be used to turn the latch. The larger
plate is asymmetric so that the center of gravity is below axis which allows the natural position is a locked position. The front part also acts as a handle for the forklift mechanism to pull out the tote. Careful consideration would need to be put on the press fit force. It would need to be significantly higher than the force to pull the tote out to ensure the latch does not come a part.

In Figure 41, mating surfaces for the back stop and front latches of a tote are circled. Once unlocked, the desired tote can be slid out. The issue with this design was that four latches needed to be unlocked in order to take out the tote. Also the concept was partially invalidated. Only through modeling the actual pod assembly was it realized that the concept would not allow the tote to slide out without interference, if all the totes had the same configuration for back walls.
Figure 42 zooms into the back stop region of Figure 41. The tote that is slid out looks free but if the tote were to continue being pushed back it would hit the wall of the bottom tote before settling into its natural position. The quick simple solution was switching the direction of the insets so that the features could mate. However further analysis would reveal that since every back wall is the same, the back wall of the desired tote would also be changed and the same problem would arise. The real challenge of sliding and locking is to stop drawers from going back without restricting adjacent drawers' from moving forward.
The major second revision of the assembly is shown in Figure 43 and the aim was to solve the interference issues with the sliding and locking in the first version assembly. To minimize number of latches, only one latch is used on each drawer. A shaft went inside the channel, underneath the aluminum plate and connected the front latch with a back latch. This concept allowed a back and front latch to be connected and be actuated with just one turn.
The assembly of the locking mechanism in this second version is shown in Figure 44 and the way it works is shown in Figure 45. Similar to the design in version 1, the pieces press fit together. In this design, however, a rod is press fit into a bushing like part and these parts are welded to a metal latch which also acts as a handle. The metal rod also has a bent feature on the end which acts as a latch behind the back wall. The long axle allows the stop in the back and the latch in the front to be turned together at the same time. Strategic thought was put into determining all the configuration of this latch to ensure the totes could slide in and out of each other without interference and be locked when needed. For this concept, the forklift needs to manipulate two latches. The one on the tote and the one above the tote.

In Figure 45, the pod on the farthest left highlights the desired tote and the position of the front and back latches in the locked state. In locked state the handle is perpendicular to the floor and in front of the front wall. The long latch on the back is behind the back wall. This makes the totes constrained in position. To unlock a tote, the top latch should be rotated 180 degrees counter clockwise. The bottom latch is rotated 90 degrees counter clock wise. These two latches allow the tote to slide freely out. The bottom latch has a small nub that can slide out a cut out in the front wall of the below tote. A stop on the back wall is what strategically interferes with the short nub to ensure that the tote is not pushed too far back.
In order to reduce the number of unique parts, the front and back walls were designed to be the same except this small piece called the "back plug". The back plug allowed both front and back wall to be the same, while providing a stop for the selected tote when reinserted back into the pod. This back plug could just be a simple part injection molded or die casted. It could be inserted at the supplier but it would also be fairly easy to install so it could be inserted during onsite assembly.

In this version, rails being molded directly into the plastic side walls was another major change. This change reduces the number of parts and assembly operations which ultimately reduces cost. The primary risk is sway due to likely lower stiffness.
Finite element analysis would be used later to finalize the wall geometry parameters or determine if an aluminum rail was mandatory.

A guiding feature was another feature that was integrated into this version. This chamfer is injection molded into the side wall rails so that the tote could be slid into place with even with tighter tolerances.

From a mechanical perspective, the stiffness of the pod assembly is concern with the latches being the locking mechanism. The latch on the back in the bend of the metal rod and the handle in the front would need to have very stiff bending stiffness. While this concept was well thought out in terms of how to get a locking mechanism to work for a sliding stackable pod, the manufacturing, parts needed and interaction needed with unlocking and locking seemed rather cumbersome and complicated.

Multiple iterations were designed after the first version. However, no matter what there were issues regarding locking and unlocking the tote. Finding a way to release a tote from a pod while not releasing other totes or interfering with an adjacent tote was a fairly major challenge to overcome. This tote concept named as version 2 was the only one that was able to solve a latching mechanism which could lock, unlock, and provide some sort of back stop.
There was always a concern for the need to lift up the desired pod just a little in order to slide the tote out. The tradeoff would be a sliding stackable pod with more mechanical reliability issues and an easier simpler forklift mechanism or a much simpler static stackable pod assembly with a slightly more complex forklift that needed to lift an above tote, lift and shift the desired tote out then down. Any complexity should be moved to the lifting mechanism because there is only a few of those units, where as any complexity on the pods means it would need to be multiplied by a million pods. In short, the pod and tote design should be as simple as possible.

Version 3

Figure 49. Version 3: Tote (Left) and Assembly CAD (Right)

The turn key latch was removed and the path forward included lifting the totes slightly. High rails are integrated into side walls so that issues with aligning side to side could be slightly relieved. The front and back walls also had features for locking totes together, similar to the “Lego” concept described in the idea generation phase. Figure 49 shows an assembled tote on the left and a desired tote being lifted and slid out while remaining within the side rails of the 2 adjacent totes. This version also includes coring out the walls and adding ribs for stiffness to resembled a part more realistic for injection molding.
The locking mechanism in this design is relatively very simple compared to the turn key latch mechanism. On the bottom of the front and back walls is a protruding feature that mates into an inset on the top of the front and back walls. The features are kept short so that the lifting motion is minimal to reduce the amount of extra head height.
needed for moving the totes. In this version, the features are half an inch. This means one tote would be moved slightly more than half an inch up. The desired tote would then be move half an inch up to clear the tote below and be pulled out. These steps are highlighted in Figure 51.

The high rails of the version help the desired tote to stay with the walls of the pod. The only alignment necessary is in the stowing action, which is guided by a chamfers on the top and bottom rails shown in Figure 53. Once the target tote is slid into place, the rails constrain the tote from moving side to side and the tote could be dropped into place.
Version 4

Figure 54. Version 4 Tote and Pod Assembly

Version 3 and version 4 did not have any major differences. Primarily the protruding features from the front and back walls were moved to be embedded directly into the side walls. There was concern that the protruding features would aid in pushing the front wall to unsnap open if product hit the front wall. Since the side walls were taking all the axial load from the weight of the pod and a large majority of the front back sway load, the side walls were thickened up while the front and back walls were thinned out. In this version, the front and back walls are used simple for completed the 4 walls of the tote and holding the product in. As the side walls were thickened up, the rails would also become stiffer. Similar to version 3, version 4 also had high rails, but just much thicker. In overview, version 4, from a conceptual standpoint satisfied all the requirements regarding the interaction between totes and totes and forklift.

Figure 55. Version 4 Tote High Rails
6. Major Design Changes with Finite Element Analysis

Finite element analysis was used to refine the version 4 design to meet mechanical based requirements. This section highlights the materials used in simulation and focuses on the evolution of an embedded snap hinge in the injection molded side wall to a metal plate hinge allowing the walls to fold 360 degrees with one another. Materials used in the analysis were a PC-ABS material, galvanized steel and aluminum.

Materials

The three primary materials considered are: a flame retardant acrylonitrile-butadiene-styrene (ABS) / polycarbonate (PC) blend, 6061-T6 Aluminum, and galvanized steel. The primary properties needed for finite element analysis are the young’s modulus, yield strength, density and poisons ratio.

* **ABS-PC**
  An easy flow, flame retardant grade of injection moldable plastic called Bayblend FR 3005HR is selected for the walls. The balanced blend of ‘ABS and polycarbonate provides its high heat resistance, high impact resistance, strength and stiffness.
  For finite element analysis the properties are given as below:
  - Young’s modulus of 2.7 GPa
  - Yield strength of 60 MPa
  - Density of 1180 kg/m^3
  - Poisson’s ratio of 0.35.

* **Steel: Galvanized**
  The hinge connectors are galvanized steel, a noncorrosive and much cheaper alternative to stainless steel with the same properties.
  For finite element analysis the properties are given as below:
  - Young’s modulus of 200 GPa
  - Yield strength of 203 MPa
  - Density of 7870 kg/m^3
  - Poisson’s ratio of 0.29.
Aluminum: 6061-T6

The bottom plate of each pod has a 6061-T6 aluminum plate. With a goal of minimizing thickness of the bottom plate to minimize GCU, metal is needed for stiffness. Aluminum is also selected for its benefits with reducing weight, given its relatively low density compared to other metals. For finite element analysis the properties are:

- Young’s Modulus: 69 GPa
- Yield Strength: 276 MPa
- Poisson’s Ratio: 0.33
- Density: 2700 kg/m^3

Snap Fit Hinge Verification

The snap fit hinge was the highest risk feature in the assembly. In order to de-risk the snap fit hinge, stresses via a nonlinear contact finite element analysis needed to be 1.5 times below the yield stress of the plastic material. A nonlinear stress analysis is necessary for the snap fit hinge because of the time-dependent load and large component deflection. A nonlinear analysis is a much more complex approach compared to a linear analysis, and consequently requires more computational power and simulation time. Figure 56. Finite Element Mesh of 2 Snap Feature Bodies displays the baseline model and mesh used for finite element analysis representing the snap features in the side walls. A representative model for the hinge was used to save computational power. Extra mesh controls were also applied to the hinge for higher fidelity results on hinge stress.
These results were compared to those from Solidworks simulation provided by MIT, which showed similar results. As a nonlinear analysis provides the stresses through each step in the range of motion, the Solidworks simulation was stopped as soon stresses surpassed material yield stress to save time.

![Peg Diameter](Image)

Figure 57. Snap Fit Hinge Parameters

The snap fit hinge parameters that changed were peg length, peg diameter, snap length, snap angle, snap gap, and hole diameter. These parameters are shown in Figure 57. Snap Fit Hinge Parameters. The other parameters not explicitly shown is the wall thickness and slit width. As these are plastic injection molded, the part must be cored out.

Analysis was completed primarily for insertion of the snap. Given a low insertion force with no yielding a simulation to get the removal or retention force was conducted. Figure 58. Snap Fit Hinge Simulation Setup shows how the simulation was set up. The bottom part was fixed. A displacement to insert the pegs, indicated by the large green arrows was applied down on the top part and roller slider fixtures were applied to the walls parallel to the direction of motion.
For a snap to be successful, the pull out force should be greater than 60 N, which is derived from the max weight of the product inside a tote and acceleration of the pod when being moved. The insert force should be below the pull out force, but be minimized. Finally the max stress on the part should be less than 40 MPa. The stress was carefully watched through a simulation to not surpass 40 MPa. To save time, the simulation was stopped as soon as the stresses were too high and a new iteration was designed and analyzed.

**FEA Baseline Results**

![Figure 58. Snap Fit Hinge Simulation Setup](image)

![Figure 59. Baseline Snap Fit Von Mises Stress Plot at 0.80" Displacement](image)
ANSYS was able to successfully solve the snap in concept on the insertion side only with a simulation time of 1.5 hours, which made it particularly important to find strategies to iterate quickly. The max yield stress was seen at 0.8” displacement shown in Figure 59. Baseline Snap Fit Von Mises Stress Plot at 0.80” Displacement with a max stress of 350 MPa, which is much higher than the plastic materials yield strength. Figure 60 shows the reaction force in the z-axis reaches a high 438 lbs or 1980N in order to install the part. In order to reduce the amount of load to necessary to install the part, the amount of interference between the pin and the opening was reduced in later iterations.

Snap Fit Hinge Parametric Study

Many iterations of the snap fit hinge geometry were tested through nonlinear contact finite element analysis. The values for the parameters and the results for 6 versions are highlighted in Table 4. Snap Fit Parametric Study Results. Both the baseline and V2 were fully solid models, but increasing the snap length and opening up
the snap gap, reduced the stress and insertion force by a magnitude. However, both forces and stresses still were too high.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>V2</th>
<th>V3</th>
<th>V4</th>
<th>V5</th>
<th>V6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snap length [in]</td>
<td>0.5</td>
<td>0.75</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snap gap [in]</td>
<td>0.123</td>
<td>0.2</td>
<td>0.35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snap angle [deg]</td>
<td></td>
<td></td>
<td>150</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hole size [in]</td>
<td></td>
<td>0.375</td>
<td></td>
<td>0.575</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peg diameter [in]</td>
<td></td>
<td>0.3</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall thickness [in]</td>
<td></td>
<td>Solid</td>
<td></td>
<td>0.079</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slit width [in]</td>
<td>n/a</td>
<td>0.12</td>
<td>0.24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stress [MPa]</td>
<td>350</td>
<td>49.8</td>
<td>101.6</td>
<td>158.5</td>
<td>74.1</td>
<td>70</td>
</tr>
<tr>
<td>Insertion Force [N]</td>
<td>1980</td>
<td>188.5</td>
<td>108.1</td>
<td>100.3</td>
<td>86.4</td>
<td>60</td>
</tr>
<tr>
<td>Retention Force [N]</td>
<td></td>
<td>--</td>
<td>--</td>
<td>125.4</td>
<td>95.9</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 4. Snap Fit Parametric Study Results.

V3 was the first cored our model to be tested. The snap hinge assembly had 0.079 or 2 mm walls. To account for the peg being hollow, all the parameters except snap angle and slit width were slightly increased for peg robustness. A packaging engineer had mentioned that plastic pegs are very unreliable unless the diameter is pretty big. Half inch diameter pegs would be reasonable and was the basis for selecting parameters for V3. By coring out the part, stresses increased and increasing feature sizes may have accounted to lower insertion force. V4, pretty much the same as V3, except with a longer snap length had a study for both insertion and retention force. The idea behind a longer snap length was to reduce insertion force. The force did increase, but surprisingly the stress had increases which could be from the peg deflecting more. Yielding was clearly a large risk based on the analysis results.

For the last two versions that were ran, a slit was tested in the snap design to relieve stress. This slit is indicated by the orange arrows in Figure 61.
The slit effectively relieved stress by a factor of 2 between version 4 and version 5 as well as reduced insertion and removal forces. Nevertheless the 74.1 MPa max stress would still yield the material. V7 was a final attempt made in this thesis to test a snap fit design. The slit was increased from 0.12" to 0.24", which unfortunately barely reduced the stress and reduced the forces as well. At 70 MPa max stress, 60N insertion and insertion force, V7 was the closest to meeting the requirements. V7 had a full 1.5 hour simulation which provided force-displacement curves for the insertion and retention force. The stress plots on insertion are shown in Figure 62. The results for contact forces for insertion are in Figure 63 and for removal are in Figure 64.
Figure 62. Snap Version 7: Stress Nodes (Top) and Stress vs Time on Various Nodes on Insertion (Bottom)
Figure 63. Snap Version 7: Contact Force vs Time on Insertion
Study name: Nonlinear 2 (Closed)
Plot type: Contact/Friction force

Figure 64. Snap Version 7: Contact Force vs Time on Removal
Snap Design Conclusion

While this study reveals results for 6 iterations, over 30 undocumented iterations were actually completed. The high number of iterations and consistent redesigns was an indicator that the concept of snap fit plastic hinges would be particularly risky given the loading requirements. Even though V7 could be continued to be massaged to achieve the exact results, the geometry started getting so complex that manufacturing and tooling it up would be unnecessarily complicated. Also to get the right feel and parameters for the geometry, these snaps would need to be prototyped with the material and process that would be used for production. Especially when these snaps would be injection molded, prototyping costs would also be very high. More development time would definitely be necessary if the snap fit hinge concept were to be further explored. For the sake of simplicity and assurance that a design would work, the final design utilizes a steel metal plate with two holes for self-tapping screws that go into the tote walls.

Hinge Design

In version 4, the walls had features that could be hinged together on site and the first and end walls would be snap fit together. Through finite element analysis on many iterations, the challenge of creating a plastic snap design which met the insertion and retention force specifications without yielding the plastic material was realized. To solve the issue, a galvanized steel metal plate with two holes, each having a self-tapping screw for plastic, is implemented as the connection or hinge between two walls for the final iterations. This joint shown in Figure 65 is designed to allow the walls to be able to rotate 360 degrees with respect to one another.

Figure 65. Galvanized Steel Plate Hinge with Plastic Self Tapping Screws.
Furthermore, as every tote needed to be built on site and each pod has 21 totes, on site assembly time was a point of concern with previous iterations. Table 5 provides very liberal estimates on the time for each step in a Version 4 stackable pod. The analysis reveals that with 1 worker, a pod could be built just under half an hour. The beauty of the modular design means that multiple workers can be building multiple totes at the same time to drive down assembly time. For example 5 workers, each taking 4 to 5 totes could drive down the pod assembly time to 6 mins per pod at more labor cost.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Unit Time</th>
<th># Times</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slide into other walls</td>
<td>3 s</td>
<td>3</td>
<td>9 s</td>
</tr>
<tr>
<td>Fold &amp; lock walls</td>
<td>3 s</td>
<td>3</td>
<td>9 s</td>
</tr>
<tr>
<td>Insert Al bottom plate by aligning into channels</td>
<td>1 min</td>
<td>1</td>
<td>60 s</td>
</tr>
<tr>
<td>Hammer / snap in last side</td>
<td>5 s</td>
<td>1</td>
<td>5 s</td>
</tr>
<tr>
<td>Time to build 1 tote</td>
<td>~ 83 sec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to build whole pod (target 21)</td>
<td>~29 mins</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Version 4 Assembly Time Estimate

Nevertheless, the hinge design for the final tote iteration was guided by the intention to remove any steps or any amount of time to build a single tote, given the understanding that the time needed to build a single tote would aggregate across 20 other totes. Moving more assembly steps from an onsite worker to the supplier would also mean more process control and thus greater pod yield rate.
With the proposed hinge design, all four walls of the final iteration seen in Figure 71 can be folded into a flat configuration seen in Figure 66. All the walls would be preassembled and hinged together at the supplier with a galvanized steel plate and two custom plastic self-tapping screws on the top and bottom of the tote. This hinge mechanism allows the walls to rotate 360 degrees to be folded in an accordion-like manner for shipping. In initial iterations, there were conversations about having the walls be joined with traditional hinges and just ship completely flat (e.g. all four walls on one layer). Intuition said that walls for the different size totes could just be layered. However, response from packaging and shipment team urged a redesign of the hinge which would allow the walls to fold into 4 layers of 1 wall or at least in half with 2 layers of 2 walls.
Figure 67. 170mm Wall Tote Folded (zoomed on Hinges)

Figure 68. Final Tote Design Top View
In the assembled as tote configuration, the final design from top view looks like Figure 68 and a zoomed in CAD model of the hinged region can be seen in Figure 69. A bag of the custom self-tapping screws for plastic would be sent in a bag with the tote & pod shipment. Only 2 screws, one for the top and one for the bottom of the hinge are needed to complete a tote.
7. Refining and Verifying the Final Design Assembly

![Figure 70. All Fully Assembled Totes for 1 Pod](image)

![Figure 71. 170mm Wall Fully Assembled Tote Design](image)

Section 6 highlights the major transition from a plastic snap in hinge assembly to a 360 degree hinge mechanism made with metal. Many features were modified based on finite element analysis, as well as high level manufacturing, assembly and packaging analysis. Figure 71 displays the final concept proposal culminates for this work. This section will discuss how and why specific features were refined for this final proposed design. Finite element analysis is also included for verification where necessary.

The Aluminum Plate

From previous work on the stackable pod using plastic sidewalls and an aluminum plate, there was already an understanding that a plastic floor would not be the
most efficient for gross cubic utilization as it would need a good amount of thickness. Given the previous work, aluminum was selected for the plate thickness study.

The only parameter that was looked at in this simulation study was plate thickness. For the setup, the 6061 plate is placed into a groove in an ABS-PC frame with no penetration. The bottom faces of the frame are fixed. A distributed load of 555 N/m² or 464N over 36” x 36”. The objective was to select the thickness that would allow a droop of no more than 5 mm given the loading condition. Another insight was that plate thickness should not go much higher than 14-15 gauge aluminum sheet metal due to past issues with thinner metal. This corresponds to 0.0571-0.0641 inches or roughly 1.5 mm. As such a 1.5 mm thick 6061 aluminum sheet metal was the first test.

![FEA Result: Stress on Bottom Plate](image)
Figure 73. FEA Result: Deflection on Bottom Plate

Figure 72 and Figure 73 reveal the stress and displacement on a 1.5 mm aluminum bottom plate given loading representative of product inside a tote. The max stress at 3.1 MPa and displacement at 0.6 mm is well below max stress and displacement requirements. As such, a 1.5 mm aluminum bottom plate was verified.

Figure 74. Aluminum Plate

The aluminum plate in Figure 74 shows the final aluminum plate with the 1.5 mm ideal thickness to support the max weight of product inside a tote and maintain within
specification. From version 4 to the final proposal, the center channel was added and minimized in width to maximize gross cubic utilization. The channel also has a 120 degree angle with the floor for ease of manufacturing and nesting in packaging purposes. With the current geometry, the 120 degree angle allows plates to be nested with 0.125” separation.

Side Walls

As the side walls are load bearing axially and side to side, they required the most fine tuning through finite element analysis.

Side to Side Sway Verification

Sway is a particularly difficult phenomenon to model without running a contact simulation on the entire assembly. With a lack of computational power to run such a simulation with contact on the assembly, simplified methods of validating or at least providing reassurance that the total pod would have less than 1 in sway were needed.

Since the goal was to minimize sway, the nominal wall thickness was set to the material’s suggested maximum wall thickness for injection molding at 3.5 mm to maximize stiffness. The parameters that were changed to affect sway were total wall thickness and number of ribs.

The simulation setup is shown in Figure 75. Sway is maximized when force due to acceleration on the sidewalls is maxed. This acceleration also varies with the weight of the pod.
An acceleration of 1.1 m/s² was imposed on the part in the direction normal to the wall highlighted in pink. The green arrows indicate the regions, where the part is fixed. This region is fixed because this bottom rail would generally be sitting mating with the top rail of a tote below. A distributed load of 227 kg was placed on the faces of the part.

Figure 75. Sway Simulation Setup
To determine a ball park estimate of the maximum deflection on 1 tote wall, the bending behavior of 85 inch long PC-ABS material of 3 wall geometries was analyzed in Solidworks simulation. The 85 in length represented the height of the tote. 3 geometries were analyzed to identify the extent to which cross sectional shape affects the bending. The bottom of the walls were fixed and a deflection of 1 in was imposed on the top of the 3 walls.
The similar color gradient across all the walls in Figure 76, shows that all 3 walls deformed in a similar manner. The difference in the behavior can be seen in Figure 77. Due to different cross sectional geometries, the stiffness varies and thus the reaction forces at the tip are different. The result of this experiment was that for a 1” deflection on a 2160 mm (85 inch) tall PC-ABS pod wall at 30 mm in thickness, the differences in stiffness and cross sectional area did not result in differences in bending behavior. Consequently the shape of the bend given the deflection could be used to model the shape of the bend on the actual pod walls with ribbing and mating features.

![Diagram showing deflection and cross-sectional areas.]

By Similar Triangles:

\[
\frac{1 \text{ in}}{85 \text{ in}} = \frac{\text{max deflection for wall with height, } h}{\text{wall height, } h}
\]

max deflection for wall with height

- 45 mm: 0.53 mm
- 70 mm: 0.82 mm
- 110 mm: 1.29 mm
- 170 mm: 2.00 mm
- 300 mm: 3.53 mm

Figure 78. Modeling Max Deflection of Bending Side Walls given 1” Sway

The true scale displacement plot resulting from the simulation is shown on the far left in Figure 78. The 1 in displacement appears to make the wall bend in a very rigid way, almost as if a rigid wall pivoted on a hinge at the fixed end. A zoomed in displacement plot scaled up by a factor of 10 is shown right next to it with annotations. The closer look reveals that the wall is not completely straight when bent. If the wall were completely rigid, it would be collinear with the black dotted line. If the wall actually bent with this behavior, the maximum allowed deflection for each wall can be calculated.
by using similar triangle theorems. The allowed maximum deflection for each wall height given this model is revealed in Figure 78. The 170mm wall is what was used for most finite element analyses and this model indicates the deflection limit is at 2 mm. However this is the best case scenario. As can be seen near the blue region, the angle of deflection is actually much lower than the angle made by the black dotted line and ground, 0.67\degree. Even the angle through the red, yellow and green region to the ground is less.

As sway is particularly hard to model but a high risk failure mode, another more model to was set up to determine more conservative deflection specifications. In Figure 79, the deflection of the bending side wall given a 1” sway is scaled up by 100x to magnify the bending angles. Estimate angles were taken from the blue region and the red, orange, yellow region, which resulted in 105 degrees and 150 degrees respectively. As these were scaled up by 100x and the angle to use for similar triangle theorems should be taken from a line perpendicular to the ground, the actual angles would be 0.15\degree and 0.6\degree respectively. These angles would be used to determine upper and lower bounds of a more conservative max deflection for each side wall.
Using similar triangle theorems, the upper and lower bounds for the maximum allowable deflection specification for each side wall for different heights are calculated in Table 6. For example, a 170 mm wall height should not deflect more than 1.78 mm. Within the bounds of 0.45 mm and 1.78 mm, the risk would be relatively low and the design would succeed with a first pass validation. If the deflection was below 0.45 mm, the risk for sway would be nearly completely mitigated. These values were used to guide a parametric study using finite element analysis to determine the side wall geometry parameters, including total wall width, and number of horizontal and vertical ribs. The middle value of 1.1 mm was used as a target for a parametric study in simulation.

<table>
<thead>
<tr>
<th>Wall Height</th>
<th>Deflection at 1.05° (0.15°) [mm]</th>
<th>Deflection at 1.50° (0.6°) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>0.12</td>
<td>0.47</td>
</tr>
<tr>
<td>70</td>
<td>0.18</td>
<td>0.73</td>
</tr>
<tr>
<td>110</td>
<td>0.29</td>
<td>1.15</td>
</tr>
<tr>
<td>170</td>
<td>0.45</td>
<td>1.78</td>
</tr>
<tr>
<td>300</td>
<td>0.79</td>
<td>3.14</td>
</tr>
</tbody>
</table>

Table 6. Maximum Allowable Deflection Boundaries for Different Tote Heights

The results for max displacement and max stress for 10 iterations from a parametric study on the side wall varying total wall width, number of horizontal ribs, and number of vertical ribs is shown in Table 7. The first two iterations, baseline 1 and baseline 2, were fully solid un-ribbed walls to determine what nominal thickness is necessary to hit a less than or equal to 1.1 mm deflection. The rational is that if a solid

<table>
<thead>
<tr>
<th></th>
<th>Baseline 1 (Solid)</th>
<th>Baseline 2 (Solid)</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Wall Width</td>
<td>25</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td># of Horizontal Ribs</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td># of Vertical Ribs</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>MAX DISPLACEMENT [mm]</td>
<td>1.18</td>
<td>0.525</td>
<td>13.72</td>
<td>7.48</td>
<td>4.62</td>
<td>3.10</td>
<td>2.38</td>
<td>1.43</td>
<td>1.12</td>
<td>0.81</td>
</tr>
<tr>
<td>MAX STRESS [MPa]</td>
<td>12.54</td>
<td>7.04</td>
<td>14.64</td>
<td>12.2</td>
<td>11.36</td>
<td>9.86</td>
<td>7.64</td>
<td>6.54</td>
<td>5.98</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Table 7. Ribbing Parametric Study Results
wall cannot meet the specification then a cored out wall of the same thickness would definitely not meet it.

![Graph of Solid Wall Thickness vs Max Displacement](image)

**Figure 80. Solid Wall Thickness vs Max Displacement**

The stresses for all iterations were well below the yield stress of the PC-ABS material and hence, the displacement is most important. Figure 80 graphs the expected deflection for solid wall thickness for a total thickness of 25mm, 30mm and 35mm. Expecting displacement would increase with coring out the material, 30 mm was selected for the nominal total wall thickness, which would have a deflection of 0.525 mm at best.

![Graph of Max Displacement vs. Number of Vertical Ribs](image)

**Figure 81. Max Displacement vs. Number of Vertical Ribs from FEA Results**
Iterations 3 through 9 in the parametric study varied the number of vertical walls from 0 to 12, while keeping the number of horizontal walls constant at 4. Figure 81 charts the resulting displacement versus the number of total ribs. The first few ribs have an exponentially high impact on the displacement. The effect on displacement for each additional rib seems to taper off around 12 ribs. At 16 ribs, the deflection is at 1.12 mm, just about the target specification. To improve this result further, 4 more horizontal ribs were added which reduced the deflection to 0.81 mm. While not fully optimized, this analysis guided the selection of parameters for a wall geometry that could pass a first pass validation.

Figure 82. Final Proposal Side to Side Deflection Results
The displacement and stress plot results can be seen in Figure 82 and Figure 83. A 30 mm total wall thickness with 16 vertical ribs and 8 horizontal ribs was chosen. The expected bending deflection of the 170 mm tote wall would be 0.81 mm which is below the target of 1.1 mm. The stress of the final proposal is 5.4 MPa which is about a magnitude lower than the yield strength.

**Axial Loads on Side Walls Verification**

In the design, only the two side walls are load bearing. The front and back walls merely complete the square structure of the tote and retain the product within the tote. Finite element analysis was used to analyze stress on a wall if it was axially loaded with a weight equal to half the max weight of a pod. As the height and length of the wall are relatively fixed, total wall thickness could be changed to meet specifications.

The objective of this simulation study is to determine if the part would be axially stiff enough and not yield under an expected loading equal to the max weight of a pod with product. To decrease the computational time, simulation was performed on only one of the side walls, which made expected loading cut in half. The wall was fixed on the bottom and a total force of 1667 N was applied on the top wall. This setup is shown.
in Figure 83. To change the stiffness of the part, some parameters that could be changed are total wall thickness, rib web thickness, and number of ribs.

Through simulation, axial loading can be seen as not high risk. The deflection plot shown in Figure 85. Side Wall Axial Load Displacement Plot reveals the max displacement is fractions of a millimeter. Figure 86 also shows that the max stresses on the part due to maximum loading on a tote would be a magnitude less than that for the material to yield.
Figure 85. Side Wall Axial Load Displacement Plot

Figure 86. Side Wall Axial Load vonMises Stress Plot
Guiding Surfaces and Chamfers

In the final proposal, extra attention was also paid to manufacturability of the injection molded ribbed walls. Side actions, overmolds and complex tooling were aimed to be minimized. For the most part, the walls would be a basic 2 part mold, a core and cavity, with cylindrical inserts to make the holes for the screws. Alternatively the hole could be a post operation if the plastic is machinable. The highlighted surfaces in Figure 87 were strategically chosen to be the smooth side of the ribbed wall as they will be sliding surfaces with a below or above tote.

Figure 87. Smooth Walls on Sliding Surfaces

Figure 88. Embedded Chamfers for Alignment
Chamfers highlighted in Figure 88 are integrated in the design to help with alignment. Chamfers on the front and back help with sliding the desired tote back into the pod envelope. The chamfers on the top ledges help the desired tote to sit back into place once back into the pod envelope.

The Handle

![Figure 89. Embedded Handles](image)

Figure 89 shows a perspective side view of the tote walls. A slot feature is integrated into the walls for the forklift to hold and move the tote. Quick finite element analysis was able to provide initial validation for the structural strength of the handle.
The plastic yielding from the weight of the pod is the primary concern. Figure 90 shows the von Mises stresses on a side wall with the embedded handle. A distributed mass equal to half the maximum weight of the pod with product and gravity was applied to the part. The top surface of the handle is fixed indicated by the green arrows. The analysis reveals a safety factor of about 5, which indicates low risk of yielding.

The edges did have a maximum displacement of 2.7 mm shown in Figure 91. While this displacement does not pose a yielding risk, if it poses other concerns, the displacement can easily be reduced by lengthening the handle slot so that the forklift grip supports more of the pod weight along the length.
Different Size Totes

There are 5 different heights of totes: 300mm, 170mm, 110mm, 70mm, and 50mm. The tote presented in this final design proposal section thus far is the 170mm tote, which is similar in geometry with the 110mm and 70mm totes.

The 300mm tote also has the 360 degree hinge mechanism, which enables the walls to be folded for shipping in the same configuration as the 170mm tote.
The only difference with the 300mm tote shown in Figure 94 is that it does not have the top rail. It is the tote at the top of the pod and does not need to interface with any tote above it. Similar to the 170mm tote it can be folded for shipping.
The 6 totes on the bottom of a pod are 45 mm totes. Given the short height of these totes, packaging and shipping them as is, is possible. Directly injection molding the bottom totes would require tooling costs due to some more complexity. Tooling cost is only a one time cost and is offset by the high volume needed. With a desired production of 1 million pods a year and a minimum of 6 million - 50mm totes need to be produced a year and defected parts need to be accounted for as well. The unibody tote would eliminate the need for 2 molds (for each wall), 48 extra hinges, and 96 self-tapping screws for plastic as well as the assembly time for 6 totes for each pod. Only producing and shipping the full 50 mm tote can be justified given the short height. These small totes can just be stacked up high for shipping as is and 6 of them would be taken to start the base of the pod.

One primary concern is the droop of the tote floor. Aluminum was selected for the bottom plate of the other size totes for its stiffness given a thin geometry to maximize gross cubic utilization and low weight to minimize shipping costs. For the smallest size tote however, a total bottom wall with ribs totaling at 16.5 mm thickness is needed to meet the 5 mm droop specification.
To ensure the floor of this injection molded tote would be stiff enough, various ribbing configurations were tested in finite element analysis. Given the symmetry of the part and loads, to set up the analysis, the part was split into a quarter. The edges of the tote were fixed and a distributed load equal to the maximum weight of product in a tote was applied to the floor. As expected, most of the displacement occurs at the very center of the part. This understanding guided the placement of ribbing to be concentrated at the center.

One ribbing configuration that met the specification has 46 ribs in one perpendicular to the side walls and 19 ribs parallel to the side walls. The finite element analysis on the final design proposal estimates the droop at 4.3 mm, meeting the 5 mm specification. The results for displacement is shown in Figure 97 and the maximum stress on the part is 6.5 times below yield of the material.

As the proposed design is merely a proof of concept, the bottom wall geometry can be altered to optimize weight and gross cubic utilization. For example, the total thickness of the bottom wall can be reduced to save gross cubic utilization by adding more ribs to compensate for the lost in stiffness due to thickness. Other more strategic
formations for the ribbing, particular adding more ribbing where displacement is most, could also reduce material in the future.

Gross Cube Utilization Analysis

Figure 98. Final Assembly of Stackable Pod

One of the validation steps for the final design was gross cubic utilization analysis. To determine the percentage of space available for product inside the pod, the allowable volume for each tote was calculated for each size tote and multiplied by the quantity of that type of tote. The cross cubic utilization of each tote was calculated as well as for the total pod considering different quantities of each tote size.


<table>
<thead>
<tr>
<th></th>
<th>/w Injection Molded 45 mm Tote</th>
<th>/w Hinged 45 mm Tote</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 mm (qty. 6)</td>
<td>967 (57.8%)</td>
<td>2057 (75.5%)</td>
</tr>
<tr>
<td>70 mm (qty. 6)</td>
<td></td>
<td>3277 (80.3%)</td>
</tr>
<tr>
<td>110 mm (qty. 5)</td>
<td></td>
<td>5211 (83.2%)</td>
</tr>
<tr>
<td>170 mm (qty. 3)</td>
<td></td>
<td>8119 (84.2%)</td>
</tr>
<tr>
<td>300 mm (qty. 1)</td>
<td></td>
<td>14426 (86.9%)</td>
</tr>
<tr>
<td><strong>Total Usable Volume [in^3]</strong></td>
<td>96843</td>
<td>96843</td>
</tr>
<tr>
<td><strong>Total Volume [in^3]</strong></td>
<td>117331</td>
<td>117331</td>
</tr>
</tbody>
</table>

**Pod GCU**  

|                      | 79.4%                           | 82.5%               |

Table 8. Gross Cubic Utilization for Pod with Fully Injection Molded and Hinged 45 mm Tote

Table 8 shows the gross cubic utilization for each individual tote size as well as the total pod without the base. The final design proposed and verified with finite element analysis in this section has a GCU of 79.4%. All the totes except the 45 mm fully injection molded tote has a GCU of above 80%. With a low 57.8% gross cubic utilization, the 45 molded tote was further analyzed. This analysis made the tradeoff for shorter assembly time for lower GCU, higher manufacturing and materials costs, and higher packaging and logistic costs seem not worth it.

Even though all the tote rails would need to be refined and modified to allow a 45 mm hinged tote to work with the assembly, GCU and cost analyses were able to be performed by linear extrapolation methods with the 170 mm, 110mm and 70 mm tote. If the smallest 45mm tote was hinged, the GCU of the tote would increase by a significant 17.7%. However since there are many other totes, the overall effect was only 3.1%. Nevertheless, even small percentages can potentially have a big impact.
analyzing the effect of maintaining a similar hinge design for the 45 mm tote was considered.

<table>
<thead>
<tr>
<th>Front/Back Wall Thickness reduction [mm]</th>
<th>/w IM 45 mm Tote</th>
<th>hinged 45 mm Tote</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>81.2% (+ 1.8%)</td>
<td>84.4% (+ 1.9%)</td>
</tr>
<tr>
<td>-5</td>
<td>80.3% (+ 0.9%)</td>
<td>83.5% (+ 0.9%)</td>
</tr>
</tbody>
</table>

Table 9. Change in GCU with Front/Back Wall Thickness

Due to prioritizing critical parts with the time available, finite element analysis was only performed on the most risky features of the design. The side and front walls are primarily used for retaining the product in the walls and feel very little load otherwise. With this understanding, a brief analysis on the effect of front and side wall thickness with GCU was done and the results are in Table 9. The baseline design has a wall thickness of 15 mm. A wall front/back wall thickness reduction of 5 mm, or 33%, would translate to roughly 0.9% increase with GCY. With a 66% reduction, the front/back wall would be 5 mm. This could be injection molded plastic with many ribs or a cheap metal plate providing the stiffness necessary. The exact material would need to be validated with FEA, but if the front back wall were 5mm, the pod could have a GCU as high as 84.4%.

8. Manufacturing, Packaging & Logistics and On-site Assembly Costs

Mechanical robustness and gross cubic utilization was analyzed in previous sections. The final analysis necessary for validating the stackable design is costs. The costs were identified to be attributed primarily from manufacturing, packaging & logistics and on site assembly costs. In section 7, a pod with fully injection molded 45 mm totes was primarily analyzed. However, the significant loss in GCU resulted in the need to analyze a pod with a 45 mm hinged totes in addition to the pod with the 45 mm fully injection molded totes. The manufacturing, packaging and logistics, on-site assembly costs are analyzed for both pods in this section. Additionally, as a base was not designed for this thesis, a base, which would need to be slightly modified to mate with the stackable pods, from a previously designed tray pod was included in the cost analysis. This base is displayed in Figure 99.
Manufacturing

This section covers how each part is proposed to be manufactured and the associated costs for manufacturing the parts at scale. To estimate costs associated with manufacturing, a baseline study was performed purely on material costs. First pass calculations revealed that the 45 mm fully injection molded tote had significant extra material costs. Consequently the weight and volume of for a hinged 45 mm tote was extrapolated and costs were analyzed for both paths. Hinging the 45 mm tote would require some redesign and validation of the rails, but could be worth it for the cost savings.

Proposal

To minimize tooling costs, the final design aimed to minimize number of unique parts. The pod assembly consists of 12 unique parts: a steel hinge plate, self-tapping screw for plastic, aluminum bottom plate, 4 wall sets (for 70, 110, 170, and 300 mm totes) each with 2 unique walls, and a 45 mm fully injection molded tote. To keep the hinge plate cheap and stiff, it is manufactured with steel by stamping processes. A galvanized steel would likely increase the price slightly but would be a lot cheaper alternative to stainless steel and be necessary to be corrosive resistant. The self-tapping screws for plastic would likely be an 18-8 steel and have a custom shoulder on them so that the hinges could smoothly rotate around. The process to make these is a standard thread rolling process used to make screws in industry. If the custom shoulder
equates to an astronomical cost, the plastic side wall housing can have a sleeve feature for the hinge to sit into.

**Expected Costs**

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
<th>Proposed Process</th>
<th>Unit material cost [$/lb]</th>
<th>Unit Volume [in^3]</th>
<th>Unit Weight [lb]</th>
<th>Quantity per Pod</th>
<th>Total Cost [$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hinge</td>
<td>Steel</td>
<td>Stamp</td>
<td>0.15</td>
<td>0.07</td>
<td>0.02</td>
<td>120</td>
<td>0.36</td>
</tr>
<tr>
<td>Self Tapping Screw</td>
<td></td>
<td>Thread Rolling</td>
<td></td>
<td>0.04</td>
<td>0.12</td>
<td>240</td>
<td>0.43</td>
</tr>
<tr>
<td>Al Plate</td>
<td>Aluminum</td>
<td>Roll form</td>
<td>0.86</td>
<td>77</td>
<td>7.52</td>
<td>21</td>
<td>97.01</td>
</tr>
<tr>
<td>300 mm wall set</td>
<td>ABS/PC</td>
<td></td>
<td></td>
<td>408</td>
<td>15.61</td>
<td>1</td>
<td>29.50</td>
</tr>
<tr>
<td>170 mm wall set</td>
<td>ABS/PC</td>
<td></td>
<td></td>
<td>278</td>
<td>10.04</td>
<td>3</td>
<td>56.93</td>
</tr>
<tr>
<td>110 mm wall set</td>
<td>ABS/PC</td>
<td>Injection Mold</td>
<td>1.89</td>
<td>205</td>
<td>6.95</td>
<td>5</td>
<td>65.68</td>
</tr>
<tr>
<td>70 mm wall set</td>
<td>ABS/PC</td>
<td></td>
<td></td>
<td>148.6</td>
<td>4.50</td>
<td>6</td>
<td>51.03</td>
</tr>
<tr>
<td>45 mm IM wall</td>
<td>ABS/PC</td>
<td></td>
<td></td>
<td>457</td>
<td>10.48</td>
<td>8</td>
<td>220.90</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>521.84</strong></td>
</tr>
</tbody>
</table>

Table 10. Stackable Pod with 45 mm IM Wall Manufacturing Processes and Material Costs

Table 10 reveals the proposed processes to make each component for the pod with a 45 mm fully injection molded tote. In addition to the processes, the part cost and total costs are estimated by just the raw material costs as pods are produced at extremely high volumes. The current industrial price of steel is $300/ton which equates to $0.15/lb [18]. The industrial price of aluminum was found to be on average $0.86/lb [19]. Assume the price of the ABS/PC is $1.89/lb. With these material costs, the unit weight of each part and quantities for each, the pod with the 45 mm injection molded wall tote would be $521.84. The 45 mm fully injection molded tote, however makes up for 42% of this cost, which provided another reason to consider a redesign to allow a hinged 45 mm tote.
Figure 100 shows how the volume and weight is linearly related with the height of the tote for the 70mm, 110mm, and 170mm hinged totes. With the equation of the linear trend lines, the weight and height was able to be extrapolated for a 45mm hinged tote.

![Graph showing volume and weight extrapolation](image)

**Figure 100. Extrapolating the Volume and Weight for 45mm Hinged Tote**

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
<th>Proposed Process</th>
<th>Unit material cost [$/lb]</th>
<th>Unit Volume [in³]</th>
<th>Unit Weight [lb]</th>
<th>Quantity per Pod</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hinge</td>
<td>Steel</td>
<td>Stamp</td>
<td>0.15</td>
<td>0.07</td>
<td>0.02</td>
<td>168</td>
<td>$0.50</td>
</tr>
<tr>
<td>Self Tapping Screw</td>
<td>Steel</td>
<td>Thread Rolling</td>
<td>0.04</td>
<td>0.04</td>
<td>0.12</td>
<td>336</td>
<td>$0.60</td>
</tr>
<tr>
<td>Al Plate</td>
<td>Aluminum</td>
<td>Roll form</td>
<td>0.66</td>
<td>77</td>
<td>7.52</td>
<td>21</td>
<td>$135.81</td>
</tr>
<tr>
<td>300mm wall set</td>
<td>ABS/PC</td>
<td></td>
<td></td>
<td>408</td>
<td>15.61</td>
<td>1</td>
<td>$29.50</td>
</tr>
<tr>
<td>170mm wall set</td>
<td>ABS/PC</td>
<td></td>
<td></td>
<td>278</td>
<td>10.04</td>
<td>3</td>
<td>$56.93</td>
</tr>
<tr>
<td>110mm wall set</td>
<td>ABS/PC</td>
<td>Injection Mold</td>
<td>1.89</td>
<td>205</td>
<td>6.95</td>
<td>5</td>
<td>$65.68</td>
</tr>
<tr>
<td>70mm wall set</td>
<td>ABS/PC</td>
<td></td>
<td></td>
<td>148.6</td>
<td>4.50</td>
<td>6</td>
<td>$51.03</td>
</tr>
<tr>
<td>45mm wall set</td>
<td>ABS/PC</td>
<td></td>
<td></td>
<td>118.2</td>
<td>3.21</td>
<td>6</td>
<td>$36.46</td>
</tr>
</tbody>
</table>

**Table 11. Pod Material Costs if 45mm Totes were Hinged**

Total: $376.52
Values in Table 10 were modified under the situation that the smallest 45 mm totes were hinged. Table 11 indicates all the modified values in red. Primarily, a hinged 45 mm tote would mean 6 more aluminum plates and hinge assemblies would be needed for the 6 new 45 mm wall sets. The weight and volume of the plastic needed for the 45 mm wall tote would also decrease. In summary, if the 45 mm totes were hinged, there would be a $145.32 cost savings. Additionally, the total weight would drop by 78 lbs.

Packaging & Logistics

The packaging analysis entails understanding what configuration the parts would be shipped in as well as what materials would be used for packing the parts. Iterations on the design were made to reduce packaging costs.

Proposal

All the foldable totes are somewhat nestable. In the shipping configuration, the walls can be in “lego” configuration with the rails nesting into another set of walls. This saves 40 mm of width of every set of walls. Additionally, this nesting increases the packing density in a shipping container or pallet. Figure 101 shows how the foldable totes would fold and nest.

Figure 101. Foldable Totes in Shipping Configuration
Figure 102 displays the 45mm fully injection molded totes as they would be stacked when shipping. These shallow 45mm height totes also nest with 40mm, the height of the rails, which keeps the totes relatively compact in shipping.

Figure 103 shows how the aluminum plates would be stacked for shipping. These 1.5 mm plates have a drafted channel which allows nesting with 3.175 mm separation between plates. The only remaining parts in terms of shipping are the self-tapping screws. Based on the packaging team’s assessment, these hardware parts can be easily shipped in a bag with no need for any external packaging quote.

Expected Costs

Many assumptions were needed for the analysis. The parts would be drop shipped directly from the vendor to the fiducial center. In other words, crossdocking would be necessary. The logistics or shipping costs for a full trailer is based on current
average shipping rates between shipping locations in the Midwest to various North American fiducial sites. All packaging and material costs were also best estimates based on drawings and not physical parts. ISTA testing will be required to validate final packaging specifications. The logistics on trailer loading configuration is also based on standard North American 53’ trailers. The costs for hardware such as the screws were excluded from the study as from a packaging perspective they are negligible. As the stackable pod base has not been designed yet, and would just need to be slightly modified, the packaging and logistics results from a previously designed base for a tray-based pod was used for a realistic close estimate. Estimated annual volume was also analyzed at 1 million units.

2 models for shipping were offered: individual and all in one component. The individual model assumes that the trailer only ships one type of item at a time. On the other hand, the all in one shipping model has every component of the pods shipping on the same trailer. This is less efficient because the various pallet sizes have to stack with one another and the trailer weight has to be evenly distributed as well, which reduces the options to stack, and reducing trailer gross cubic utilization efficiency. With the multitude of parts and types of parts, steel, aluminum and plastic, the parts will most likely need to be sourced from multiple vendors. As a result, the individual model was ultimately chosen for the cost analysis.

For the packaging and logistics cost study, a bill of materials with nesting configurations, part weights, dimensions, and quantities were sent to a packaging engineer who determined key values to achieve the complete kit piece price, or the total logistics and packaging price for 1 pod. Essentially based on the size and nesting configurations, the number of parts in a pallet, the size of the pallet, and associated costs were determined. Based on the pallet geometry, the maximum pallets per trailer and parts per trailer were identified. With this information, the price for packaging each piece and shipping logistics for each piece were calculated.
Table 12. Packaging and Logistics Cost for Stackable Pod with 45 mm IM Tote

<table>
<thead>
<tr>
<th>Part Description</th>
<th>DOM Qty</th>
<th>Parts / Pallet</th>
<th>Pallet Dim</th>
<th>pallet dim (lbs)</th>
<th>Pallet Stackability</th>
<th>Cost / Pallet</th>
<th>Inbound</th>
<th>Pkg &amp; Logistics Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Inbound</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Max Inbound Pallets / Trailer</td>
</tr>
<tr>
<td>Aluminum Plate</td>
<td>21</td>
<td>55</td>
<td>48 x 48 x 32&quot;</td>
<td>438</td>
<td>Yes</td>
<td>$40.00</td>
<td>90</td>
<td>4,950</td>
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<td>1</td>
<td>36</td>
<td>48 x 48 x 47&quot;</td>
<td>662</td>
<td>Yes</td>
<td>$100.00</td>
<td>60</td>
<td>2,160</td>
</tr>
<tr>
<td>170mm Wall Set</td>
<td>3</td>
<td>60</td>
<td>48 x 48 x 49&quot;</td>
<td>751</td>
<td>Yes</td>
<td>$40.00</td>
<td>60</td>
<td>3,600</td>
</tr>
<tr>
<td>110mm Wall Set</td>
<td>6</td>
<td>93</td>
<td>48 x 48 x 49&quot;</td>
<td>753</td>
<td>No Part Drawing Available, Extrapolated From Part 2D (170mm Wall Set)</td>
<td>$40.00</td>
<td>60</td>
<td>5,500</td>
</tr>
<tr>
<td>70mm Wall Set</td>
<td>6</td>
<td>146</td>
<td>48 x 48 x 49&quot;</td>
<td>751</td>
<td>No Part Drawing Available, Extrapolated From Part 2D (170mm Wall Set)</td>
<td>$40.00</td>
<td>60</td>
<td>8,748</td>
</tr>
<tr>
<td>45mm Injection Molded Tote</td>
<td>6</td>
<td>10</td>
<td>48 x 48 x 53&quot;</td>
<td>254</td>
<td>Yes</td>
<td>$40.00</td>
<td>60</td>
<td>1,080</td>
</tr>
</tbody>
</table>

Table 13. Packaging and Logistics Cost for Stackable Pod with 45 mm Hinged Tote

Table 12 and Table 13 indicates the values with each step of this process to determine the shipping and logistics piece price for a pod with the 45mm fully injection molded tote and the 45mm hinged tote. The final breakdown between logistics and

104 | Page
packaging costs is shown in Table 14. For the injection molded tote, the packaging cost is 61% of the total cost and for the hinged tote, it is 59% of the total cost.

<table>
<thead>
<tr>
<th></th>
<th>Logistics Cost per POD</th>
<th>Packaging Cost per POD</th>
<th>Total Pkg &amp; Log Cost per POD</th>
<th>Annualized Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>/w 45mm IM Tote</td>
<td>$23.66</td>
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<td>$56,478,698</td>
</tr>
<tr>
<td>/w 45mm Hinged Tote</td>
<td>$15.80</td>
<td>$25.03</td>
<td>$40.70</td>
<td>$40,704,153</td>
</tr>
</tbody>
</table>

Table 14. Logistics and Packaging Costs Breakdown

Onsite Assembly

Onsite assembly is typically not a highly controlled process which leads to defects and rework. Moving more of the assembly to the supplier would effectively increase yield. In building an assembly plan, the deployment team measures productivity by pods per person per hour. The target should be above 2.0 with an output of 1200-1600 pods per day at a site and a cycle time of under 20 mins per pod per person. While 2 people could build a pod in 10 mins, the goal should be in units of mins per pod per person. In the onsite assembly analysis, a proposal of how the totes would be assembled is given and a time approximation to perform the steps is used to estimate the production rate and costs.

Proposal

The assembly has 6 primary steps. The first, unpacking the base, for which the design is not included in this thesis, is estimated around 5 seconds. The second step is to unpack the wall sets which would be on pallets. An estimate of 5 seconds is needed to unpack each wall set. Since the 45mm totes are ready as is, they are immediately stacked on the base. This step is estimated to be 5 seconds and all of these first three steps are depicted in Figure 104.
Figure 104. Assembly Steps 1, 2, 3

Figure 105 shows the rest of the assembly steps. Once unpacked, the fourth step is to hinge the side walls around an aluminum plate, which should take about 8 seconds for each tote. The fifth step would be to install the self-tapping screws to lock the walls into the tote shape. Done with a power drill, this step should be about 5 seconds for each tote. After each tote is completed, it should be stacked in piles with equal size totes. A forklift, perhaps even the same one that is used to select the desired tote is used to stack all the totes on top of each other. With 4 piles to stack on top of the base which already has the 45mm totes, the total operation should be about 1 min.

Figure 105. Assembly Steps 4, 5, 6

For the modified design with the 45 mm hinged totes, the assembly steps are pretty much the same. The only difference is the third step mentioned, stacking the 45mm totes immediately on the base would now be replaced with just more totes that need to be transformed into totes.
**Expected Costs**

The expected costs for assembly are directly related to the time it takes to build a pod. All the times associated with each step are tabulated in Table 15. Based on this analysis a pod can be built in under 10-11 minutes by 1 person, which is 2 times better than the specification of 20 minutes per pod per person. A 1.5 safety factor was also put on this time for human error and imperfection. Even with this safety factor, the pod can be likely built in about 15 minutes. At $40 an hour, one pod would be around $8.93 per pod for assembly labor costs and would fluctuate slightly depending on the yield rate and speed of the worker. At this rate, a single worker could build 36 pods a day and to hit a desired output of over a thousand pods a day, 33-44 workers would be needed.

<table>
<thead>
<tr>
<th>#</th>
<th>Step Description</th>
<th>Unit Time [s]</th>
<th>Quantity</th>
<th>Total Expected Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Assemble Base</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>Unpack walls and aluminum</td>
<td>5</td>
<td>21</td>
<td>105</td>
</tr>
<tr>
<td>2</td>
<td>Stack 6x 45mm totes on to base</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Wrap walls around aluminum</td>
<td>14</td>
<td>15</td>
<td>210</td>
</tr>
<tr>
<td>4</td>
<td>Install self-tapping screw (top and bottom)</td>
<td>5</td>
<td>30</td>
<td>150</td>
</tr>
<tr>
<td>5</td>
<td>Fork lift stack totes</td>
<td>15</td>
<td>4</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td><strong>Total [s]</strong></td>
<td><strong>535 (8.9 min)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>X 1.5 S.F.</strong></td>
<td><strong>803 (13.4 min)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Assembly Cost per Pod</strong></td>
<td><strong>$8.93</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Pods per day per person</strong></td>
<td><strong>36</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Number of workers need</strong> (for 1200-1600 pods/day desired output)</td>
<td><strong>33 - 44</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>#</th>
<th>Step Description</th>
<th>Unit Time [s]</th>
<th>Quantity</th>
<th>Total Expected Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Assemble Base</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>Unpack walls and aluminum</td>
<td>5</td>
<td>21</td>
<td>105</td>
</tr>
<tr>
<td>2</td>
<td>Stack 6x 45mm totes on to base</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Wrap walls around aluminum</td>
<td>14</td>
<td>15</td>
<td>210</td>
</tr>
<tr>
<td>4</td>
<td>Install self-tapping screw (top and bottom)</td>
<td>5</td>
<td>30</td>
<td>150</td>
</tr>
<tr>
<td>5</td>
<td>Fork lift stack totes</td>
<td>15</td>
<td>4</td>
<td>60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>#</th>
<th>Step Description</th>
<th>Unit Time [s]</th>
<th>Quantity</th>
<th>Total Expected Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Assemble Base</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>Unpack walls and aluminum</td>
<td>5</td>
<td>21</td>
<td>105</td>
</tr>
<tr>
<td>2</td>
<td>Stack 6x 45mm totes on to base</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Wrap walls around aluminum</td>
<td>14</td>
<td>15</td>
<td>210</td>
</tr>
<tr>
<td>4</td>
<td>Install self-tapping screw (top and bottom)</td>
<td>5</td>
<td>30</td>
<td>150</td>
</tr>
<tr>
<td>5</td>
<td>Fork lift stack totes</td>
<td>15</td>
<td>4</td>
<td>60</td>
</tr>
</tbody>
</table>

|    | **Total [s]**                    | **535 (8.9 min)** |            |                          |
|    | **X 1.5 S.F.**                   | **803 (13.4 min)** |            |                          |
|    | **Assembly Cost per Pod**        | **$8.93**     |            |                          |
|    | **Pods per day per person**      | **36**        |            |                          |
|    | **Number of workers need** (for 1200-1600 pods/day desired output) | **33 - 44** |            |                          |

Table 15. Onsite Assembly Time Estimates for Pod with 45mm IM Tote

The same analysis was performed on the design which has hinged 45mm totes. Instead of having 6 totes already prebuilt, the 45mm totes would come hinged and folded like all the other totes, which would take a little more assembly time. Precisely, if
the time to wrap the walls around the aluminum took about 14 seconds, the final screwing operation takes about 5 seconds, and the forklift stacking took about 15 seconds, the design with all hinged totes would take about 17.2 minutes or 3.8 mins more. This drives the cost up to $11.47. The number of pods one worker can build in a day reduces by 8, which means that the number of workers needed to hit the desired output of 1200-1600 pods per day increases to 43-58. In any case, both designs fulfill the requirement to be capable of being assembled onsite in under 20 minutes. These results can be seen in Table 16 and the changes from the 45 mm injection molded tote design are highlighted in red.

<table>
<thead>
<tr>
<th>#</th>
<th>Step Description</th>
<th>Unit Time [s]</th>
<th>Quantity</th>
<th>Total Expected Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Unpack Base</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>Unpack walls and aluminum</td>
<td>5</td>
<td>21</td>
<td>105</td>
</tr>
<tr>
<td>2</td>
<td>Wrap walls around aluminum</td>
<td>14</td>
<td>21</td>
<td>294</td>
</tr>
<tr>
<td>3</td>
<td>Install self-tapping screw (top and bottom)</td>
<td>5</td>
<td>42</td>
<td>210</td>
</tr>
<tr>
<td>4</td>
<td>Fork lift stack totes</td>
<td>15</td>
<td>5</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td><strong>Total [s]</strong></td>
<td><strong>689 (11.5 mins)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X 1.5 S.F.</td>
<td><strong>1034 (17.2 mins)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Assembly Cost per Pod</td>
<td><strong>$11.47</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pods per day per person</td>
<td><strong>28</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Number of workers need</strong> (for 1200-1600 pods/day desired output)</td>
<td><strong>43-58</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 16. Onsite Assembly Time Estimates for Pod with 45mm Hinged Tote

9. Summary & Conclusion

The conceptualization and design for a stackable based storage solution has been extensively explored in this thesis. The final proposed design resulted from analysis from angles of mechanical feasibility, gross cubic utilization, and costs for manufacturing, packaging and logistics, and on-site assembly.
The first phase of research heavily focused on gathering requirements and creating concept designs to meet those specifications. These requirements fit in three areas: the need to be interacted with a forklift like mechanism, to withstand basic loading requirements on the tray and walls to ensure minimal sway and to be within cost and assembly constraints. In the design conceptualization, the five main categories investigated were: how the product would be accessed, how the totes would be shipped, how the totes would be assembled, how the totes would be stacked, and how the totes would lock with one another. Multiple versions were developed guided by finite element analysis to iterate towards a design that achieved all the loading based functional requirements.

In the second phase of research, the gross cubic utilization as well as the manufacturing, packaging and on-site assembly costs were studied for 2 similar concepts—one with all totes collapsible by hinges except the smallest one being fully injection molded and the other with all totes collapsible by hinges. The gross cubic utilization achieved was satisfactory. Insights from experts in these fields guided refinement in the design. The onsite assembly costs were relatively low. Manufacturing costs were surprisingly high due to a more plastic volume needed than expected.

The overall design process of identifying the problem, gathering specifications, generating concepts, iterating the concept, and verifying the design on the basis of mechanical robustness and costs was used to create a novel new to the world stackable based storage solution. In the end the goals of the project, developing a mechanically feasible concept stackable design within cost requirements was achieved. The important values from the analysis is summarized in Table 17 with the winning design being the one with the 45 mm hinged tote.

<table>
<thead>
<tr>
<th>Design with 45mm Fully Injection Molded Tote</th>
<th>Design with 45 mm Hinged Tote</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Weight [lb]</strong></td>
<td>442</td>
</tr>
<tr>
<td><strong>GCU</strong></td>
<td>79.4%</td>
</tr>
</tbody>
</table>
### Manufacturing (Material Cost)

<table>
<thead>
<tr>
<th></th>
<th>$521.84</th>
<th>$376.52</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Packaging</strong></td>
<td>$32.82</td>
<td>$24.98</td>
</tr>
<tr>
<td><strong>Logistics</strong></td>
<td>$23.66</td>
<td>$15.72</td>
</tr>
<tr>
<td><strong>Time to assemble</strong></td>
<td>13.4 mins</td>
<td>17.2 mins</td>
</tr>
<tr>
<td><strong>Onsite Assembly</strong></td>
<td>$8.93</td>
<td>$11.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$588.32</td>
<td>$429.52</td>
</tr>
</tbody>
</table>

Table 17. Summary of Results

---

10. Areas for Future Investigation

[1] Features were not optimized. In particular, the side wall has a very thick wall thickness as very conservative models were used to ensure sway was below 1 in. More rigorous finite element analysis on the entire pod with a high processing power computer should be done on the full assembly to identify the minimum thickness, number of vertical, and horizontal ribs necessary. Material can likely also be cut out in areas not feeling much load, which finite element analysis on the assembly could aid.

[2] As the pod design with all hinged totes was more ideal, the totes for this design would need to be modeled. The height of the rails and mating features will need to be refined so that the 45 mm tote can fit them.

[3] Further attention should be paid on the insert and lip holding the tray. As the lip design was expected not to affect the cost analysis significantly, not a lot of work went into understanding how much engagement and slot thickness was necessary to hold the tray in place.

[4] The plastic side walls need to go through rounds of design for manufacturing. While the ribs were designed in a way that could be easily injection molded, features needed for injection molding like draft angles have not been included yet. Mold flow analysis will also be beneficial in determining whether the part will warp.

[5] The material selected for injection molding may also need to be reconsidered. PC-ABS is a tough but not the stiffest plastic material. PC-ABS was used. However, this material may not have been the most suitable for stackable pods as a lot material was needed to make up the stiffness needed. Plastics with
reinforcing fibers or particles may be more expensive but the less material needed and the space saving on GCU may outweigh the costs. Alternatively the front and back wall could also be replaced with aluminum or steel to save cost and space while maintaining or even improving the stiffness.

[6] This designs in this project were highly conceptual and tested via simulation. Real prototypes should be tested to gain a better understanding of the tote to tote stacking and sliding interactions. The sway and other mechanical concerns can be validated on a real model.

[7] The largest concern for a stackable based storage solution is that there is not forklift or tote handler developed yet. Further analysis should go into the feasibility of such a tote handler to determine whether the stackable pod route is worth further consideration.
References


