Retail pack mandrel tooling and production process improvements

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By

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Problem statement

Kyocera Senco bought 3 tray forming machine from an independent contractor (Wayne automation) to increase production of boxes used to house their products (staples and nails). There is a set of box models (the Retail Packs), however, for which the Wayne Automation machine does not have hardware or programming for. Additionally, there is no guarantee with the current set-up that these models can be produced reliably. There must be a method of retrofitting the machine to produce these models reliably.

<u>Research</u>

Background

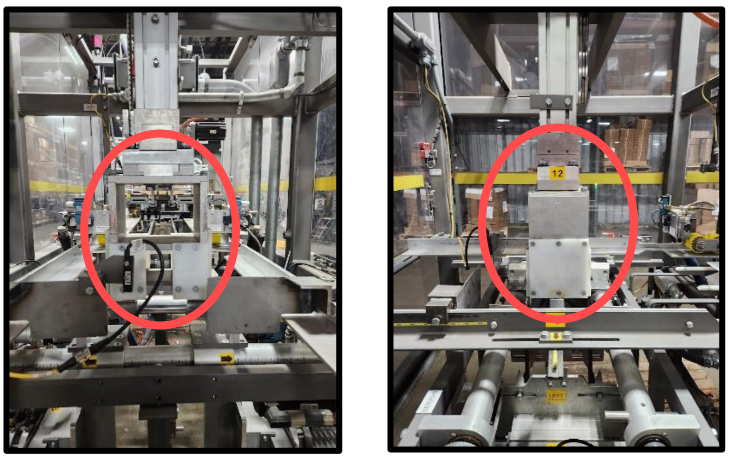
Kyocera Senco is a manufacturing facility located in Newtown, Ohio. They primarily produce automated fastener tooling (nail and staple guns mainly) for the construction industry. The original company, Senco, was absorbed into Kyocera in 2017. I have been working there since May 2023. In August of 2023, I was introduced to the tray forming machines (Wayne Automation). Senco produces its own boxes for all production nails and staples in-house. Senco purchased 3 of the same machines costing roughly 600,000 USD each. These machines have been integral to increasing overall production efficiency for staples and nails. However, as time progresses, changes in the shape and size of our boxes occur. Recently, a series of box (Retail Packs) have been created by the marketing department for a new line of retail product. Programs, hardware, and set-up information for these models does not exist (nor does the knowledge that these models will functionally work in the tray former). To gather more information, an interview was conducted with our manufacturing manager for the nail and staple departments, Mitch Roberts. From his account, there has been a push to be able to manufacture hardware for and program the Wayne tray formers for any model we make in the future. Senco would like the freedom of accessibility for the Wayne tray formers. The first step to this goal (or more accurately the first experiment) would be the Retail Pack carton models. As it stands, Wayne Automation will not be assisting with any physical changes to the tray formers but will be able to assist with the programing and implementation of the Retail Pack models into tray former production. The in-house hardware modifications for the Retail Pack were assigned to me.

To understand the mechanics of the system itself, interviews were conducted with Wesely Larson (Staples Manufacturing Engineer), Jeff Bihl (staples department manager), and the box production technicians throughout the month of September. Notes were taken as to the nature of how the Wayne tray forming machines operated. I personally ran the tray formers and produced over 500 boxes of varying models to understand the mechanics of the tray former. The tray former performs 4 basic functions: flat stock procurement and transport, glue dispersion, forming, compression and ejection. All these processes have programmed physical parameters dependent on the geometry of every individual box model. The first study performed was investigation to the physical limitations of each process, and whether it could support the Retail pack cartons.

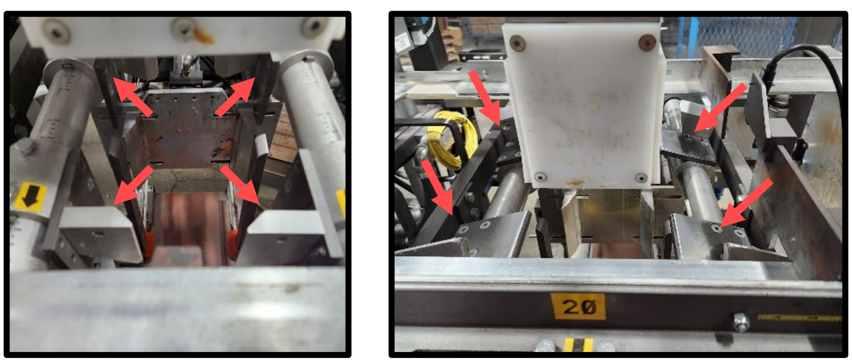
There are 22 physical parts for adjustment on the Wayne tray former (see appendix A). All of which play a part in each one of the 4 basic functions. The first function requiring changes is forming. The forming process involves 2 main components: The forming mandrels (see figure 1a and 1b) and the minor flap dies (see figure 3). To start, new mandrels must be designed for the Retail Pack models, as there have not been any designed nor will Wayne Automations provide Senco with mandrels Cost-free. Each new mandrel Costs 1500 USD each, which is not economical. Exploration will be needed to make a more cost-effective in-house option. The minor flap dies (see figure 2a & 2b) are appropriate sizes, however, to effectively form the Retail Packs.

In addition to alteration of physical components to the forming function an additional method of securing the flat stock to the mandrel during forming and compression operations will need to be installed. Shown by direct observation, the flat stock has significant play of movement under forming and compression operations. Additionally, there is no official securing mechanism (of the of the cardboard flat stock to the mandrel) besides spring tension and friction from the corrugated cardboard flaps during forming/compression (see figure 4). There is no guarantee that these forces would be enough to successfully form the Retail Pack cartons.

Insert image of wayne tray former sheet of adjustable parts



Figures 1a and 1b – Images of forming mandrel front and side views



Figures 2a and 2b – Images of minor flap forming dies horizontal and vertical orientations

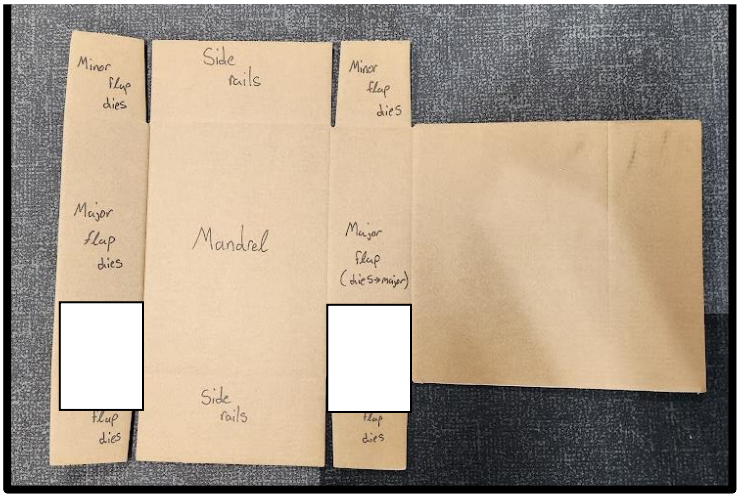


Figure 3 – Anatomy break down of forming die interactions for flat stock

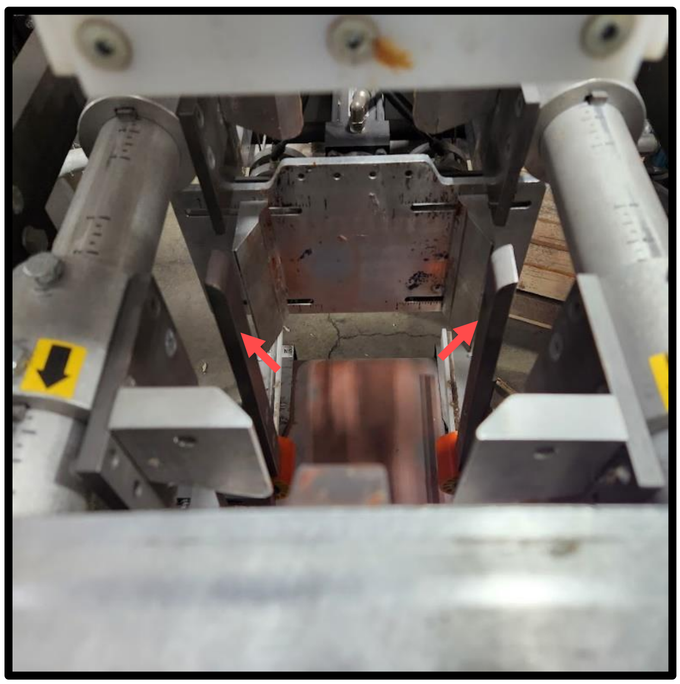


Figure 4 – Points of spring tension/friction after moving past the minor flap dies

State of the art

Many tray formers exist on the market today. All fall within the 4 basic functions listed in the background section. As found with research, there are two main orientations vertical tray formers and horizontal tray formers. Horizontal tray formers form flat stock with a horizontally placed mandrel. Vertical tray formers, however, use vertically oriented mandrels to form flat stock. The formed box is then usually ejected via a gravity chute. The latter is more frequently used than the former. Horizontal tray formers will not be elaborated, as the design for the Wayne tray former is vertical. The focus of this project is optimization, not full redesign.

The current state of the art within Senco is for a model set not supported by the Wayne tray former due to a lack of spring tension and friction available for its geometry. That model set are the DA cartons. These cartons are manufactured within Senco by the Econoseal tray former (see figures 5a – 5d). Made by Econocorp Inc. This tray former can produce between roughly 20 cartons per minute. Both the Wayne automation and the Econoseal follow the 4 basic functions outlined in the background. The most noticeable difference is the full length-of-travel chute present in the Econoseal. This chute allows additional friction to keep the small DA cartons attached to the mandrel during travel down to compression. Although having the clear advantage of the chute, using the Econoseal tray former isn't a long-term solution, however. The machine is no longer in production from Econocorp, being made in 1999 (see figure 6a). Replacement parts have been notoriously difficult to find for this machine and will continue to get more difficult as time goes on and more points of failure show up. Using a chute on the Wayne tray former is possible. However, with so many parts to adjust already, adding an additional step to machine set-up would lower production capacity. Additionally, a chute would need to be produced for each mandrel manufactured (increasing costs).

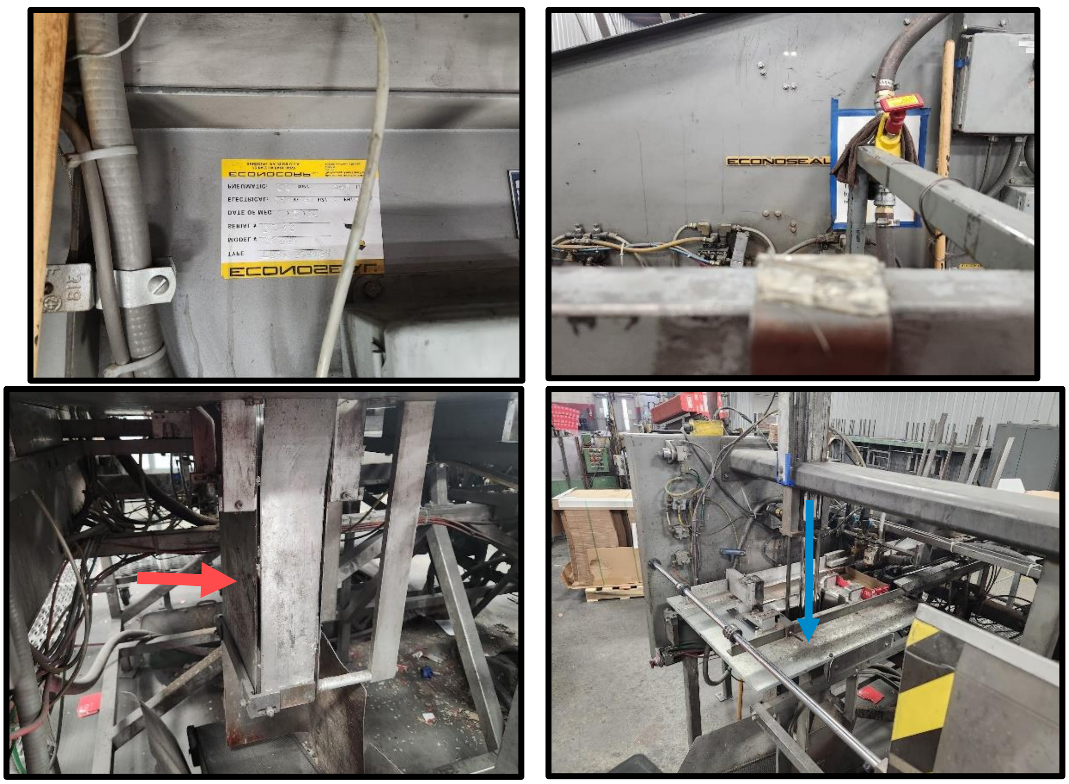
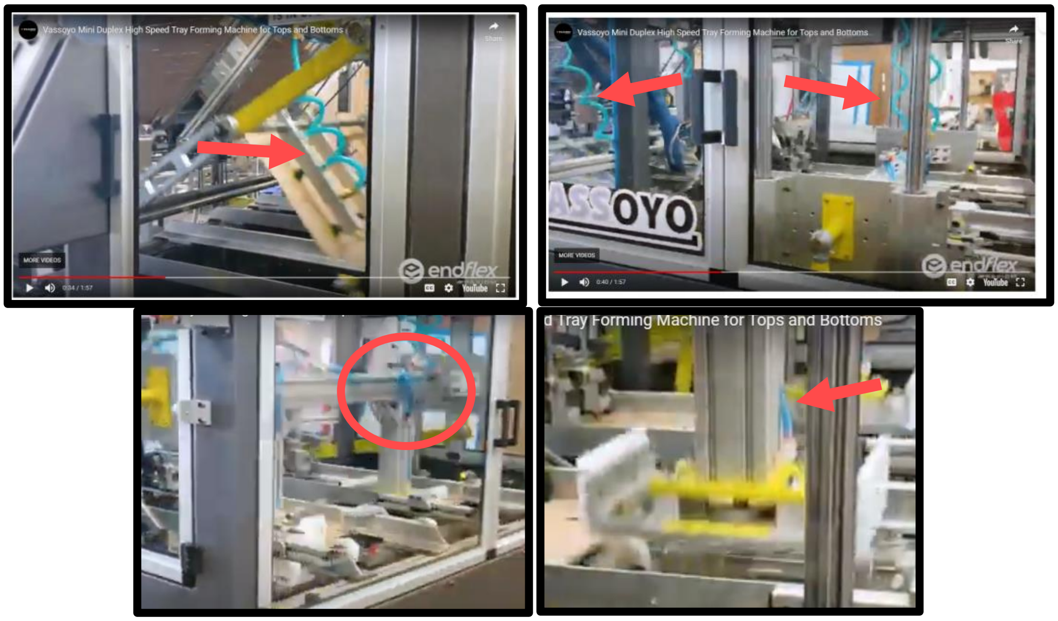


Figure 5a-5b – Images of Econoseal tray former manufacturing date, logo, travel chute and mandrel interaction with chute

The first VATF state-of-the-art solution for maintaining carton stability is made by Paxiom group. Paxiom group created a secondary mechanical system which works in tandem with the mandrel operation. The Vassoyo Mini Duplex tray former uses a flat manifold panel vacuum manifold at the bottom of the mandrel. This can be evident by the blue pneumatic tubing attached to the mandrel (1). Having suction end effectors attached to the bottom of the mandrel would solve the overarching potential problem for the Retail Pack cartons (security to the mandrel, extra degrees of freedom during compression). A majority of the Wayne tray former is pneumatically actuated, which makes this addition rather easy to install and automate. Having the suction end effectors attached to the bottom of the mandrels would also eliminate having to add additional moving parts (reducing points of failure, additional programing, and design time). However flat panel manifolds can become relatively expensive. The cost for flat suction end effectors (for large areas) on McMaster-Carr start around 1500 dollars (2). A less expensive alternative for vacuum end effectors would need to be explored should this option be chosen for integration.



Figures 6a-6d – Images from the Vassoyo Mini Duplex video demonstration. 6a (top left) shows vacuum fittings evident on the flat stock picking arm. These same fittings are shown over the forming mandrel arm (6b (top right)). The bottom two images (6c – left, 6d – right) are meant to confirm these vacuum connections lead directly into the forming mandrel.

The second state-of-the-art for VATF machines comes from the IPAK TF385 made by Wexxar Bell. The TF385 includes retractable overhang arms in-line with the position of compression (3). This allows a solid and level foundation for the carton/mandrel to mate with prior to compression (eliminating the degrees of freedom present in the Wayne tray former during compression). The arms are pneumatically powered, which is very compatible with the Wayne tray former (most of the moving parts are pneumatically controlled). However, clear disadvantages are present. First, these components are foreseeably expensive. Potentially 4 additional components would need to be designed, integrated, and programmed into the current Wayne tray former. Additionally (and most importantly), the arms stabilize the carton to the mandrel during compression only. This would not solve the problem of keeping the carton secure to the mandrel during travel.

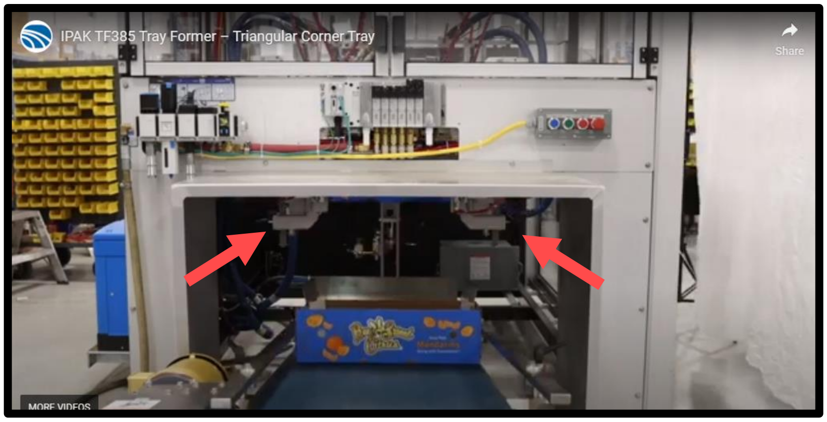


Figure 7 – Image from the TF385 video demonstration. Arrows point to the overhang arms fully extended and currently supporting a carton

End user

The current end users will be the in-house production technicians at Senco. These technicians have years of experience with the Econoseal tray former. Cross training for the Wayne tray former (unmodified) will begin in September 2023.

Quality Function Deployment

As mentioned previously in the background, I was trained on and operated the Wayne tray former. This was done so I could gather information as to the needs of any technician operating/setting up the Wayne tray former. At the time, there was only one technician operating the machine full-time, so a survey would not have been helpful due to the small sample size. So, any customer features (and their importance) relating to adjustable/swappable components (added to the tray former for the Retail Pack cartons) will be decided by my personal experience, input from the carton production technician, and input from Jeff Bhil (Engineer who helped install and functionally test the Wayne tray formers). These requirements will only pertain to the added components that the technician will be physically interacting with.

Customer Features

The customer features were ranked on a scale of 1-5 in 0.25 increments based on criteria mentioned in the previous section:

Weight (3.5)

Ease of use (4.75)

Time consumption for set-up (relative to current set-up) (4.5)

Initial investment (3.25)

Durability (4)

Pneumatic powered (2)

Maintenance (3)

Flat stock stability (5)

Engineering Characteristics

Frame materials selection

Fasteners/Joining

End effector selection

Actuator selection

Response time (seconds)

Input senser selection

Applied force (flat stock)(lbf)

Load distribution on mandrel (psi)

Air consumption (CFM)

Size (in^3)

Pneumatic hardware selection

Quality Function Deployment

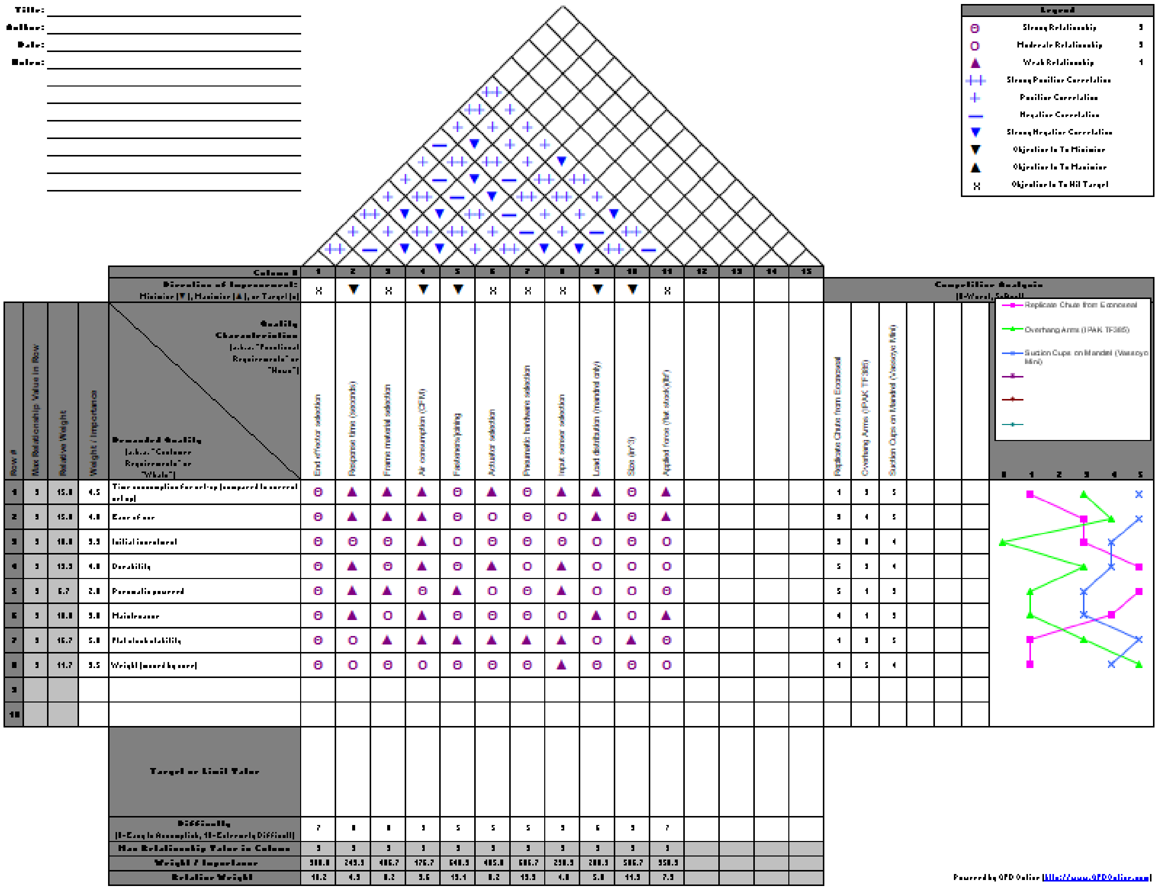


Table 1 – Quality Function Deployment Chart

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	"Requirements" or "Hows") Demanded Quality (a.k.a. "Customer Requirements" or "Whats")
1	9	15.0	4.5	Time consumption for set-up (compared to current set up)
2	9	15.8	4.8	Ease of use
3	9	10.8	3.3	Initial investment
4	9	13.3	4.0	Durability
5	9	6.7	2.0	Pneumatic powered
6	9	10.0	3.0	Maintenance
7	9	16.7	5.0	Flat stock stability
8	9	11.7	3.5	Weight (moved by user)
9				

Table 2 – Customer Features (Relative Weights)

Project Objectives

Flat stock stability (16.7%)

Flat stock stability is the overarching goal for this project in addition to being a customer requirement. Flat stock stability during forming must be a guaranteed for the Retail Packs during travel from forming to compress/during compression.

Ease of use (15.8%)

Ease of use in this instance is the amount of difficulty any adjustable part in the potential design solution will have. Features that may decrease the ease of use for the solution includes: the need for specialized tooling, working room available, tight-tolerance adjustments, and additional program settings required for operation. Decreasing the ease of use will ultimately increase the time it takes to set up the Wayne tray former. Additionally, it will also increase the learning curve for anyone being trained to operate the Wayne.

Time consumption for set-up (15.0%)

Time consumption for set-up of the Wayne tray former compares the current about of time and adjustments needed to get the Wayne operational (for each model) to new potential solution for the Retail Packs. Adding adjustable components, air fitting connections, programming steps, and tooling to swap in and out will all increase the time consumption. The goal for this project is to minimize time consumption as much as possible.

Durability (13.3%)

Durability is a requirement for many moving parts in the Wayne tray former. Carboard flat stock itself is abrasive to an extent. Containing chalks and clays (4) as fillers. Additionally, there are unaccounted contaminants within cardboard (glass, dirt, and rocks) (5) which have been known to scratch metal blades. Small abrasions caused by the flat stock will eventually present a large issue, considering the tray formers produce approximately 1200 boxes per day. Any additional components added to the tray former for the solution will need to withstand this wear.

Weight (11.7%)

Weight is crucial to the use of the machine by the production technicians. Any mandrels and/or additional components added to the machine/mandrels will need to be within a reasonable limit. Increasing the weight of the mandrels and/or added components will limit the time for production set up by slowing down the production technicians. Additionally, added components cannot be so heavy as to be incompatible with Wayne’s current pneumatic and electric motor capacities.

Initial investment (10.8%)

Senco has no assigned budget for the project (only that the cost of the project should be minimized as much as possible). However, any mandrels produced for the project must be under $1500 each (the pricing from Wayne automation). Increasing the affordability of the mandrels was a goal of the project stated by Wesley Larson.

Maintenance (10.0%)

Additional components come will additional potential points of failure. For each additional component (adjustable or not) will cause additional downtime for production (once a component has failed). The solution for the Retail Packs will need to be designed with repairability in mind.

Pneumatic powered (6.8%)

A pneumatic solution (for any moving devices) is preferred for multiple reasons. Many components on the Wayne tray former are pneumatically powered. The tray former is connected to the manufacturing plan's main air line, which can support 150 CFS (cubic feet per second). The Wayne tray former operates on 220 CFM due to inlet pressure regulator limits. 220 CFM is a substantial amount of supply. More than the machine uses during operation (additional usage should be kept to a minimum, however). Senco has been using pneumatic components on nearly every production machine for years. The experience from buying, installing, and maintaining pneumatic equipment would make a pneumatic solution more valuable.

Engineering Characteristics	**Relative Importance**
The end effector must be pneumatically actuated. It also must provide the required applied force onto the carton/mandrel	18.2%
A separate vacuum pump will be used to supply the suction cup end effector. The pump and its connective hardware will produce sufficient vacuum to meet the applied force (inHg)	13.9%
Fasteners will be made of corrosive-resistant materials to be paired with aluminum components already existing on	13.1%

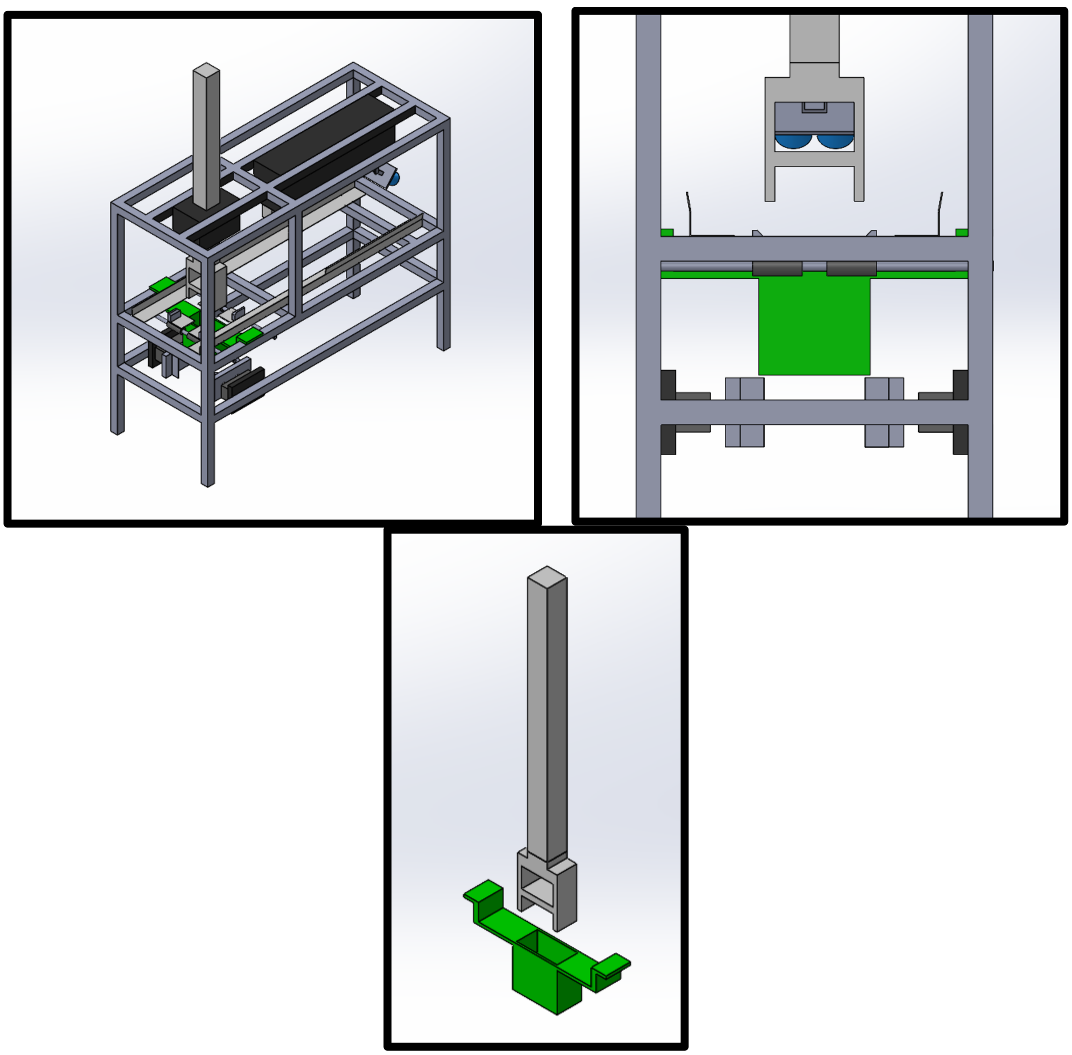
the Wayne tray former. Additionally, the amount and size of fasteners should be kept to a minimum (zinc plated or black-oxide coating)	
The forming mandrels shall be kept under 14 inches in total height	11.9%
The actuator for the vacuum must be powered by 24 V and be able to withstand between 75-150 psi of air pressure input.	8.2%
The frame of the mandrel will be made from 6061 T6 aluminum. Contact wear parts (such as mandrel teeth) will be made from HDPE.	8.2%
Applied force must meet a minimum of 5 lbf across the flat stock during forming/compression operations	7.3%
Maximum load distribution on the mandrel (in event of failure) must not exceed the yield stress of 6061-T6 aluminum (35,000 psi (275 MPa)) with a factor of safety of 3	5.8%
Response time for the vacuum end effector to reach the required lifting force should be no greater than 250 ms	4.9%
Input senser should be a laser senser similar the current ones in use on the Wayne tray former	4.8%
Additional air consumption for the suction cup end effector	3.7%

and additional hardware shall not exceed 10 CFM	
Total	100%

Table 3 – Engineering Characteristics

Percentages from the above chart were calculated from the percentages for the product objectives and the QFD tabulations. Engineering characteristics were created and categorized under on of each product objectives. The percentage importance was distributed amongst each engineering characteristic under each product objective category.

Concept 1



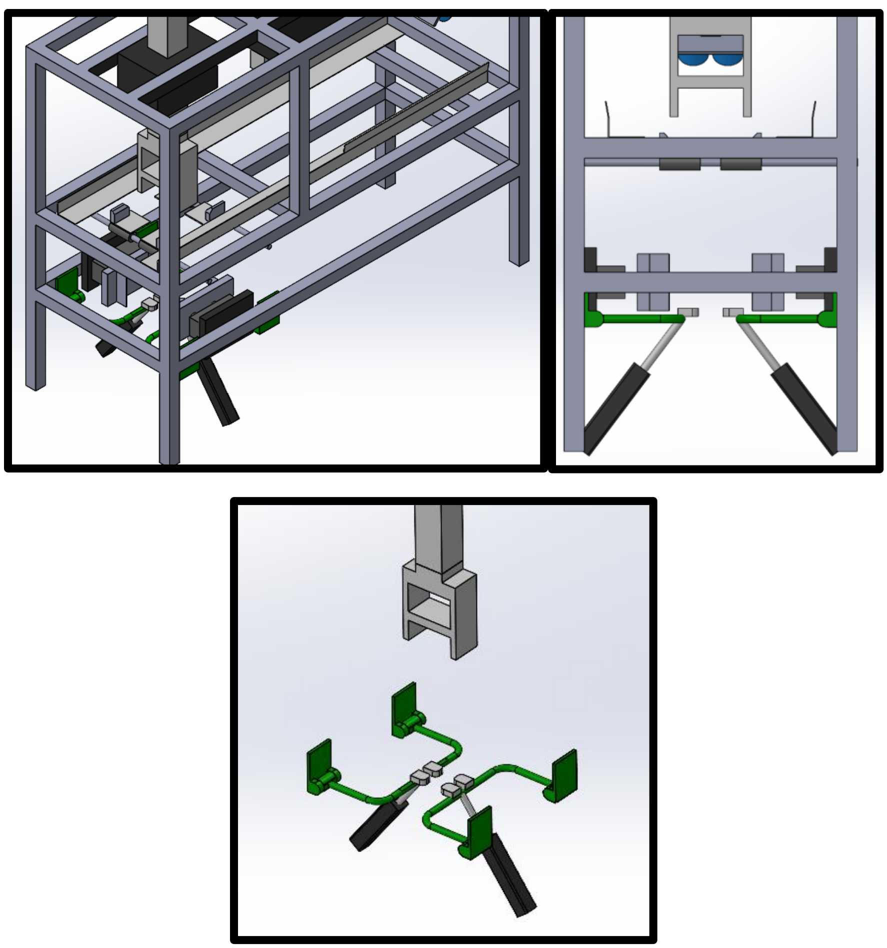
Figures 8a-8c – Above are images taken from SolidWorks for concept 1, the attached chute. All representations of the mandrel arm, mandrel, and tray former are representative and not to scale.

Concept 1 is taken from the Econoseal tray former. An addition of a mountable chuted will be made to the tray former between the space from the minor flap forming dies to the compression clamps. The chute can be adjustable for length and width while being fastened to the position as shown. Different chutes would be made for a range of box sizes, which would need to be attached and/or adjusted by the operator.

Using this concept would not use any air as there would be no moving parts under operation. Coincidentally, this also makes this potential solution the most maintainable and durable. No moving parts in respect to the machine's operation means minimal points of failure and minimal downtime. Additionally, it is proven to keep spring tension the full length of travel down to the compression plate on the Econoseal.

There are downsides to this concept, however. Having multiple chutes manufactured will make this solution costly upfront and, in the future, should carton designs change. The chute itself does not assure stability within the compression plates. The chute being potentially made of all metal (like the Econoseal) will make it heavy. The additional adjustments (and weight for the operator to carry) will increase the time consumption for set-up. The ease of use will be reduced for new Wayne tray-former trainees by adding an additional part for adjustment. Finally, there is a large potential for catastrophic failure if not adjusted properly. If the chute happens to be set too small for the box model/mandrel, the mandrel arm will run directly into the chute (causing potential damage to the tooling).

Concept 2



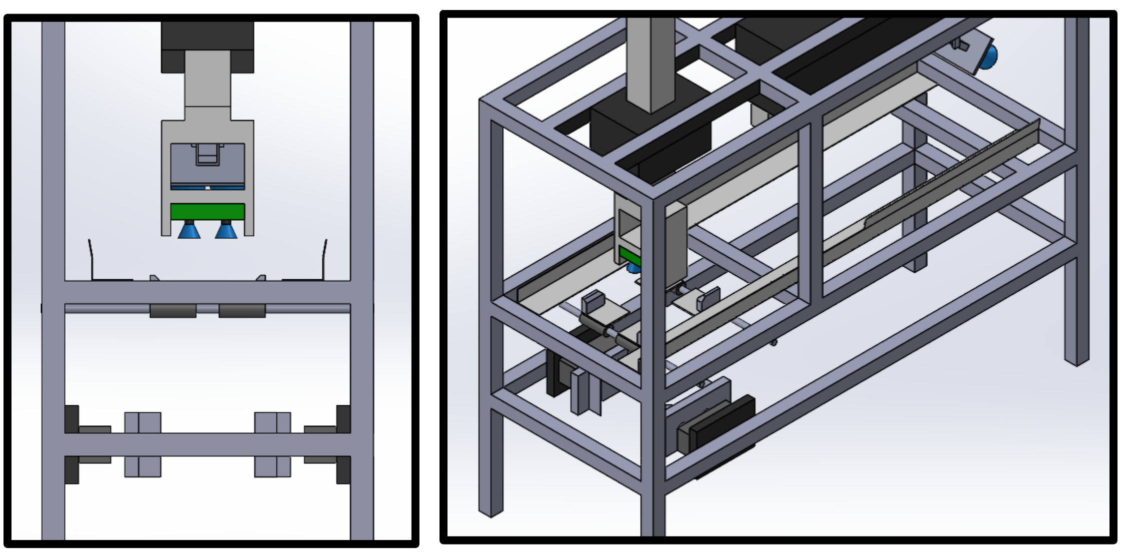
Figures 9a-9c – Above are images taken from SolidWorks for concept 2, overhang stabilizer arms. All representations of the mandrel arm, mandrel, and tray former are representative and not to scale.

Concept 2 vitalizes the overhang arms present in the TF385. Pneumatically actuated arms would be spaced apart wide enough to be mounted without obstructing the compression clamps. The contact surfaces for the mandrel/carton should be adjustable from side to side (to compensate for different carton widths). The contact surfaces must also need to lie inside the length of the mandrel die to avoid being hit by the compression plates. The contact surfaces will be made from a soft material with abrasion resistance to avoid damage to the carton during compression processes. After Compression processes are completed, the attached pneumatic actuator will retract the arms and allow the carton to be ejected.

Concept 2 meets many criteria from the customer requirements. Ideally the tooling on the arms would not need to be swapped out. The contact surfaces would simply need to be adjusted from side to side, and the vertical position for contact with the mandrel arm would be a fixed point. This would take significant weight away from what the technician needs to move during set-up (unlike concept 1). This solution guarantees stability within the compression clamps for all carton models. Finally, the moving components are pneumatically powered, which is compatible with current systems on the Wayne tray former.

This design solution comes with many benefits, it also has its downfalls. The solution needs 2 pneumatic actuators at minimum with a very long length of travel. This will make the price of the system rather high initially compared to concept 1 but would have less long-term cost in the future. Adding 4 separate items to move (all 4 contact platforms) will increase the overall set-up time for the Wayne tray former. Finally, and most notably, his design solution does help with stability on the Wayne tray former during travel from the forming to compression processes.

Concept 3



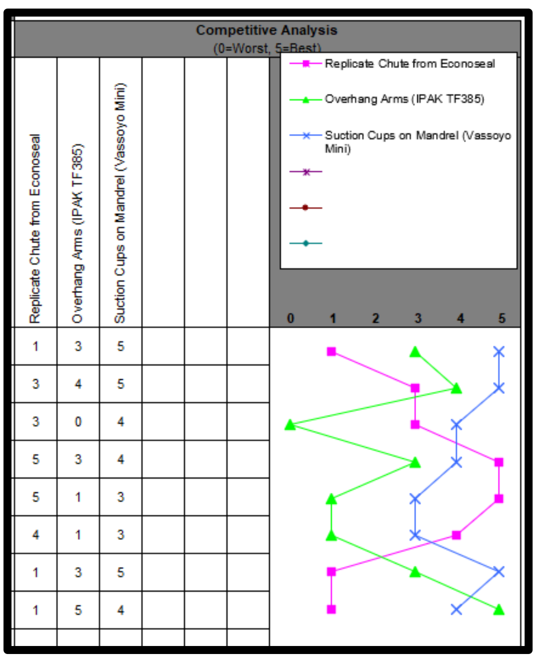
Figures 10a & 10b – Above are images taken from SolidWorks for concept 3, in-line suction cups. All representations of the mandrel arm, mandrel, and tray former are representative and not to scale.

Concept 3 has the least moving parts. Taken from the Vassoyo Mini Duplex tray former. Suction cups will be added to the bottom of the mandrel. The overall design of the mandrel will remain. However, it will need to be modified to accommodate attachment of a suction manifold. Ideally, there will be some adjustments added to the mandrel for one common manifold to accommodate all mandrels. Each mandrel would have its individual manifold and suction cups assembly for ease of use. Although a suction device, it is still a pneumatic system. The tray former already has a suction line installed in the system. The suction cups can be tied into this system, or an alternative vacuum source powered by air may be used. Each mandrel can have a quick disconnect into the air system.

Although the weight will increase for each mandrel, the weight difference will be much smaller relative to concept 1. The ease of use, however, should remain the same. Each mandrel will have their suction cups set to a pre-adjusted permanent height (Ideally). This should not have to be adjusted every set-up (Unlike with concept 1 and 2). Finally, this concept will consume virtually no additional set-up time, as the only step added for set up would be connecting the quick-connect coupling(s). The biggest potential issue would be cost, which can be minimized via off the shelf components.

Concept of choice

Concept 3, the suction cups, will be the concept of choice for this project. This was mostly determined by the average weight provided by the QFD spreadsheet (see figure 11b). Additionally, Senco uses multiple different variations of suction cup end effectors. Issues with a suction cup end effector have a high chance of being diagnosed at Senco during testing due to their experience.



	Concept 1	Concept 2	Concept 3
	1	3	5
	3	4	5
	3	0	4
	5	3	4
	5	1	3
	4	1	3
	1	3	5
	1	5	4
Avg Rating	3	3	4

Figures 11a & 11b – 11a (above) is the active evaluation from the QFD spreadsheet (see table 1) of how well each concept matched the customer requirements. The weight was scaled from 0 (being the worst) to 5 (being the best) at satisfying the aligned customer requirement. 11b is a tabulation in excel to calculate the average overall weight for each concept.

<u>Design Solution</u>

Design Note

Any graphical renderings or representations of the design solution (and coinciding measurements of said graphical representations) were designed in SolidWorks 2020.

Project management

The budget of this product is to keep the cost of mandrel below $1500 each. Additionally, the entirety of the project should remain under $10,000 in materials costs.

Design Solution Research

<u>Vacuum generator research</u>

There are many different types of vacuum pumps in production today. However, may are used for specialty applications which are incompatible for this project. 3 types of vacuum pumps were researched which can be used in the design solution: rotary vane, diaphragm, and venturi ejectors.

“Rotary vane pumps are the most common type of positive displacement vacuum pump” (6). This pump vitalizes centrifugal force generated by moving vanes (attached to its rotor) to move different types of fluid (including air). Rotary vane pumps are typically found in portable air compressors. Rotary vane pumps can achieve very high CFM due to the nature of its centrifugal force. To achieve larger cfm, simply increase the housing, motor, and vane sizes. This would unfortunately increase the price, however. When looking for vacuum pumps for this application, a 3 CFM vacuum pump was found for under 200 USD (10). The maximum vacuum achieved by the compressor is 3 pascals of local pressure (97.04% total vacuum) (9). Significant as its maximum vacuum may be the pump is very large. Being 19 lbs. and

469.359 cubic inches (10), it would be difficult to place it anywhere within the machine. It is imperative to place any pump used as close to the suction cups as possible to minimize response time. This pump also is powered by 120V AC. This means that the pump cannot be ran off the tray former's integrated 24V DC lines, so auxiliary power would need to be ran beside the Wayne tray former.

Diaphragm pumps are another form of positive displacement vacuum pump. However, they typically come in smaller sizes than rotary vane pumps due to their functional nature. "Diaphragm vacuum pumps use a deformable metallic or elastomer membrane permanently joined into the chamber creating a hermetic seal" (6). Diaphragm pumps work on pulsating flow, creating multiple disconnected bursts of air or vacuum. This can be undesirable depending on how fast the piston is operating. Contrary to rotary vane pumps, the overall housing doesn't need to increase to accommodate a larger vacuum capacity. Either the rpm of the rotor needs to increase, or the diaphragm needs to increase in total size. This can be accomplished by using an elastic material and/or increasing the piston's stroke. To do either of these will unfortunately still make the pump more expensive. The diaphragm pump for example comes from sprayer supplies and sells for under 150 USD (12). It operates on 12V (compatible with the integrated 24V Wayne tray former power line after conversion) and has a fluid flow of 5 GPM (0.134 CFM usage). Its maximum vacuum the pump can reach is 14' of head (12.354 inHg), which is a 40.10% total vacuum (much lower than the rotary vane pump). However, the diaphragm pump is significantly smaller than the rotary vane pump (3 lbs. in total) (size unknown). Being much smaller gives it the ability to be places closer to the suction cups and within the tray former itself, minimizing the response time to achieve the required vacuum pressure.

Venturi vacuum ejector pumps operate using the Venturi effect (Bernoulli's principle) (6). The basic concept of involves increasing the velocity of a fluid to reduce its overall pressure. A jet nozzle (inside the ejector) shoots air into a gradually expanding cavity. The air interacts with 2 orifices: the exhaust at the end at the cavity and the vacuum inlet below the cavity. The low-pressure high-velocity air draws atmospheric pressure air in through the inlet and ejects it out the exhaust. The vacuum capacity of the Venturi ejector can be increased by increasing the flow rate of the inlet air or by altering the geometry of the ejector itself to accommodate more inlet air and faster vacuum speeds. There are a variety of advantages to the Venturi ejector. Venturi ejectors are the smallest vacuum devices among these three options. The sourced ejector of choice weighs 140 g (0.308 lbs.) and has a total volume of 2.69 in^3 (7). Additionally, there is no auxiliary electrical power required. Being light and compact, the venturi ejector can potentially be mounted on the mandrel arm, ensuring the quickest possible response time for achieving a vacuum. The selected vacuum ejector is comparable to the flow from the rotary vane vacuum pump, producing 2.2 CFM of vacuum flow. Additionally, the venturi ejector had comparable vacuum flow while being under 50 USD (being the cheapest option) (8). Having no moving parts also makes the venturi ejector more affordable in the long-term than the two other options.

The venturi ejector was selected to be the vacuum source for the end effector. It's low cost, small size, and quick response time made the end effector and ideal choice. Pneumatic hardware was chosen to integrate it into the Wayne tray former post selection.

Solution overview

To deliver on the engineering characteristics, it was decided on a product similar in design to concept 3 outlined in the "concept overview" section. The following are isometric and front views of the mandrel/suction cup assemblies:

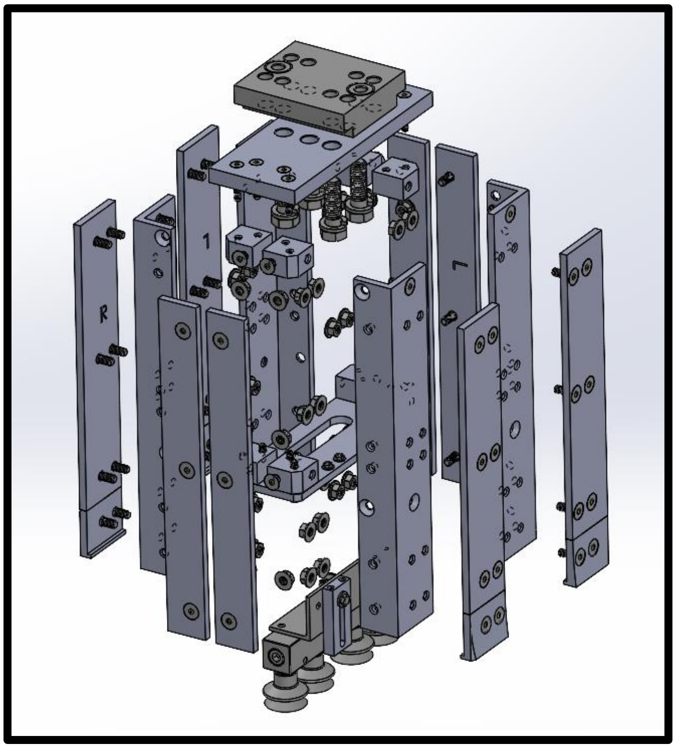


Figure 12 – Exploded view of retail pack mandrel. This mandrel is specifically the NM 2508-2511. However, the overall assembly is similar for all 3 mandrels.

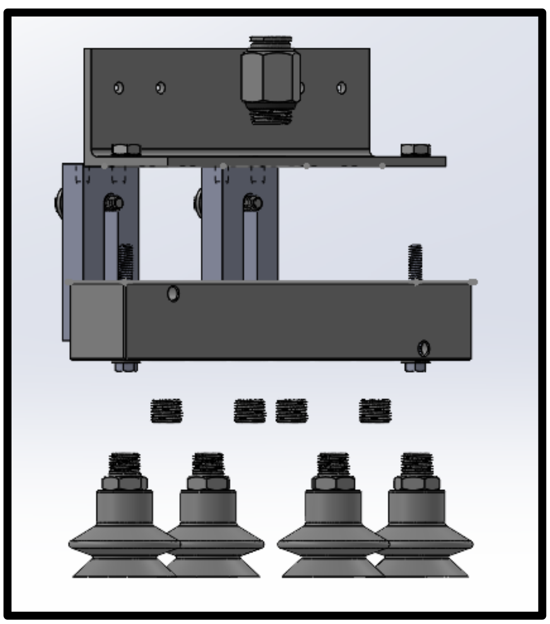


Figure 13 – Exploded view of the suction cup end effector assembly

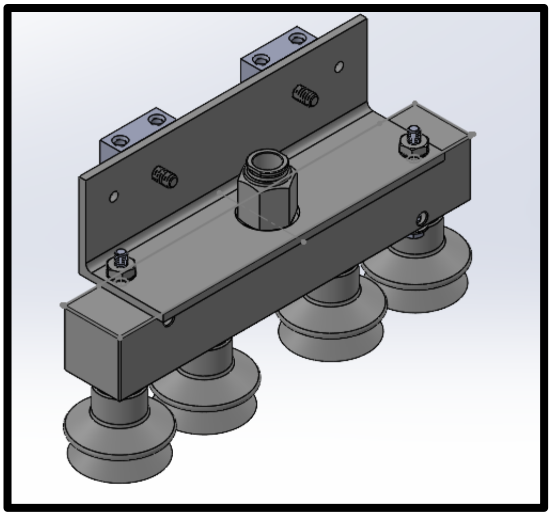


Figure 14 – Suction cup end effector assembly

The end effector will have 4 suction cups attached on an air manifold to the bottom of the mandrel. The suction cups shall be attached and ran in-line with the forming tooling. Quick-connect fittings will be provided to each mandrel manufactured. 3 mandrels were designed in total to form the required retail pack carton models (NM 2500-2511). Only 3 mandrels were required due to similar geometries across multiple models. The grouping is as follows: NM 2500 & NM 2502-2506, NM 2501 & NM 2507, NM 2508-2511. The designs were only possible by first reverse-engineering Wayne's original design (see Appendix H). Fastener typing, materials, overall structure design, and size tolerancing (to the die lines on the carton flat stock) were analyzed from the original hardware and integrated into the design. The overall height for the mandrels were reduced to reduce weight, however.

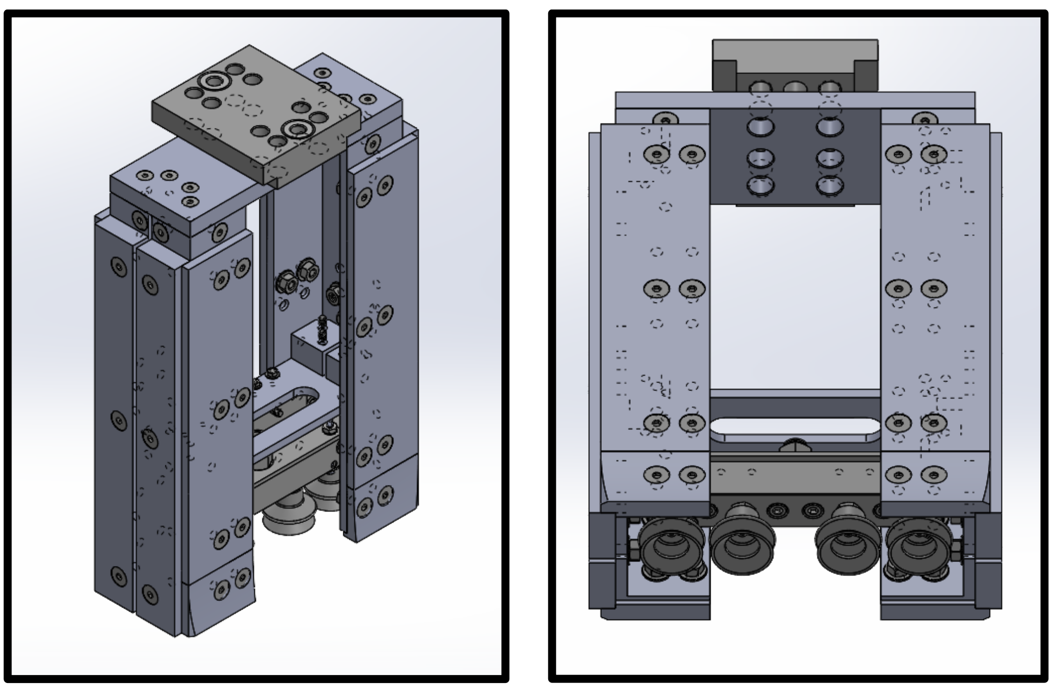


Figure 15a & 15b - Retail pack mandrel for carton models NM 2500 and NM 2502-2506

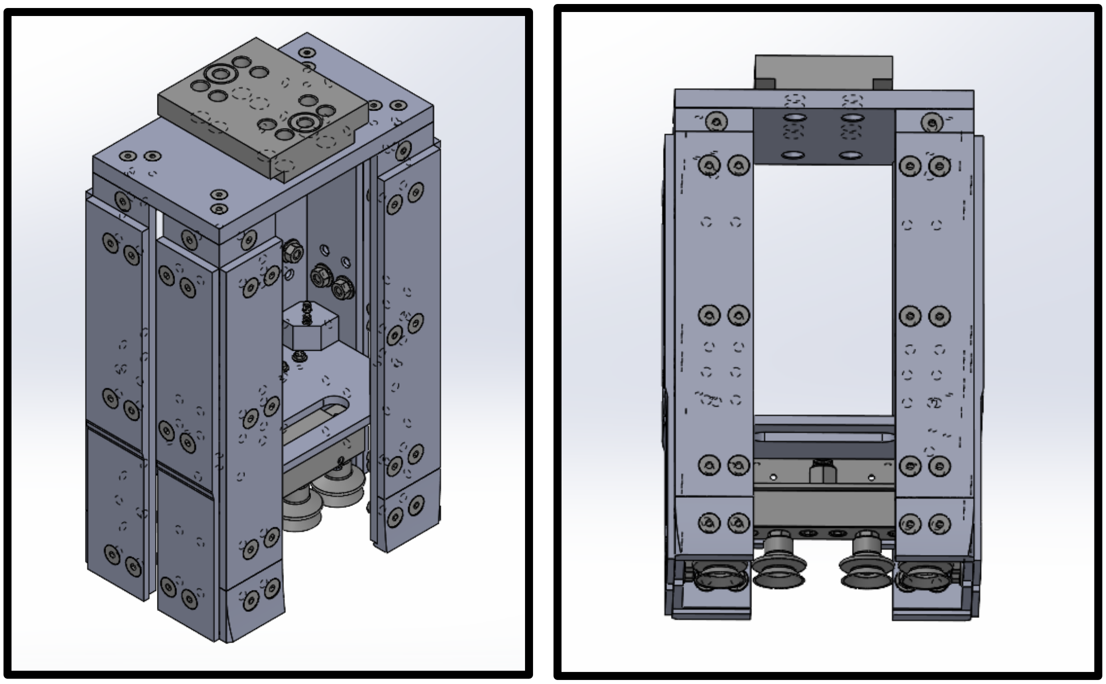


Figure 16a & 16b - Retail pack mandrel for carton models NM 2501 & NM 2507

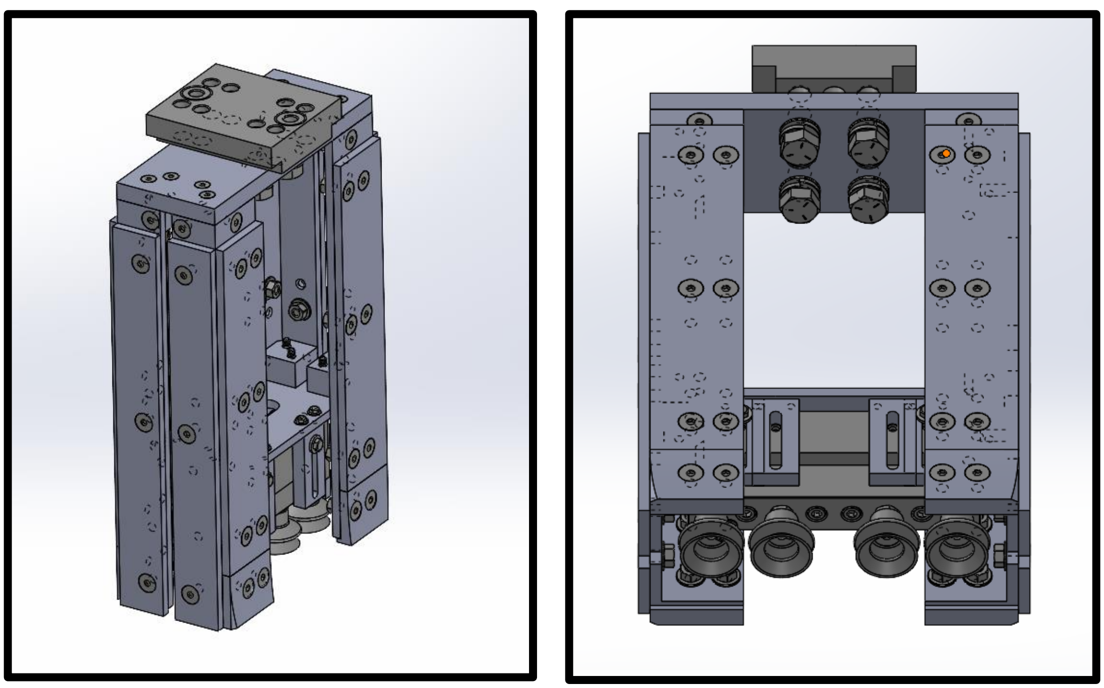


Figure 17a & 17b - Retail pack mandrel for carton models NM 2508-2511

Mechanical architecture and applied forces

As mentioned previously, all 3 mandrels are at or under 14" in height (allowing each mandrel to be at or under 5 lbs. Each mandrel is made with an all-aluminum (6061-T6) frame (built with mounts for the suction cup manifold). Each mandrel is covered in Profiled teeth (HDPE) to both protect the frame from wear, and to endure the proper geometry of the carton. Referring the bottom teeth in figures 15a & 15b, the bottom teeth on each side have a flared profile. This profile adds space (and reduces friction) to that the box can be grabbed by the stripper wheels and ejected properly. All the side teeth will need to be separately cut and/or machined. For testing purposes, the teeth may be 3D printed out of PLA. All mandrels have an attachment to the mandrel arm bolted to the top. This attachment slides into a clasp and is aligned properly via center pins on the mandrel arm (self-lubricating brass bushings accept these pins). The numerous fasteners shown in each figure above are going to be made from steel coated in a corrosion resistant coating (black oxide or zinc) to prevent galvanic corrosion to the aluminum frame. The current design shown above does meet the stress requirements outlined in the engineering characteristics (see Appendix D and E for a view of the SolidWorks stress analysis).

To meet the minimum 5 lbs of gross force (weight of flat stock is considered negligible) applied across, an appropriate vacuum pressure needs to be applied. Based on the geometry of the suction cups, the vacuum required to achieve this level of force is 6.428 inHg. At 6.428 inHg, the venturi vacuum ejector can move 1 cubic foot of air in 5.760 seconds (after extrapolating the data from the ejector's spec sheet (7)). After tabulations, the worst-case scenario would leave the response time for the venturi ejector to reach the required vacuum pressure being 11.12ms. This is acceptable as it meets the requirements outlined in the engineering characteristics.

Pneumatic architecture

For the suction cups to operate with the tray former, 3 critical components added to the tray former: The venturi vacuum generator, a pressure regulator, and a control solenoid (Normally closed (NC)). Air flow will begin the supply line for the Wayne tray former. Then, the air will be regulated to 75 psi and ran into the solenoid with pressure already build up. When vacuum is needed, an electrical signal will actuate the solenoid and provide air pressure to the venturi vacuum generator to actuate the suction cups. Please see Appendix B for a detailed diagram of this architecture.

Electrical and computational architecture

The electrical architecture only pertains to the solenoid in the pneumatic system. The selected solenoid runs off 24V. The Wayne tray former has 24V controllable connections able to power the solenoid without any additional hardware. The signal to control the tray former will come from a currently existing laser sensor. This laser sensor originally identifies if flat stock is present below the mandrel ready to be formed. However, the same sensor can be used to actuate the solenoid for the venturi vacuum generator since the suction cups are attached to the mandrel itself. The sensor is simply and indication of when the mandrel should move. Logically, the same signal can be used to indicate when the vacuum should begin. The figure for this rough architecture can be found in Appendix B.

Programing for the system will be straight forward. The signal for actuation the venturi vacuum system will be from the same signal powering the mandrel arm. Said signal will send the 24V supply output to the solenoid (NC) from the Wayne's PLC and activates the venturi vacuum. The timing for the vacuum generator is also straight-forward. There shouldn't be any need to compensate for heavy time delays for start-up if the vacuum generator. The venturi vacuum generator begins generating a vacuum as fast as the it takes for the in-line supply pressure to rush into its supply (travel speed from air line supply connection to the vacuum ejector). The inlet CFM from the pressure regulator is 83 SCFM (11). With the selected air hose ID of 0.25, the linear velocity of the air can be tabulated to be over 4000 ft/s. So, the time it takes for the vacuum to begin generating will be assumed to be instant for the sake of calculation. Secondly, the delays in time for the suction cups to form a 6.428 inHg seal is approximately 11 ms (milliseconds) with the given volume for the suction cups and estimated tubing. This will be more than quick enough to run the vacuum at full speed (30 CPM). The vacuum will inevitably shut off prior to the compression cycle and before ejection of the carton. The compression and ejection positions (along with the overall position of the mandrel arm) are known and monitored values. Once the mandrel is between the compression and ejection positions, the solenoid will be turned off along with the vacuum. This cycle will repeat for every carton.

All alterations to the programming and ladder logic will be altered by a collaboration between out on-site programmer and experts at Wayne Automation.

Fabrication overview

Most of the parts needed will be manufactured through hubs.com (Protolabs Network). The parts will be outsourced from Senco to speed up the manufacturing process. The current manufacturing facilities are being used for various other projects going on at Senco. To put this on the on-site machinist staff with their current workload would be unreasonable. The following list of items sent to hubs can be found below:

Item	Qty	Cost each USD	Total cost USD
2500 2502 2503-2506 plate bottom	1	80.96	80.96
2500 2502 2503-2506 plate top	1	94.22	94.22
25012507 plate bottom	1	84.27	84.27
2501&2507 plate top	1	87.57	87.57
2508_2511 plate bottom	1	83.77	83.77
2508_2511 plate top	1	96.42	96.42
75046 Wayne tech OS	3	53.18	159.54
Corner braces type 1	20	11.11	222.2
Corner braces type 2	4	39.64	158.56
plate mount suc cup OS	4	28.77	115.08
Suc cup mount rail OS	2	96.73	193.46
Upright column	12	69.24	830.88
Total part qty	51	Gross cost	2206.93
		Cost/mandrel	735.64

Table 4 – List of outsourced parts to be machined: For the retail pack mandrels. The cost/mandrel meets the engineering characteristic for each mandrel to cost under $1500. This is a save assumption

since the cost for 3D printing will be negligible and the cost of hardware (standard screws and nuts (150 of each)) will not reach 765 USD.

There are 3D printed components involved in this project. All the teeth attached to the outside of the mandrels will be 3D printed during testing and machined out of HDPE in the future. Limitations exist on some of the teeth, however. A Bambu Labs P1S 3D printer will be used to produce the required teeth. However, it's maximum dimensions of the build plate are 10" x 10". Some of the teeth are outside of this limitation and will need to be printed in selective orientations. Below is a time estimate to manufacture the teeth:

Item	Time (hrs)	Qty	Total time hrs
Tooth die long 2500s mod	1.867	2	3.734
Tooth die long 2 2500s mod	1.867	2	3.734
Top tooth die 2500s rev 2	2.567	6	15.402
Top tooth die 2 2500s rev 3	2.567	6	15.402
bottom tooth die 2500s rev 2	0.833	6	4.998
bottom tooth die 2 2500s rev 3	0.833	6	4.998
Tooth die long rev 2 (single part print)	3.917	4	15.668
Tooth die long 2 rev 2 (single part print)	3.917	4	15.668
		Total time hrs.	79.604
		Total qty parts	36

Table 5 – List of 3D printed parts

The rest of the components will be OTS (off the shelf). Pneumatic hardware, fasteners, the suction cups, and manifold, etc. will be bought for this project. The list of projected OTS hardware will be found below:

Item	Count	Cost ea	Cost total
Manifold, suction cups 8 outlet	1	36.44	36.44
Suction cup	6	12.7	76.2
Venturi vac pump	1	106.65	106.65
3/8" OD push to connect fitting 1/4" male npt	4	5.4	21.6
3/8" OD push to connect fitting 1/8" male npt	4	10.2	40.8
3/8 OD air tubing	50 ft	1.31/ft	65.5
90-degree zinc coated steel angle (for suction manifold mount)	3 ft	20.34	20.34
Solenoid	1	135	135
pressure gage	1	21	21
Pressure regulator	1	123.5	123.5
Pressure reg coupling	1	19.27	19.27
plugs 3/8"	4	6.89	27.56

plugs 1/4"	4	5.59	22.36
plugs 1/8"	6	4.25	25.5
		Gross cost	741.72

Table 6 – List of OTS parts to be ordered

Projected timeline	
5-Jan	Parts files have been sent to hubs.com. and ordered for machining.
8-Jan	3D printing begins for mandrel teeth
11-Jan	Contact with Wayne has been made regarding programming for suction cups/venturi vacuum.
29-Feb	All parts received. All assorted hardware acquired. 3D parts completed
15-Mar	All parts completed. Assembly begins.
18-Mar	Assembly finished. Programming begins
21-Mar	Programming finished. Functional testing begins.
27-Mar	Functional testing and troubleshooting completed
1-April	Final report completed

Table 7 – Projected Timeline for Manufacturing and Assembly

Fabrication results

Fabrication for the design solution was split between outsourced parts, equipment, and materials from hubs.com (Protolabs Network) and in-house production capabilities. All parts were successfully manufactured according to spec from hubs.com and via in-house methods.

Manufacturing of aluminum frame for each mandrel

3 Sets of nearly identical parts were manufacture out of 6061-T6 aluminum to satisfy the engineering requirements. The order for these parts was sent at the beginning of January for all 3 mandrels. All 3 mandrels came in together simultaneously on March 5th, a few days after the projected timeline. Below is an image of the unassembled aluminum frame:

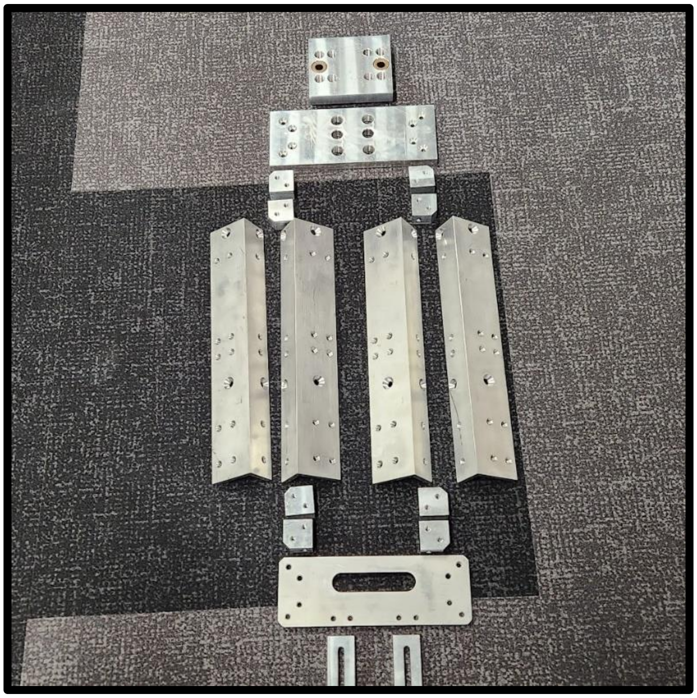


Figure 18 – Frame parts for NM 2508-2511 mandrel – 3 similar sets of parts were made for the frame of all 3 Retail Pack mandrels. All threading, countersinking and machining operations were done by hubs.com

<u>Manufacturing of 3D printed parts</u>

The outside die teeth set to be made from HDPE were instead 3D printed out of Kingroon and Protolabs brand 1.75mm filament. Different sets of teeth were produced to slight differences in thickness and overall dimensions. Due to last minute adjustments, however 3 sets of 3D-printed teeth were manufactured on the in-house Bambu Labs P1S printer at 100% infill. Unfortunately, due to delays, all 3D printed parts were finished March 10th. This was 5 Days behind schedule. However, it was still withing the deadline for full mandrel assembly. Below is the standard set of 3D-printed teeth made for each of the 3 mandrels:

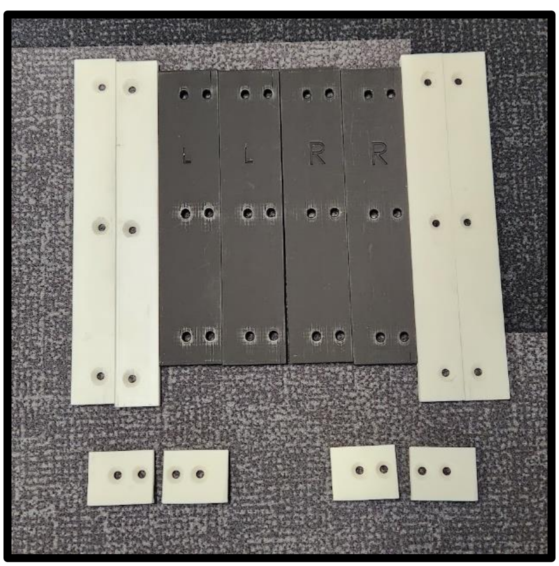
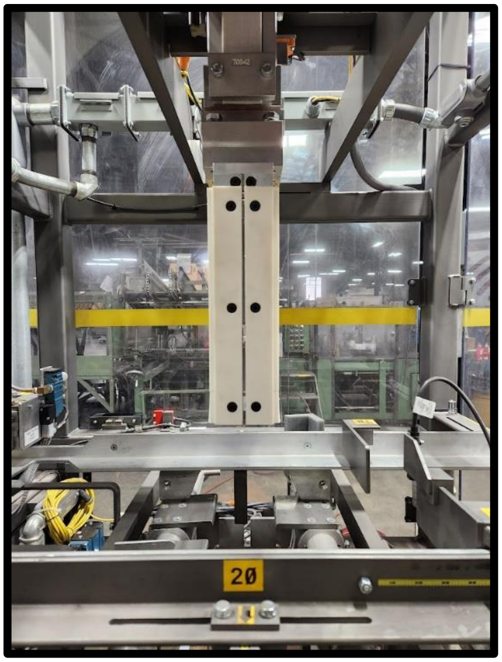
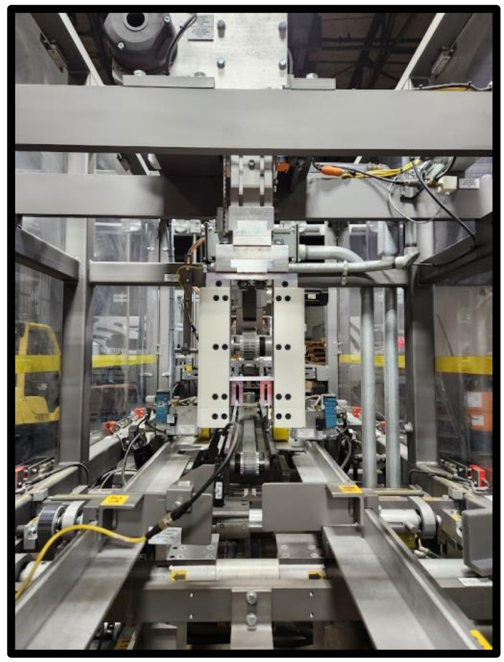


Figure 19 – Outer die teeth, NM 2508-2511 mandrel, **3D printed PLA -** 3 similar sets of parts were made for the teeth of all 3 Retail Pack mandrels.

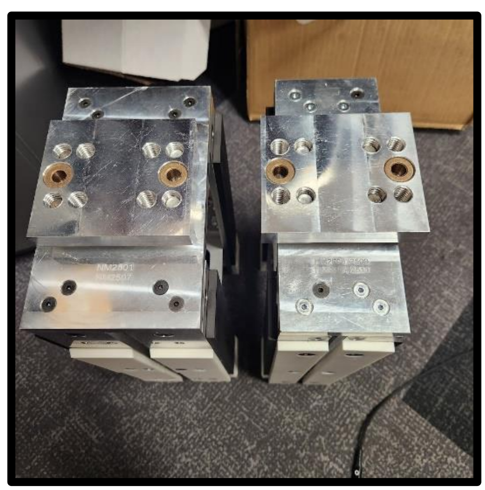
<u>Assembly of mandrels</u>

The assembly of the 3D mandrels was completed by March 18th. Over 50 fasteners were required to assemble each mandrel of various size sizes ranging from #8-32 to 1/2”-13 screws, washers, and nuts. The fully assembled mandrels can be seen below:





Figures 20a & 20b – Images of fully assembled mandrel for NM2500, 2502-2506

Figures 21a-21c – Images of fully assembled mandrels for NM 2501 & 2507 (left) and NM 2508-2511 (right) – In figure 21b (top right), both mandrels have had their respective carton models laser engraved on. This is also the case for the mandrel in figure 20a & 20b.

The most difficult part of the physical assembly involved the press-fit brass sleeve bearing (with embedded lubrication). These bearings needed to be cut to size, chamfered, and pressed into the aluminum housing. This process was done by the writer of this report. The purpose of these bearing was to accept alignment pins when being mounted to the mandrel arm. The original size of the bearing can be seen below along with the finished press-fit product:

Figure 22 – Stock length brass bushing and result after cutting and pressing into mandrel arm attachment - 3 of this item was made for each respective mandrel

The assembly was not without issues. The largest of which involved the 3D printed teeth. Half of the teeth were printed vertically rather than horizontal and flat on the plate. Printed the teeth in this orientation gave each part a poor grain structure during assembly. Upon fastening to the mandrel, the screws split these teeth lengthwise with the grain. All fasteners which split in this way had to be reprinted.

Figure 23 – Image of split die tooth

Pneumatics and the suction cup end effectors

The area of this project with the most importance was the pneumatic system and suction cup end effector. Unfortunately, this was the area with the most problems. The first and most pressing issue was the programming with the additional solenoid to the Wayne tray former. Wayne automation holds the license to each machine's individual programming. Without access to that license, we at Senco cannot program additional components into the machine's ladder logic. Wayne automation was contacted March 18, 2024, for access to the software license required or for a programmer to meet with myself personally to assist with the programming. Access to the license nor a meeting for assisted programming by a Wayne automation employee was made. For the sake of this education project, a different configuration for the suction cup actuation and integration was needed to confirm the proof of concept.

The previous method of vacuum generation and actuation was no longer an option to functionally test. However, a different suction cup manifold and method of actuation was created, however.

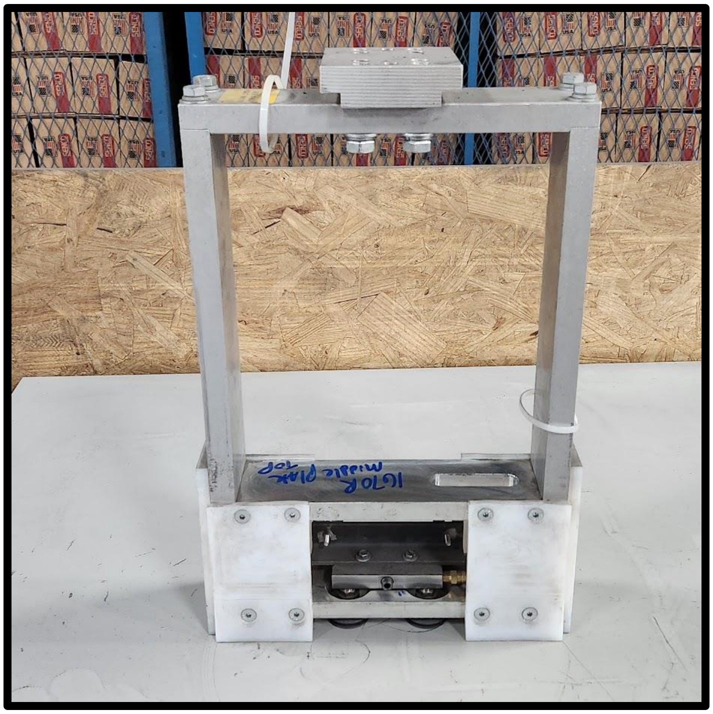


Figure 24 – Image of NM 1670 side view, with suction cups

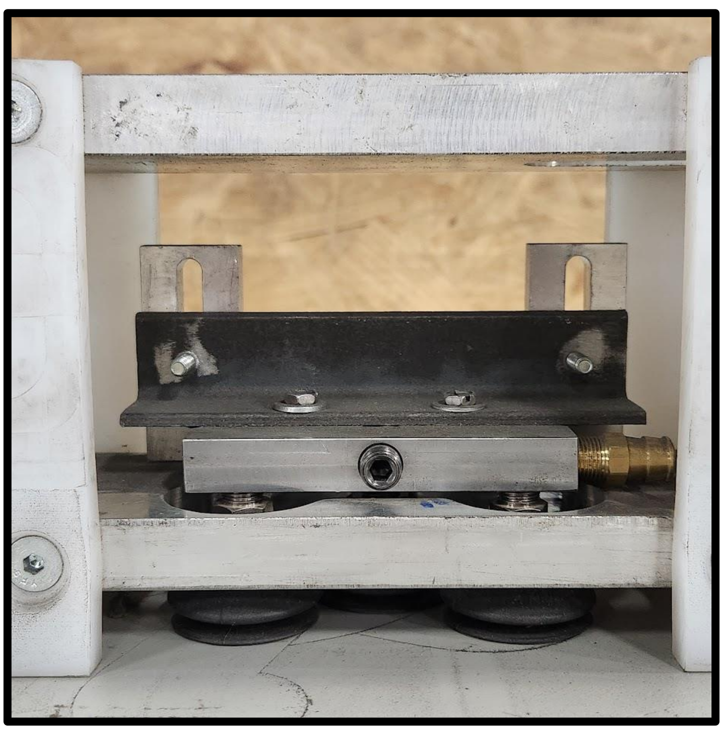


Figure 25 – Image of attached suction cup assembly NM 1670– This was the non-original suction cup assembly used for proof of concept only. The back slotted uprights were originally designed parts from hubs.com

Figure 26 – Underside view of NM 1670 mandrel with suction cups

A 3-cup manifold made from spare suction cups and suction manifold (used elsewhere in the plant) was assembled and attached to the parts already made through hubs.com. The manifold would be attached to the main vacuum tank used to power the flat stock pick-and-place suction cups already in use on the Wayne tray former. The main-line source of vacuum pressure at 12 psi (24.4322 inHg). Since the vacuum tank is a pre-generated source of vacuum (and we assume a vacuum generator is constantly replacing the vacuum), it can be assumed the response time for the suction cups will be near instant. Since the source is already at 12psi (vs the ejector which must build the pressure over time), the 12 psi of vacuum pressure will generate 14.256 lbs. of lifting force. This meets the engineering requirements for both response time and lifting force.

The 3-cup manifold was used over the previously designed 4-cup manifold for various reasons. First, all 3 of the mandrels were designed to produce brand new (not currently in production) retail pack carton models. Flat stock for these cartons initially were projected to arrive at the end of March. However, only test samples were provided for each mandrel. 15 pieces of flat stock for models NM2500 & 2502, models NM2503-2506, models 2508-2511, model NM2501 and model 2507 respectively. The small number of samples provided was not enough to run tests for both the proof of concept for improving stability via the suction cups and prove the retail pack mandrels can make their respective cartons reliably. So, the testing of stability was moved to our most problematic currently in-production box model (NM 1670). However, this model was too small to accommodate the designed 4-cup manifold. It needed to be downsized to a manifold which could fit inside the mandrel.

<u>Pneumatic attachments and actuation</u>

Using a currently existing NPT port at the top of the vacuum tank, a male air hose connection (barbed) was attached. That air hose was then strung across frame of the tray former to the mandrel arm and then attached with temporary fasteners. The rest of hose was then run to a solenoid attached to the front of the Wayne tray former. Connections from said solenoid ran over to the mandrel arm, through the attached 1670 mandrel and into the manifold for testing purposes. The following images will show the described connections:

Figure 27 – Air hose connection to vacuum tank

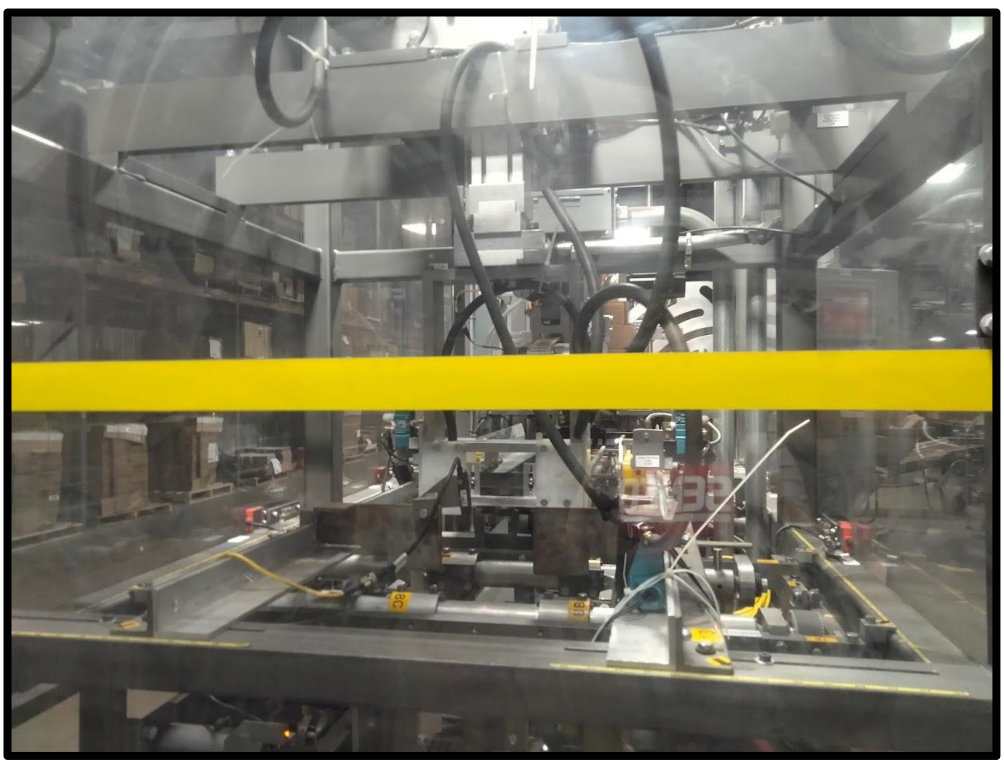


Figure 28 – Air hose connections from vacuum tank to suction cups through the solenoid, machine front

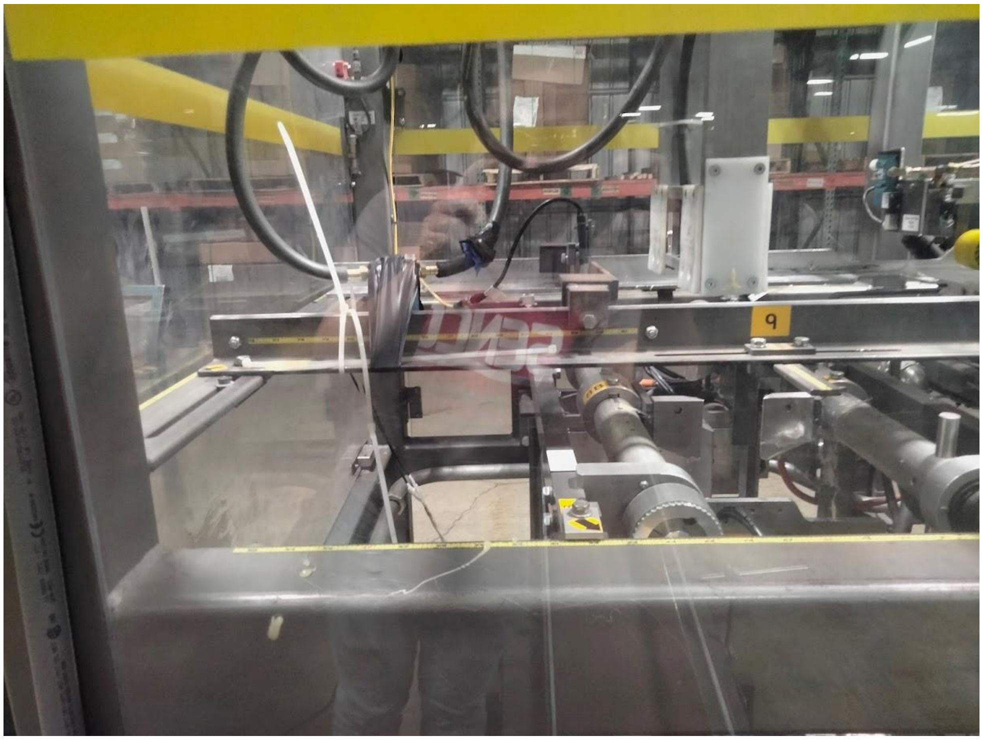


Figure 29 – Air hose connections from vacuum tank to suction cups through the solenoid, machine operator side.

The solenoid used was powered by 24V DC. Unfortunately, using programming to actuate the solenoid was not possible at the time. However, manual actuation was used in junction with normal tray former operations. This was in no means a long-term solution; however, a manual actuation can verify the proof of concept for a suction cup adding stability. 3-9V batteries were connected in series to act as an auxiliary power source under testing. To produce an appropriate 24V power source for the solenoid, a basic voltage divider in line with a manual push-button was constructed on a breadboard to actuate the solenoid under testing operations. The basic electrical architecture can be found in Appendix F

Testing operations

<u>Outline of suction cup trials</u>

80 sample tests were conducted for the proof of concept for suction cup stability on the NM 1670 carton models. 40 samples would be run without use of the suction cups and 40 would be ran with the suction cups activated. Half of each previously mentioned condition will be run at 10 CPM (cartons per minute) and the other half will be ran at 20 CPM to provide as much data as possible.

<u>Criteria for judging samples</u>

As mentioned in the background, I have been trained on and ran the Wayne tray formers. I have received instruction as to what is and is not acceptable in a carton for production. Many defects are possible through operator error, programming issues and flat stock defects. However, a limited list will be used for the verification trials. The following are defects which will disqualify any produced NM 1670 carton samples as “Acceptable”:

- Minor flap separation from the carton side wall
- Crinkles of the minor flaps on the inside of the carton
- The minor flaps being glued above the shear line for the carton.

Examples of the above can be found in Appendix G.

Results of suction cup trials

Overall, the suction cups proved to improve production efficiency even with such a limited sample size. During the slowest trial speed (10 CPM), efficiency increased by 10%, and at the fastest trial speed (20 CPM), the carton production efficiency increased by 20%. The increase in efficiency as speed increases is a correlation which makes fundamental sense. This can be found in the table below:

Trail #	Carton speed (CPM)	Total ran	Cartons folded	Folded cartons with defects	Suction cups on?	Acceptable production %
1	10	20	20	11		45
2	10	20	20	9	yes	55
3	20	20	14	12		10
4	20	20	15	9	yes	30
				% increase 10 CPM	10	
				% increase 20 CPM	20	

Table 8 – Raw data and tabulations from the suction cup trials

Results of verification for Retail Pack mandrels

All three of the retail pack mandrels were a success. Each mandrel was able to reliably form cartons from the provided samples. 10 out of each 15 flat stock samples were used for finding the appropriate machine settings for each mandrel. However, each mandrel reliably produced 5 boxes each after troubleshooting. Most operators typically waste 10-15 samples of flat stock per set-up. The waste for this trial with within an acceptable range.

Conclusion

At the beginning of this project, the overarching target was to produce the new model of boxes for the Wayne tray former reliably. 2 goals were set in motion in the problem statement: Identify a method to stabilize the new carton during production (to guarantee reliability), and for new carton models and develop said model's tooling. Inadvertently, the tooling for the mandrel turned into an additional goal: develop a process to engineer custom tooling for Senco. From repeated trials and intensive development, that process reliably produced 3 independent mandrel tooling completely independent from Wayne automation for half of the cost.

Regarding stability, intensive testing proved the methodology for the original suction cup design to be sound and applicable. Efficiency improved even under the worse conditions presented. The efficiency may have been even more significant had there been optimal conditions for engagement and collaboration regarding all parties involved for this project.

With an improvement in stability under forming operations, and a successful set of tooling made, the hardware and reliable method for manufacturing the Retail Packs (outlined in the problem statement) has been formulated. Past the scope of this project, Kyocera Senco will work with Wayne Automation to make the original pneumatic design of this project fully functional.

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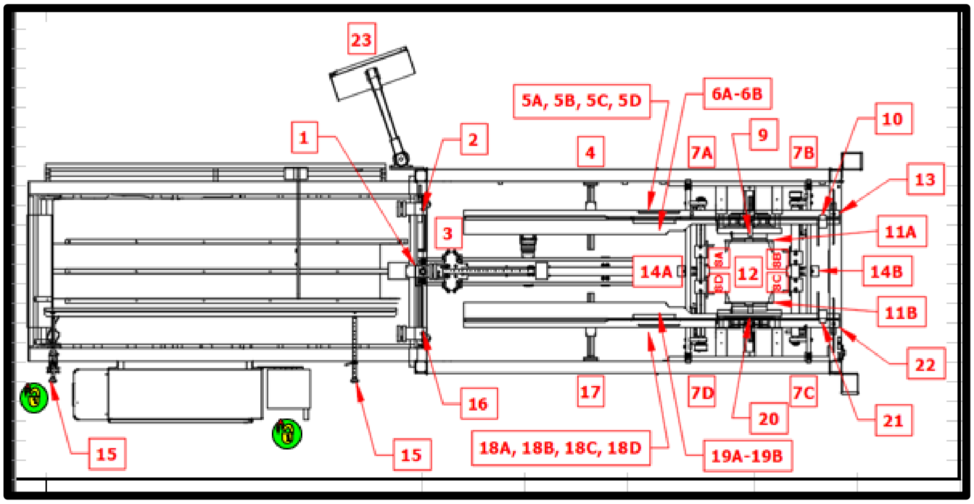
Appendix A



	OPERATOR SIDE ITEMS
1	MAGAZINE TOP GATE
2	MAGAZINE SIDE GATE
3	TRANSPORTER PUSHER
4	GUIDE RAIL
5A	HOT MELT GUN VERTICAL
5B	HOT MELT GUN HORIZONTAL
5C	COLD GLUE GUN VERTICAL
5D	COLD GLUE GUN HORIZONTAL
6A	ROLLER ASSEMBLY VERTICAL
6B	ROLLER ASSEMBLY HORIZONTAL
7A	FORMING ROUND (SHAFT)
7B	FORMING ROUND (SHAFT)
7C	FORMING ROUND (SHAFT)
7D	FORMING ROUND (SHAFT)
8A	FORMING PLATE (OPERATOR SIDE INFEED)
8B	FORMING PLATE (OPERATOR SIDE EXIT)
8C	FORMING PLATE (NON-OP EXIT)
8D	FORMING PLATE (NON-OP INFEED)
9	MINOR FLAP BREAKER BAR
10	TRAY STOP @ FORMER
11A	COMPRESSION PLATE (LEFT) INSTALL
11B	COMPRESSION PLATE (RIGHT) INSTALL
12	MANDREL INSTALL
13	GUIDE RAIL END
14A	STRIPPER (INFEED)
14B	STRIPPER (EXIT)

	FAR SIDE ITEMS
15	MAGAZINE GUIDE RAIL
16	MAGAZINE SIDE GATE
17	GUIDE RAIL
18A	HOT MELT GUN VERTICAL
18B	HOT MELT GUN HORIZONTAL
18C	COLD GLUE GUN VERTICAL
18D	COLD GLUE GUN HORIZONTAL
19A	ROLLER ASSEMBLY VERTICAL
19B	ROLLER ASSEMBLY HORIZONTAL
20	MAJOR FLAP BREAKER BAR
21	TRAY STOP @ FORMER
22	GUIDE RAIL END
23	SELECT PROGRAM ON HMI
	GLUE PATTERN SETTINGS
	OPERATOR SIDE
	1st ON
	1st OFF
	2nd ON
	2nd OFF
	FAR SIDE
	1st ON
	1st OFF
	2nd ON
	2nd OFF

Figure 30a-30c (left to right) – Figure 18a is a diagram of the Wayne tray former (front is to the right) with labels of all physical parts for adjustment. Directly below the diagram is a detailed list of all the above-mentioned moving parts. Figures 18b & 18c are images of the list of parts operators need to adjust for set-up (excluding item 23).

Appendix B

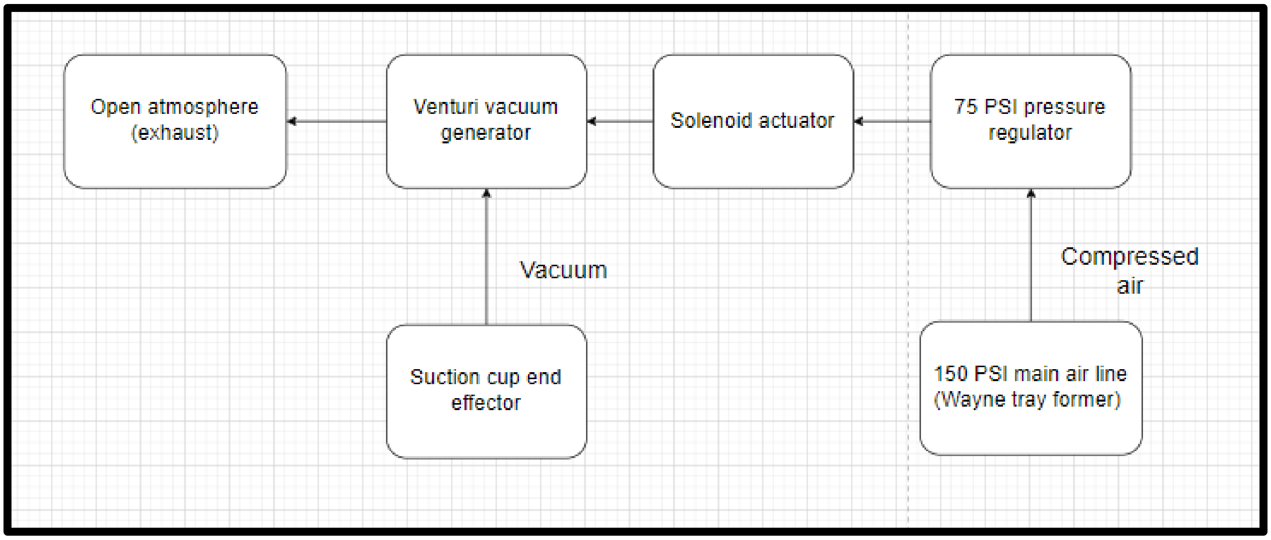


Figure 31 – Pneumatic architecture for the vacuum generation system

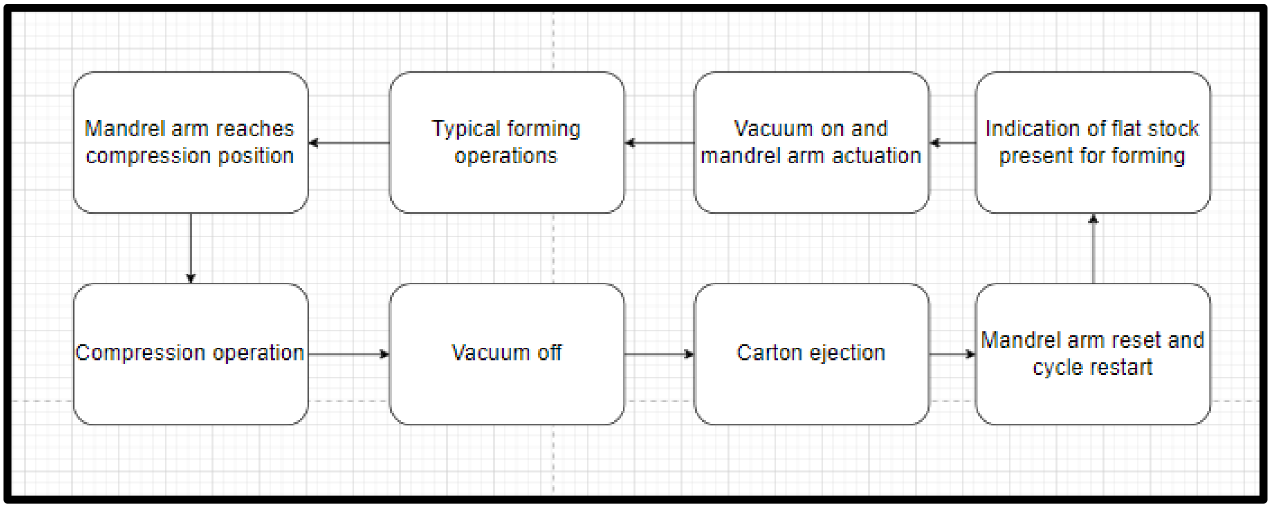


Figure 32 – Computational architecture for operation of the venturi vacuum and suction cup manifold

Appendix C

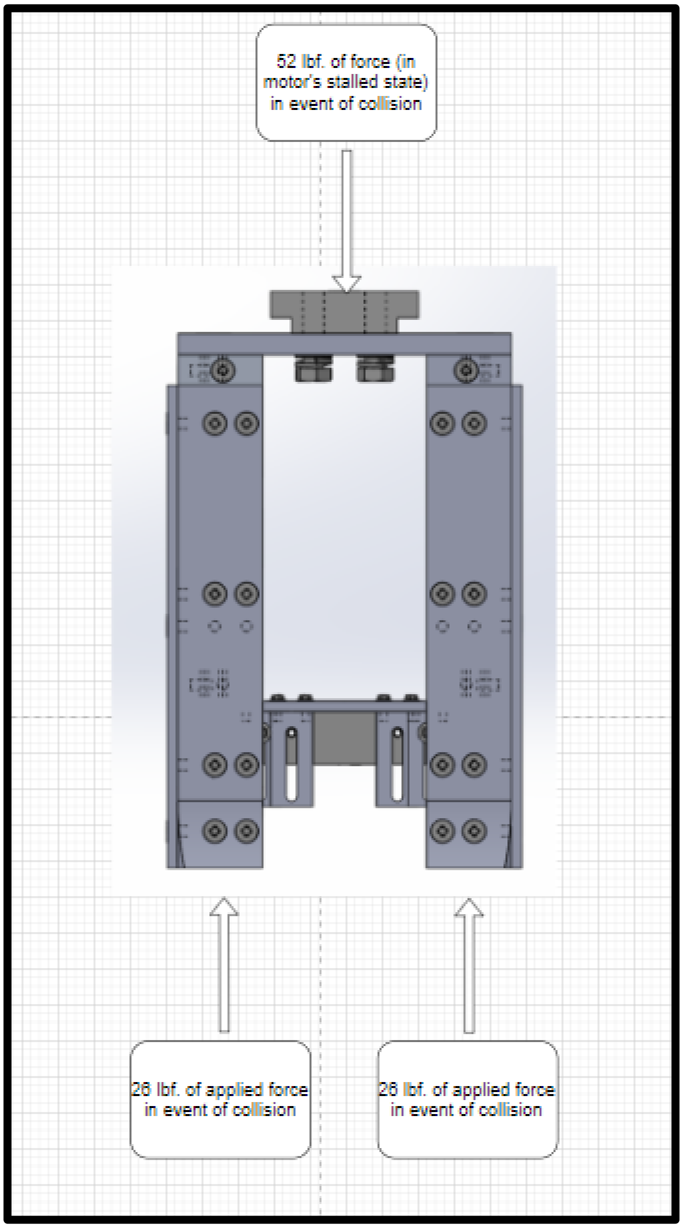


Figure 32 – Free body diagram of event of object collision (constant load under stalled motor torque)

Appendix D

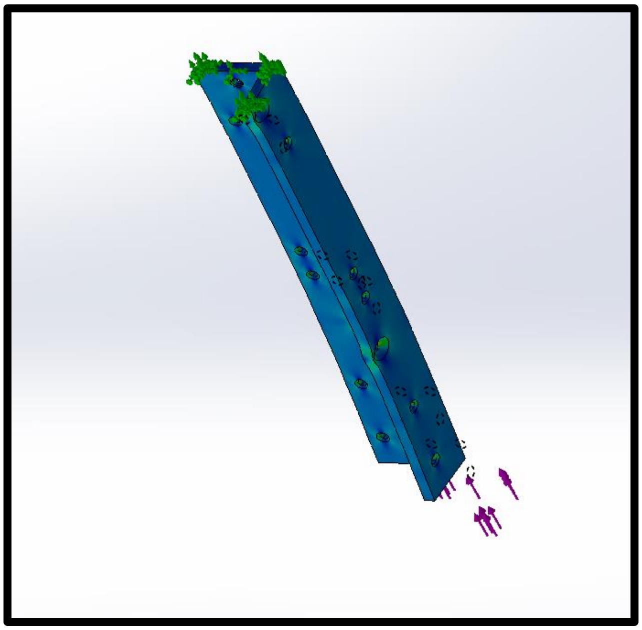


Figure 33a – Isometric view of FEA stress analysis under collision event (stalled motor torque)- The column upright (NM2500, NM2502-2506, NM 2508-2511) was used for the FEA analysis due to having the smaller compared to the NM2501 & NM2507 mandrel. The upright itself was done rather than the outside teeth due to its greater cost and the greater replaceability from the teeth themselves. The test was conducted with a safety factor of 3 for their respective load. Applied load used was 26 lbf.

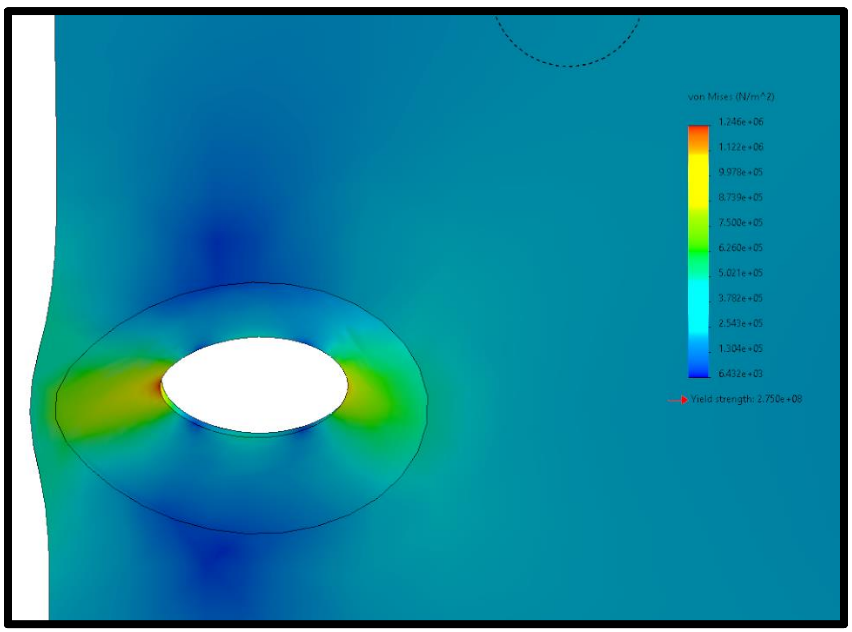


Figure 34b – Area of maximum compressive stress (top of scale) FEA on each upright – The maximum compressive stress is over 73x the factor of safety yield strength. This meets the engineering characteristics.

Appendix E

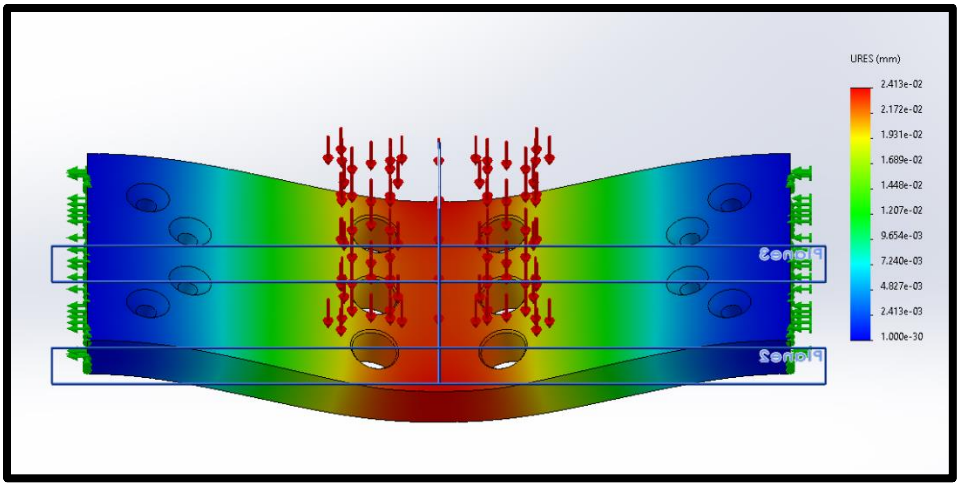


Figure 35 – Bending deflection analysis FEA for NM 2500 & 2502-2506 mandrel – This mandrel was in the FEA used since it has the smallest cross section. A distributed load of 104 lbf across the area shown was used to simulate direct contact of the mandrel arm and mandrel during collision.

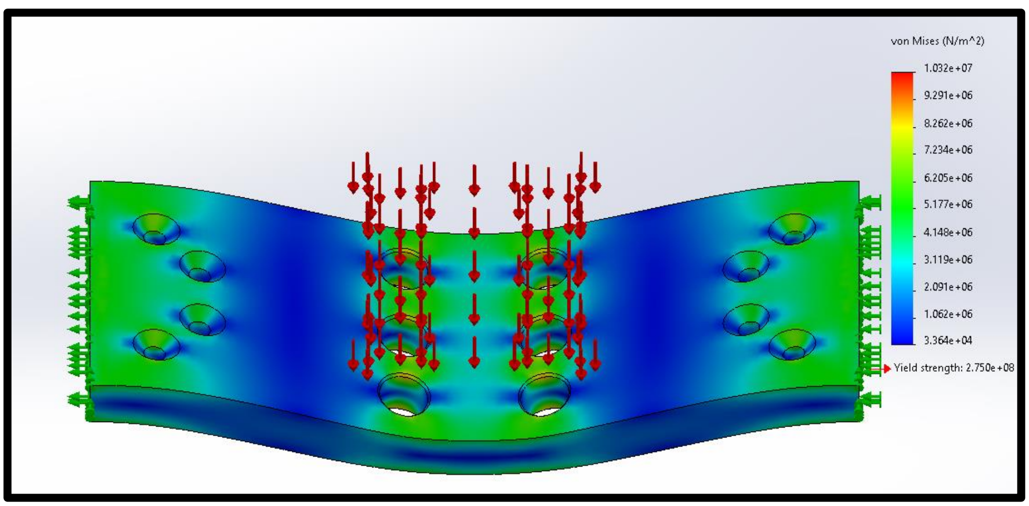


Figure 36a – Bending stress analysis FEA for NM 2500 & 2502-2506 mandrel top – This mandrel was in the FEA used since it has the smallest width and ultimately smallest cross section. The top of the mandrel was used as it is the area which makes direct contact to the mandrel arm (source of applied force). A distributed load of 104 lbf across the area shown was used to simulate direct contact of the mandrel arm and mandrel during collision.

Appendix E (cont.)

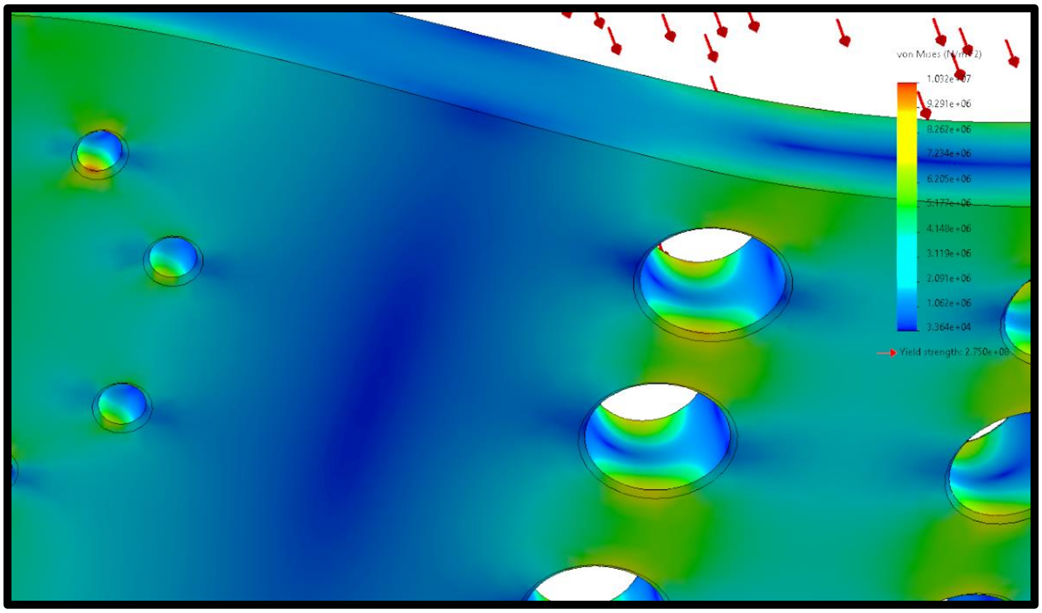


Figure 36b – Area of maximum bending stress (top of scale) FEA – The maximum bending stress shown is approx. 8.88x the factor of safety yield strength of the 6061-T6 aluminum used. This meets the engineering characteristics.

Appendix F

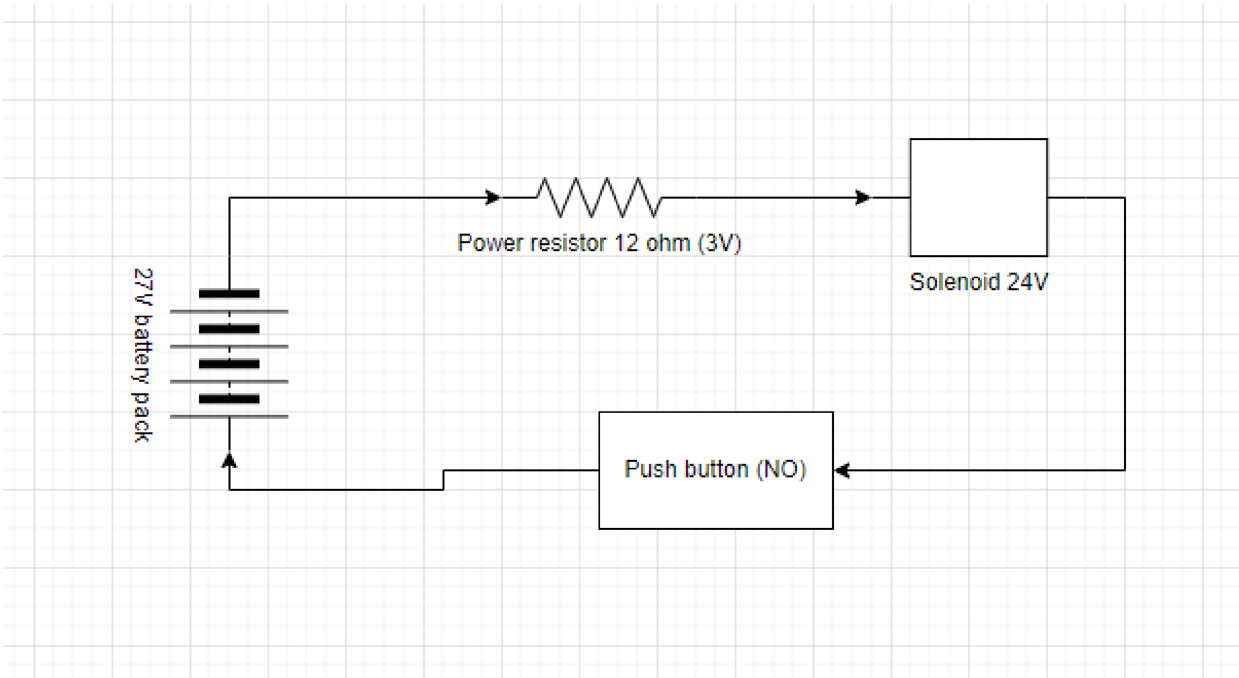


Figure 37 – Basic power source and manual actuation circuit for air solenoid, proof of concept test only

Appendix G

Figure 38 – Image example of minor flap separation (evident at sides)

Figure 39 – Image example of crinkles on the inside of the carton

Appendix H

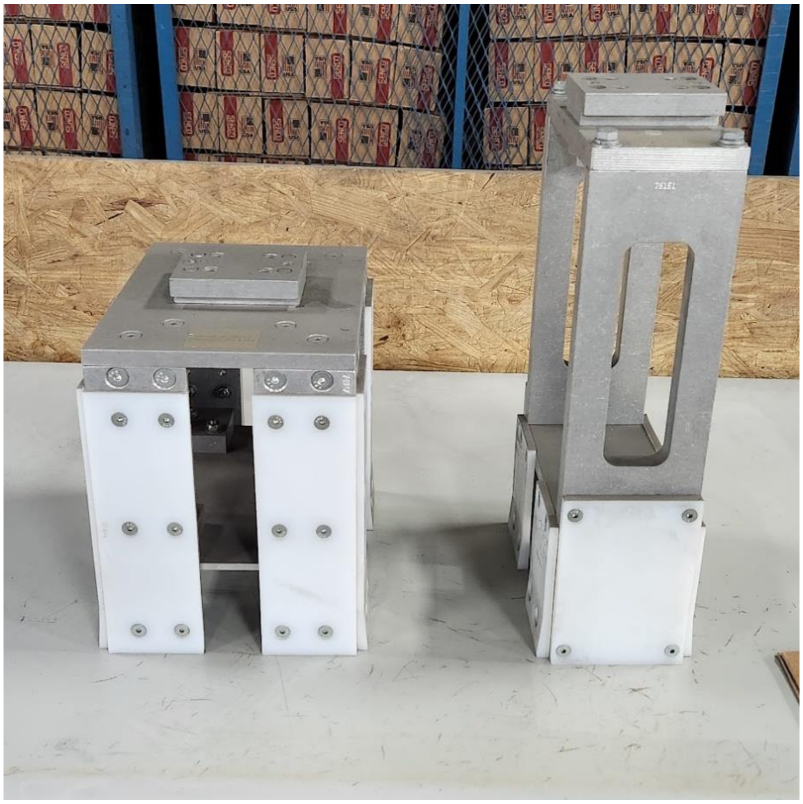


Figure 40 – Image examples of currently existing tray forming mandrels – There exists 2 basic types of mandrels: 2 column and 4 column. The retail packs were made based on the 4 column models due to the ease and availability of aluminum angle extrusions.

Appendix I

Formulas used in calculations for required vacuum pressure

Area of cup orifice

$$Area_{circle} = \pi * \frac{Ø^2}{4}$$

$$Area_{cup\ orifice} = \pi * \frac{(0.71\ in)^2}{4}$$

$$Area_{cup\ orifice} = 0.369\ in^2$$

Vacuum required per cup

$$\#\ cups = 4$$

$$\sigma_{vacuum\ pressure,cup} = \frac{\frac{F_{applied\ required}}{4}}{Area_{cup\ orifice}}$$

$$\sigma = pressure$$

$$F = Force$$

$$\sigma_{vacuum\ pressure,cup} = \frac{\frac{5\ lbf}{4}}{0.369\ in^2}$$

$$\sigma_{vacuum\ pressure,cup} = 3.157\ psi$$

Conversion from psi to inHg

$$1\ psi = 2.036\ \text{inHg}$$

$$\sigma_{vacuum\ pressure,cup} = 3.157 * 2.036\ inHg\ = 6.428\ inHg$$

Formulas used in calculations for vacuum response time

Extrapolation formula

$$y = y_1 + \frac{x - x_1}{x_2 - x_1} * (y_2 - y_1)$$

Extrapolation for time required to achieve needed vacuum pressure (data from reference item 7, model # CV15H)

$$6.428\ inHg\ = 6\ inHg + \frac{x_{response\ at\ given\ pressure} - x_{respone\ time\ at\ 6inHg}}{x_{respone\ time\ at\ 9inHg} - x_{respone\ time\ at\ 6inHg}} * (9\ inHg - 6\ inHg)$$

$$6.428\ inHg\ = 6\ inHg + \frac{x_{response\ at\ given\ pressure} - 5.32\ sec/ft\text{^}3}{8.4\ sec/ft\text{^}3 - 5.32\ sec/ft\text{^}3} * (9\ inHg - 6\ inHg)$$

$$0.428\ inHg\ = \frac{x_{response\ at\ given\ pressure} - 5.32\ sec/ft\text{^}3}{3.08\ sec/ft\text{^}3} * (3\ inHg)$$

$$0.440\ = \ x_{response\ at\ given\ pressure} - 5.32\ sec/ft\text{^}3$$

$$x_{response\ at\ given\ pressure}\ = \ 5.76\ sec/ft\text{^}3$$

Net volume tabulation

$$Volume_{internal,each\ cup}(calculated\ by\ solidworks) = 0.2in\text{^}3$$

$$Volume_{internal\ cups,total} = 0.8\ \text{in^3}$$

$$Volume_{internal,cup\ manifold}(calculated\ by\ solidworks) = 1.358in\text{^}3$$

$$Volume_{cylinder} = \pi * \frac{\emptyset^2}{4} * height$$

$$\emptyset\ \ = Diameter$$

$$Max\ length\ of\ tubimg\ from\ mandrel\ to\ ejector = 12in$$

$$ID\ of\ tubing = 0.25in$$

$$Volume_{tubing} = \pi * \frac{0.25^2}{4} * 12in$$

$$Volume_{tubing} = 1.178in^3$$

$$Volume_{net} = 3.336in^3$$

Response time tabulations

$$x_{response\ at\ given\ pressure}\ = \ 5.76\frac{sec}{ft^3} = 0.003\frac{sec}{in^3}$$

$$Volume_{net} = 3.336in^3$$

$$Net\ response\ time\ for\ 6.428inHg\ vac\ (s) = Volume_{net} * x_{response\ at\ given\ pressure}$$

$$Net\ response\ time\ for\ 6.428inHg\ vac\ (s) = 3.336in^3 * 0.003\frac{sec}{in^3} = 0.01112\ (s) = 11.12\ ms$$

Calculations for force on mandrel

$$T = F * (\frac{diametral\ pitch, driving\ gear}{2})$$

$$156\ lbf * in = F * (\frac{3\ in}{2})$$

$$F = 104\ lbs$$

$$F_{per\ upright} = \frac{104\ lbs}{4} = 26\ lbs$$

$$T \quad = torque\ from\ driving\ gear\ during\ stall$$

$$F = force\ of\ total\ applied\ load\ on\ belt\ from\ motor\ stall\ torque$$

Factor of safety calculations

$$\sigma_{allowed} = (\frac{S_y}{N})$$

$$\sigma_{allowed} = \left(\frac{275\ MPa}{3}\right) = 91.667\ MPa$$

$$N \quad = factor\ of\ saftey$$

$$\sigma_{allowed} = stress\ allowed\ for\ designated\ factor\ of\ saftey$$

$$S_y = Yeild\ stress\ for\ aluminum\ 6061 - T6$$

Formulas used in calculations for air velocity

$$Velocity_{air} = \frac{SCFM_{pressure\ regulator}}{ID_{air\ tube}}$$

$$Velocity_{air} = \frac{89\ ft^3/\min}{\pi * ID_{air\ tube}^2 * 0.25}$$

$$Velocity_{air} = \frac{89\ ft^3/\min}{\pi * 0.25in^2\ * 0.25}$$

$$Velocity_{air} = \frac{1.483\ ft^3/\sec}{0.049\ in^2} = \frac{1.483\ ft^3/\sec}{0.0003\ ft^2} = 4{,}943.33\ ft/sec$$