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DESIGN PROCESS OF A CARDBOARD CUP MODIFIER

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TIIVISTELMÄ

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Kartonkikuppien muokkauskoneen suunnitteluprosessi

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Tässä työssä käydään läpi kartonkikuppien muokkauskoneen suunnitteluprosessi vastaamaan toimeksiantajayrityksen tarpeita. Suunnittelussa pyritään löytämään toimintavarmat ratkaisut kuppien muokkaukseen ja käsittelyyn, käyttäen mahdollisimman paljon valmiina saatavilla olevia ratkaisuja ja komponentteja. Erityistä huomiota kohdistetaan myös laitteen yksinkertaiseen toimintaan, huollettavuuteen ja helppoon valmistettavuuteen, sekä kokoonpanoon. Laitteen tulee kyetä erottelemaan kupit toisistaan, rei'ittämään niiden pohjat, poistamaan palat alareunan sokkelista, ja pakkaamaan kupit uudelleen pinoon käsittelyn jälkeen. Useita vaihtoehtoisia ratkaisuja näiden tavoitteiden saavuttamiseen tarkastellaan ja vertaillaan sopivimpien löytämiseksi.

Iteratiivisen suunnitteluprosessin edetessä päädytään paineilmatoimiseen laitteeseen, johon kuppipino syötetään ylhäältä, jonka jälkeen kone erottaa pinosta yhden kupin kerrallaan painovoimaa hyödyntäen. Yksittäiset kupit putoavat kolmepesäisen revolverin ensimmäiseen pesään. Revolverin käännyttyä toiseen asentoonsa kuppien pohjat lävistetään sisältä ulospäin, ja alareunan taitos lovetaan useasta kohtaa, käyttötarkoituksen mukaisen toiminnan takaamiseksi. Kolmannessa asennossa kupit puhalletaan paineilmalla ylös koneesta, haluttuun paikkaan reititettyä putkea pitkin pinoon. Tämän jälkeen tyhjä pesä pyörähtää takaisin ensimmäiseen asentoon, ja uusi kuppi voidaan syöttää. Kone käsittelee kolmea kuppia kerrallaan revolverin kääntöjen välissä. Yksi on ladattavana revolveriin, toinen työstettävänä ja kolmatta puhalletaan pois koneesta.

Lopputulos saavuttaa täysin sille asetetut vaatimukset, mutta se sopii vain tietyn kokoisten kuppien käsittelyyn. Siihen on kuitenkin mahdollista joko valmistaa komponentit myös pienempien kuppien käsittelemiseksi, tai se voidaan kokonaisuudessaan skaalata eri koon kupeille, joita toimeksiantajayrityksen on tuotannossaan käsiteltävä.

ABSTRACT

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Design process of a cardboard cup modifier

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In this thesis, the design process of a cardboard cup modifier, for client company's needs is presented. In the design, various suitable solutions for making the required modifications, and handling the cups through the process are presented, evaluated, and compared. The solutions, most suited for the company requirements are selected and designed using as much readily available components as possible. Emphasis is given especially for production reliability, serviceability and simple manufacturing and assembly. The machine needs to be able to separate each cup individually from a pile fed to the machine, make holes through the cup floor, remove sections of the skirt, and then restack the cups as they were.

The outcome of the iterative process is a pneumatic machine to which stacks of cups are fed from the top. Next step in the machine separates the cups, with the help of gravity, feeding them one at a time into the first chamber of a three chambered revolver. After the revolver has turned to its second position the floor is pierced from inside out and the skirt is notched in several places to ensure the functionality in the intended end use. In the revolver's third position the cup is ejected with an air nozzle through a pipe to a stack in a designated location. Then the revolver turns a third time returning the chamber in the starting position for a new cup to be inserted. In reality the machine handles three cups simultaneously between the rotations, one in each step of the process. As one is placed in the revolver, the second is being modified and the third is being ejected out of the machine.

The finished prototype model fulfills all the requirements set by the company, albeit being able to only handle the largest specified size of cups. Either adapters and smaller tools can be manufactured into the same frame, or the machine can completely be scaled down to properly suit the smaller sized cups the company needs to handle in their production.

ACKNOWLEDGEMENTS

Thank you, Amir Toghyani, for connecting me with Bionido Oy representatives, who then provided me the topic for this thesis with suitably a hasty timetable. Eeva Jernström from Bionido Oy, for the company viewpoint and continuous feedback and support. And lastly Professor Juha Varis for the support, positive feedback and for challenging my proposed solutions with ideas of your own, even if in the end I mostly managed to justify my solutions over your propositions for the final machine concept.

Siivertti Malkamäki

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1 INTRODUCTION

Bionido Oy has developed a pot made out of a plastic free paperboard material, that can be cost-effectively manufactured with traditional cardboard cup forming machinery. Unfortunately, these machines are only able to form waterproof cups, as pre-cutting required holes in the material causes issues in the forming process. To be suited for the intended end use, the cups thus need some modifications after they have been formed. The aim of this research was to design a machine that can cost-effectively fulfill this need.

1.1 Research questions

During this design process, various possible solutions to the questions on how the cups can be unpacked, handled, modified, and repacked were thoroughly assessed. How to make sure that the modifications do not weaken the cups excessively was considered as well. The evaluations were based on company preferences, literature sources and a virtual prototype modelling, with which the safety and functionality could be assessed, refined, and discussed with the company representatives. The most suitable solutions were gathered and developed as a viable machine concept, able to perform all these functions reliably and cost-effectively in commercial scale. When reasonable, the suitable manufacturing methods of specific designed components were compared.

1.2 Objective of research work

The use of ready-made components and systems was aimed to be maximized for reliability, replacement part availability, cost, and timetable reasons. As making holes to watertight containers seems somewhat counterintuitive, no premade solution for the whole process, or even any of the individual actions needed is available for this specific use, and therefore some parts needed to be designed from scratch as well.

The design process was carried through with much emphasis on the simplicity, manufacturability, reliability, serviceability, and ease of assembly. Many of these aspects are essential in Design for manufacturing and assembly (DFMA) methodology, therefore it was chosen as the backbone for this design process. An integral aspect of the DFMA mentality is to consider manufacturability aspects during, and throughout the design process, not after it, making sure that the concepts are functional and cost-effective to manufacture. Some basic DFMA actions that were performed during this design process, were: minimizing the number or components in the construction, utilizing modularity, incorporating multiple functions to components, utilizing same manufacturing methods for as many components as possible and maximizing the utilization of standardized components. Designed components were also optimized with manufacturing method specific aspects. (Eskelinen, H. 2020.)

At First the machine functions were designed with focus on the end product and finding the most functional rudimentary solution to fulfill the user requirements. Then as functional solutions were found, the subassemblies were designed in more detail, giving more focus to DFMA aspects. Components and whole assemblies were completely redesigned several times during the iterative process using SolidWorks 2020 to find the best possible overall design. The fact that the final outcome is a prototype machine, not a finished commercial product, means that not everything could be optimized to the fullest considering only DFMA aspects. For example, from the viewpoint of DFMA, a complex part performing several functions, combined to one easy to assemble/manufacture component would be preferred to multiple individual components that take more time and effort to assemble. For a proof-of-concept type machine like this one, more adjustability and possibilities to change and modify components and their positioning is much more important.

1.3 Limitations

Detailed component selection, control system design, and final assembly details were ruled out of the scope of this design process, per the company's request, as they were willing to do the procurement themselves, based on the initial testing and available utilities. For some components, preliminary comparison of pricing from different vendors was still done. Mainly to provide food for thought about possible alternatives for the person doing the procurement at a later stage. Actions taking place before individual cup piles are fed, and after the finished cups exit the machine, were limited out as well since they can be done by hand initially. After the concept is proven to be functional, and the production is upscaled, these steps of the process can be automated too.

Many of the production processes and components specified for the machine during this research are so common in the mechanical engineering field that they are not presented in detail. Detailed understanding of their functioning is not relevant for this work either, as the details are to be specified later in the development process, based on the prototype model crated during this research. This research is mainly a product development process largely based on 3D-modelling various solutions and assessing them based on own deliberation. The quality requirements for the edges of the openings created are much lower than those of common cardboard cutting processes where clean-cut edged are required. No available commercial processes for such rough cutting of cardboard were found, limiting the amount of usable literature sources. The present global situation also rendered physical literature unavailable.

1.4 Cardboard cup characteristics

A cardboard cup structure (Figure 1) consists of two formed sheet panels, the body, and the floor. These two parts are connected together in the skirt fold. The floor is folded in between the opposite direction body panel hem, holding it firmly in place and making the cup watertight. The rim improves the rigidity and comfort of use on the top edge. The parts are held together with heat activated bonding agents.

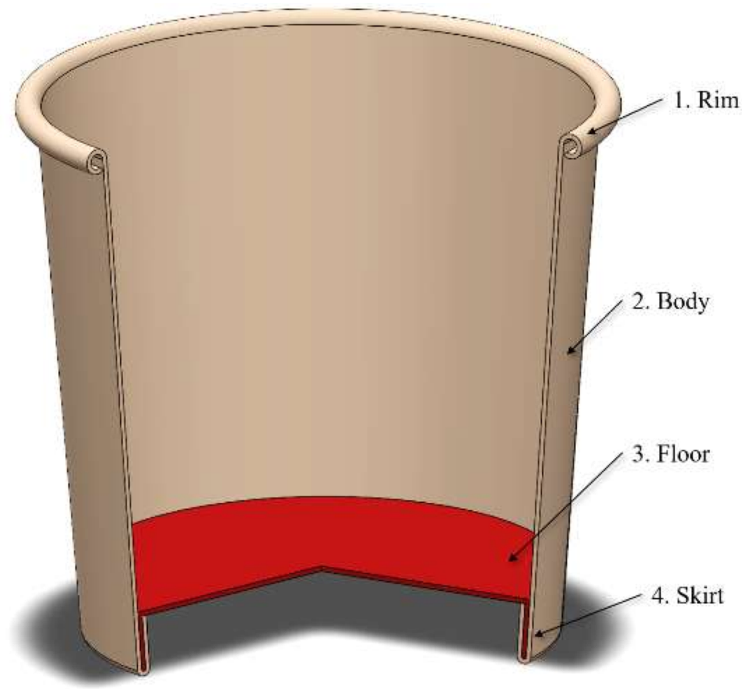

Figure 1. Cutout of a cardboard cup structure

If comparing a cardboard cup with a sheet metal bucket, which has a nearly identical construction, with rolled top and folded bottom edge with the bottom panel in between the fold, some clear differences can be detected. The material difference is significant considering the design of a modifying machine. In many ways cardboard is easier to form. It tears with a smaller force, wears down cutting blades much less and the requirements for cutting dies are more relaxed. The smaller density is also an asset in handling as the cups are lighter weight, but at the same time makes cardboard cups slightly more challenging to handle as they are easily compressed or crinkled. The overlapping material sections on the top and bottom edges make the cups more rigid, as they do with metal buckets, but cutting through multiple layers is more complicated, but unavoidable in this case. Precise reshaping with bends and folds on the other hand is more difficult with cardboard than steel. The forces are smaller, but as a result of the more heterogenous material composition, cardboard bends tend to spring back more, and the bends are less stiff and the angles consistent in general.

2 EXPERIMENTAL RESEARCH

As there are several tasks the machine needs to perform, the machine design was divided into respective subassemblies.

1. Separating the cups from each other to be processed individually
2. Making holes through the floor
3. Making notches in the skirt
4. Somehow moving the cups and/or tools through these steps
5. Piling the cups back to be separated to units of 50 or 100 as they were

These subassemblies were initially designed separately, with the others in mind, and then finalized and combined as one unit later in the design process.

It was clear from the beginning that several sizes of cups need to be modified, either with the same, or separate machines. For the most flexible machine possible, regarding the cup sizes, the initial design was made with the largest cup dimensions provided by the company. This design process focuses on the largest size, but the solutions can mostly be scaled down. This way all the other sizes fit within the machine, and all the tool and cup handling movements are long enough.

The expected annual production numbers are in the millions. As a result, somewhere between 8 000 to 40 0000 cups need to be processed daily. Achieving such production speeds leaves mere seconds of time for processing each cup. The machine prototype must be designed to credibly be expected to achieve such production speeds reliably without compromising safety. If multiple cups are be processed simultaneously, the time used per cup is of course divided in straight relation. If the cost of the machine is kept low, using multiple machines may be a feasible alternative for upscaling the production as well.

2.2 Separation

Cardboard cups enter the process in stacks of 50 or 100 and need to leave the process in the same fashion. The most straightforward option would have been to make the needed alterations to the cups while they stay stacked, eliminating the need for any unstacking or handling movements. Notching the bottom fold within the required 1 mm down from the underside of the bottom, would be a significant challenge as the cups are tightly nested within one another. There is no possible way of altering the side walls of a single cup without affecting others while they are in a continuous stack where the bottom of any given cup is within the next 8-12 cups. Making holes through the bottoms might be possible in a stack with long enough piercing tools or some form of media blasting. However, the tallest possible stacks being over a meter tall, making holes mechanically through such a long distance accurately, reliably and without tearing any of the cups seems rather cumbersome. Making the bottom holes individually for each cup was thus preferred, as it gives more possibilities with simpler methods and the cups need to be separated for the notching step anyway.

Initial idea was to separate each cup from the next with a suitably dimensioned circular gear since the side profile of the cup stack resembles that of a linear gear. Both, the option of separating a cup with an incremental revolution, and a full revolution were analyzed. Main issue with the incremental turn alternative was that especially when handling smaller cups, the rims are small, the cups stacked close to one another, and the distance needed for reliable separation rather long in relation. Trying to design a gear geometry able to push a flimsy, tightly stacked cup far enough away from the next, proved to be challenging without excessively counting on the flexibility of the cups. Using an asymmetric gear, and a full revolution gave more freedom and possibilities, but the idea was put on hold too on the account of simplicity, as the other functions designed simultaneously started to steer heavily towards pneumatic actuators. Achieving accurate angular movement with affordable pneumatics is difficult and options with simple linear movement were yet to be assessed.

Linear movement -based alternatives were evaluated next. First idea was an evolution from the previous designs. The idea was to push the first cup forward by the rim with a simple linear pneumatic actuator slightly angled towards the centerline of the cups with a suitably shaped end piece “hooking” to the rim. The difficulty in this design was keeping the other cups in place and not following the one being moved as well as making sure that the cup being moved is firmly in place after the movement. Achieving a linear movement of the cup might also have required multiple actuators on opposing sides.

Next iteration of the linear actuator design was a wedge inserted perpendicularly between the rims of the first two cups in the stack. With a suitable wedge geometry, the cup could be moved a precisely specified distance (the width of the wedge) simultaneously from two sides with a single movement. The challenge in this design was similarly as in the one before, making sure that only a single cup moves forward in the machine. This issue was overcome by designing a groove system into the trailing edge of the wedge. While the first cup was pushed to the furthest possible position, and the actuator all the way out, the next cup could slide into the wedge, just enough to hold it in place, but not allowing for the next cup to fit in the same groove.

2.3 Hole making

Ability to make holes through the cup floors is the most important feature of the machine for the intended end use. Clean-cut edges were not required, and the hole shape was not predefined. The holes needed to be located on the outermost third of the bottom and no protrusions were allowed on the inside face. Methods with removing the hole material, and piercing through the material without removing any, were analyzed. Punching the holes with traditional cardboard cutting tools would provide clean edges and allow the making of any shape of openings. This method could possibly end up leaving the hole blanks inside the cups or otherwise disturbing the handling process and use.

Since the hole shape was not predefined, the optimal solution needed to be found. A simple, single straight cut would possibly be the easiest to make, but it would not provide a large enough opening to fulfill the functional requirements. Forcing such cut to any other shape with sufficient area would be unreliable and might cause the material to tear in random directions. More cuts per hole were needed. Making two equal cuts perpendicularly, with the same middle point, provides the possibility to fold down the paperboard sections left between the cuts forming a square hole. Similarly to the straight cut, the corners are weak spots that enable the cuts to continue with relatively small force. When also considering the continuous moisture stress during use, the effect the holes have to the strength of the cup bottom should be minimized. An option would be to cut the holes in such way that the part bent down from the opening would support the bottom against the surface the cup sits on. As the largest cup was used as the initial reference, this option needed to be ruled out. The distance from the edge of the bottom fold to the actual cup bottom is roughly 12 mm in the biggest cups. The size of the holes, defined by the company is 6-10mm. For the folded edge to give any reasonable support to the cup, the width of the folded section would need to be greater than the height, which is not possible if the maximum hole dimension in one direction is 10 mm.

Since the edges of the hole did not need to be clean or precise, puncturing the holes through the material without specific cutting blades was also a possibility. Piercing leaves the material from the hole around the edges, so this method was selected to be used from the inside outwards. Aiming to minimize the risk of the holes tearing further than desired, a rounded shape was chosen. Oval, and other elongated shapes were abandoned as they had no advantages compared to a circular hole but would have required more accurate positioning and orientation to fit within the specified area of the bottom surface with the tools themselves. Puncturing can be done as a one step process, and no opposing die is needed. This gives more flexibility for altering the hole sizing and pattern during production, without significant cost increase.

2.4 Notching

Openings were required on the bottom edge of the skirt as well. According to the end use requirements the openings must be made in a way that leaves no material at the bottom edge of the skirt, and the least amount possible below the floor (maximum of 1 mm allowed). As there were multiple options for making the holes, even more were evaluated for creating the notches. The notches could possibly be made from inside out, outside in, both at the same time, or diagonally. Main initial limiting factor was that no material is allowed to be left protruding outside the cup's original outer profile, since it could interfere with the restacking and other further handling processes.

A solution would have been to just crease the skirt. No material would need to be removed and no sharp tools or high movement speeds would be needed. Combined with piercing hole making process the debris created could be nearly nonexistent if no material were to be removed in this step either. If done from outside inwards, there is plenty of usable space for the creased material to occupy without causing issues. The direction however causes a problem. The thickness of the fold is three times the material thickness, so even when bent completely flat against the bottom side of the floor, it exceeds the 1 mm limit above the opening, since the maximum material thickness used is 0.6 mm (3 * 0.6 mm > 1 mm). How the creased section would behave during the use, under constant or alternating moisture exposure, could not be reliably predicted. Possibly the crease could even spring back, to some extent, restricting the opening. For these reasons, the focus was shifted to methods cutting the skirt material.

Cutting a slit in the material and folding the material further away was assessed with various geometries. Triangular opening could be created in multiple ways. The lowest number of cuts needed is one. A possibility would be to make a diagonal cut and fold along the adjacent side (Figure 2). Another way is to cut two sides and fold along the third. This would better withstand the negative effects stated considering the creasing option as the folded section could be folded to stay against the bottom, making it harder for it to move back partially covering the opening.

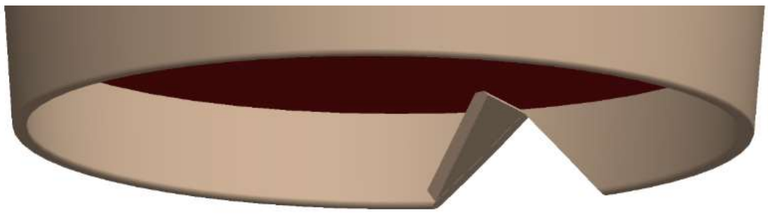

Figure 2. One cut edge, one fold, skirt opening option

A rectangular opening could be made with two cut sides (Figure 3) having the same benefit. An additional benefit could be that the folded section could act as an extra support below the floor. Such support would however only be useful near the center and making the needed three to six folds long enough to reach anywhere near the center would compromise the rigidity of the entire skirt.

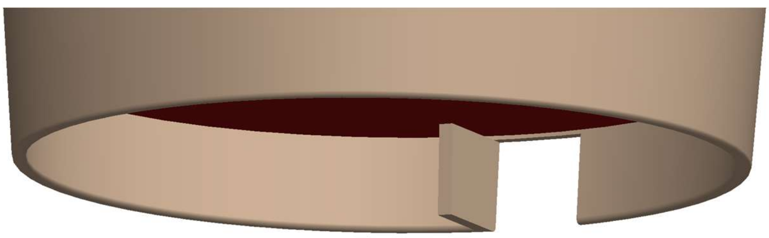

Figure 3. Two cut edges, one fold skirt opening option

T-shaped cut (Figure 4) is also a possibility and would be equally simple to create. This would support the skirt on both sides of the cut, but even less the floor. The same skirt rigidity issues are equally present for this as for the previous option.

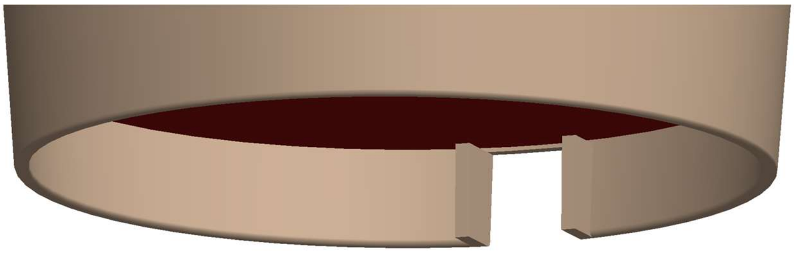

Figure 4. Two cut edges, two folds skirt opening option

Cutting the opening material completely off leaves behind the cleanest edges and therefore the lowest likelihood of the skirt material blocking back the notched openings. This means that the holes can be made from any direction. Choosing the most suitable direction comes down to optimizing the mechanics of the cutting rather than the blade positioning itself. It is worth noting that the skirt is significantly stiffer when force is applied from inside out rather than from outside in, due to the conical shape of the cups.

As with the cutting and bending options, a triangular opening seemed like the simplest solution for creating a complete opening. With only two straight cuts, an opening could be made. The shape would also retain the strength of the skirt better than a rectangular version, as the opening would taper to a single point near the floor bottom. The cutting blade needs to hold its orientation during cutting, which would be easy to achieve with an angular blade in a simple groove.

Taking into consideration the manufacturing of the blades themselves changes the assessment slightly as the hole and notch making tools blades are the most prone to wear, and so should be simple and cheap to manufacture. Designing from a manufacturing point-of-view, a circular tool seemed to be the lowest cost alternative. It would be simple to turn on a lathe. One issue a circular profile tool has, is the lack of a sharp penetration tip. As the machine design had already at this point started to steer heavily towards using pneumatics as the main driving force, the sufficiency of force needed to be evaluated.

In addition to mechanical cutting methods, other methods were looked into. Media cutting, such as water or abrasive jet, is one possible option. Such “contactless” methods could have a simplifying effect for the machine as the cutting and notching could be done from a distance, whereas cutting blades need to be moved to and through the cup sections needing modification. The media cutting nozzles could be stationary in the machine and the cups would only need to move to a suitable location. These techniques would give more freedom regarding the shape of the notches as well as the holes, if used for them too, if the jet/jets were computer numerically guided. Even if special shapes might have some benefits regarding the end use of the cups, the mechanical solutions do suffice, and such a big cost and system complexity increase could not be justified.

Laser cutting would provide similar possibilities and results as the previous procedure. An additional gain might be that the laser could incinerate the waste material removed from the holes and notches during the cutting, removing it from causing issues or requiring further processing down the line. While this would streamline the production process, it would not go together with the sustainability principles, that are the basis of the whole product to be created with the machine in question. Laser as well as media cutting processes are very energy intensive processes, at least when compared to simple pneumatic movements that suffice in this case just fine. The upfront equipment cost is also an aspect steering the selection more and more towards mechanical alternatives. (Caristan, C. 2004.)

2.5 Repacking

Since the cups need to be separated from stacks to individual cups for the aforementioned reasons, they need to be restacked as well. Eventually the stacks need to contain equal number of cups as they did when inserted into the machine, but in the scope of this prototype, creating a continuous stack was deemed enough. Being one of the steps not affecting the performance of the cups in any way, the machine design already was well on its way, when the design on this step began properly.

Simplest solution that was found is to remove and restack the cups using gravity. Zero components would be needed to move the cups. By designing the flow of cups, being it circular, linear, or something else, through the machine so that after the holes and notches are made, the cup just falls vertically down onto or into the previous one. This clearly limits the cups possible exit directions to just one, downwards. Additionally, if not assisted in any way, it must be made sure that there is no possibility for the cups to get stuck or have excessive friction with the components they are in contact with, because the cups are lightweight and thus the gravitational force is rather limited.

Another option to remove the cup from the machine is to use a simple linear pneumatic actuator with long enough stroke to push the cup off the working area of the machine, making room for the next cup. The speed of the movement could be easily adjusted and with an opposing load from a spring for example, it could be made sure that the cups are all the way in one another. Pneumatic cylinder, when functioning properly, would reliably move the cup away in any direction specified, every time, even with tight cup fitment as it has more force than gravity in this application. The drawbacks of such system are the number of moving parts that require some maintenance, even if not that frequently, and movement lengths limited to the stroke lengths of available pneumatic cylinders.

A solution that has no moving parts and much less limitations regarding cup movement direction or movement distance is utilizing pneumatic tubes. A method commonly used for various granular materials. An additional benefit of this method is that the cup does not need to contact any additional parts, possibly damaging the cups during high-speed production, since only the airflow is needed to move the cup. The requirements for Pressurized airflow can easily transport cardboard cups in a suitably sized tube for even distances of several hundred meters. A possible drawback with this solution is the limited maximum force, defined by the available air pressure. The holes made in the main perpendicular surface used to propel the cups forward with the airflow lower the maximum force even more. Either negative or positive pressure could possibly be used. Blowing the air into the cup would be more reliable, and the movement would be stabler, compared to blowing it against the bottom, but the needed orientation is dictated by the other mechanisms on the machine. Pressurized airflow can equally be used to support other cup movement actions within the machine, if needed. (Mills, D. 2004.)

2.6 Handling movements & actuators

While the various cup modification methods were evaluated, different possibilities for accomplishing those steps consecutively were assessed as well. Either the tools need to move to the cup, or the cup to the tools, or a combination of the two. Whenever moving any object there are two possible movements, translation, and rotation, or a combination of the two. From these linear translation movement is simpler to achieve with pneumatics. Straightest passage of cups through the machine would be linearly in from the top and out from the bottom. No actuators would possibly be needed since gravity is in line with the cup movement throughout the process. At this point of the design process, it was already clear, that at least some of the tooling would need to move along the cup's imagined center axis. To not to interfere with the cups passing through the tools would then need to first move into position and then through the cup, making the movements unnecessarily complex.

The cups being much lighter than the tools, it requires less energy to move the cup rather than the tool. A seemingly simple solution would be to push the cup aside with a pneumatic cylinder or solenoid, use the tooling to make the needed modifications, and then push the cup back allowing it to continue further down in the machine and the process. An issue that arises from this approach is due to the miniscule mass of the cups combined with the production speed aspirations. Pushing the cups from one location to another from the side in a controlled manner is challenging, as the cups can easily either get crushed and/or move to unwanted directions or orientations.

To prevent the need for tackling this problem a rotation-based alternative was evaluated with the virtual prototype next. When guiding each cup to a revolving "chamber" they can hold their shape and orientation no matter the operation speed. Even if the openings made in the cups, decrease their overall strength slightly, all the holding and moving can happen higher up, near the intact rim, still providing the original amount of support for the cup shape. Multiple operations can be done at the same time at the locations these chambers rotate through, enabling the simultaneous processing of multiple cups.

For continuous production, a completely linear, single direction process layout may have issues with the available space, and at least the machine would be tall and therefore safe operation would require additional structures, increasing cost significantly. On top of that, if the hole making and notching processes took place on the same vertical axis as the cup re-piling, separating the modified cups from the waste likely raining on them would be an additional, avoidable challenge needing to be solved.

The revolver idea suits this kind of linear layout poorly too for the following reasons. Possibly with a vertical revolver with the cups positioned radially, the cups could be inserted from the top and ejected downwards. Inserting the cups bottom first, is the most logical approach as they are conical in shape, so they hold in place without any additional elements. Unfortunately, a radial-type revolver has its own shortcomings. It is more difficult to manufacture, and as the tools have to access the cups from both, the opening, and the bottom side, one tool would then have to be inside the revolver to have access from the easiest direction. This would require the revolver diameter and therefore the entire machine to be massive, compared to an axially oriented chamber pattern.

An axial revolver would not have these issues. It actually has many benefits compared to a radial version. Suitable chambers are simpler and easier to manufacture and therefore the cost is lower. The movement paths of the tools are also simpler as they can be purely linear, as long as the cups do not need to enter or exit the machine at the modification point/points. To keep the number or moving parts as low as possible, the linear one-way-through layout was ruled out of the design process. A simpler solution for this revolver type is a to extract the conical cups back in the same direction they came in. For example, downwards in, and upwards out. Possibly the revolver could even be designed to most benefit from gravity, by orientating the chambers so that the in -direction is down (bottom first), and the out is down as well (top first), and then the tooling positions are somewhere in between. Such design would make the revolver more complicated to manufacture than one with axially or even radially oriented chambers. This would also cause the possibly heavy tool/tools to be oriented either diagonally or horizontally, causing lateral stresses in the actuators, which can be avoided by designing the cup handling to allow for purely vertical tool movements.

Another challenge needing to be solved in addition to the positioning of the cups in the revolver assembly, is the rotational movement of said revolver. It needs to be rapid, but also precise enough for the tools and inserting and extracting assists to hit their goal properly. Due to the needed accuracy, freely rotating pneumatic and electrical motors were not considered. With a belt driven electric stepper motor such movement could easily be achieved. This would require a processor and other components not otherwise needed in the machine. The simplest accurate actuator to rotate the revolver would be a linear pneumatic actuator with only one moving part and no need for any control circuitry. On the other hand, transforming the linear movement to precise partial rotations can be challenging.

Pneumatic rotary actuators are another possibility. The type of rotary actuator in which the air pressure rotates a shaft is incompatible with this use, as accurate partial rotations are as challenging to achieve as with a basic electrical motor. The other type is one where the air pressure moves a piston, just like in a linear actuator, but the piston rod is a linear gear connected to a shaft with a circular gear, forming a rack and pinion type setup. Such rotary actuators are readily available, but the selection is not as comprehensive as with linear actuators. Due to the construction, the range of motion is not continuous rotation, but commonly adjustable from zero to 180°. For this reason, these actuators are most suited for back-and-forth type rotational movement. If used in this machine some form of linkage or gearing would be needed to transform the action to repeated consecutive partial rotations in the same direction.

For simplicity, the tooling movements were aimed to be linear from the beginning. Suitable linear actuators could be either electrical solenoids, pneumatic cylinders, or hydraulic cylinders. Out of these options, pneumatic cylinders are the most suitable for this application for the following reasons: Solenoids have a limited motion length, and relatively low force. Hydraulic cylinders require a fluid, that is potentially dangerous when leaking, and the available force is excessive. A pneumatic actuator uses air as the medium, and pressurized air is readily available in most industrial facilities. The action speeds are high, the available force easily sufficient, and there is no risk of electrical shock or a fire. (Parr, A. 2011.)

3 RESULTS

From the evaluations presented in the previous chapters, the most suitable solutions were chosen for the final machine prototype. The orientation of the machine is vertical, utilizing gravity to move and hold the cups in various steps of the process, while minimizing lateral forces in the heavier tool actuator piston rods, as they are vertical as well. All the actuators are pneumatic with a 32 mm piston diameter, and only two stroke lengths are needed: 50 mm and 125 mm. This simplifies the procurement, but the main benefit is the need for available spare parts, as only two sizes need to be stocked. A horizontal revolver, with three vertical chambers is used to hold and move the cups through the three stepped process.

3.1 Input & cup separation

The cups are fed bottom first into the machine from the top through a pipe long enough to hold at least a couple of cup stacks at a time. The pile then sits on top of a pneumatically actuated separation wedge (Figure 5), bottom of the top rim against the top of the wedge. When the pneumatic actuator extends the whole stack drops down the height of a single cup skirt. This moves the top of the rim below the tip of the wedge (highlighted in blue in figure 5), allowing the wedge to separate the first cup from the next as the actuator compresses and pulls the wedge between the rims of the first two cups. As the wedge pulls the cups apart, the first one drops down to an empty revolver chamber below and the cups on top, are held in place by the top surface of the wedge. When the actuator extends again the stack drops down again allowing the next cup to be wedged loose. If needed for ensuring reliable cup separation and high enough production speeds, an airflow nozzle similar to the ejection nozzle presented in more detail in chapter 3.1.5., can be added. Suitable positioning might be angled down above the cup separator or just below.

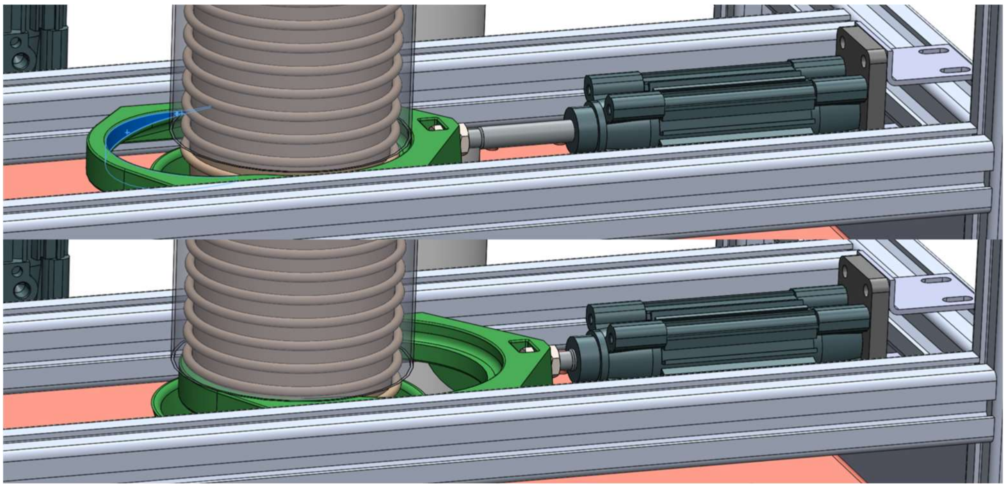

Figure 5. Cup separator action. In the extended position, the pile sits atop the lower ledge. As the piston retracts, the bottom cup falls off while the rest of the pile is held up by the top surface.

At least for the testing phase, the wedge itself is made with additive manufacturing methods from a suitable polymer material, such as PETG, ABS or nylon. The geometry is challenging to manufacture in one piece with other manufacturing methods. If the additively manufactured component cannot withstand large scale production use, modifications to the component design are needed. For proper production use, the same functionalities can be achieved by assembling the wedge from a few simpler components easier to manufacture. For this prototype, the ease of construction and testing of geometry changes was preferred, and therefore additive manufacturing was chosen. For a more stable position during manufacturing a support flange was added to the design, visible in green in figure 6. Is serves no purpose during the operation, but neither interferes with it in any way. Required support material is in grey in the figure.

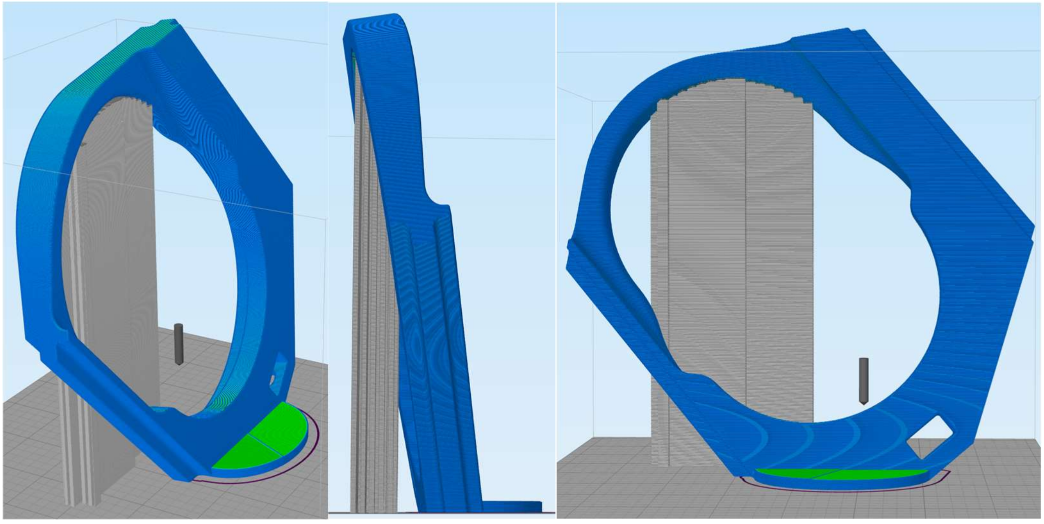

Figure 6. Manufacturing preview of the separation wedge. Support material in grey

3.2 Cup guides

After a cup has been separated from the pile it falls bottom first into a revolver chamber right below. A guide funnel (Figure 7) is added below the separation wedge to guarantee that the cup stays upright while falling to the revolver. The same guide also forces the cup all the way into the chamber as the revolver turns if the cup did not fall in all the way unassisted initially. This component can be made using the same additive manufacturing method and material as the separation wedge. There should be no issues with using such plastic component during both testing and production. During manufacturing, support material must be extruded between the build platform and the underside of the mounting tabs. It is necessary for proper functioning for the bottom of the finished funnel to be below the level of the mounting surface, coplanar with the cup guide panel bottom surface.

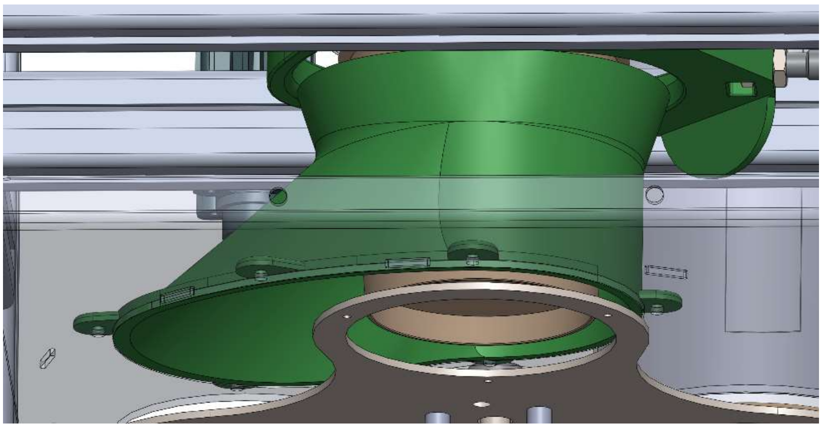

Figure 7. Cup insertion guide. Cups enter from the top, get centered to the revolver as they fall and then pushed all the way in as the revolve turns to the left form this view

The guide funnel is mounted onto a guide panel (Figure 8). At first this panel was added to the design to prevent the cups from being pulled off from the revolver along with the puncturing tool. During the design process many more features were incorporated into this laser cut sheet metal piece. The panel was extended to hold the cups vertical position from insertion to ejection. The edge after the insertion hole was bent to better direct the cups underneath the panel, but this feature was later switched to the guide funnel when it was designed, making this panel easier to manufacture. Flanges were added to all the exterior edges. On two opposite edges for mounting the panel to the frame, and for the other two to stiffen the panel itself and to allow it to be fastened to the enclosure panels, increasing the stiffness of all the panels for improved functionality and minimized noise from rattling panels. The perpendicular edges are bent to opposite directions for maximum compatibility with any width of bending tool. A pattern of holes was added to the design for attaching various components, with many possibilities for adjustment. Narrow slots in a circular pattern give a visual reference of the extremities of the revolver, aiming to minimize the risk of something being mounted too close the rotating assembly.

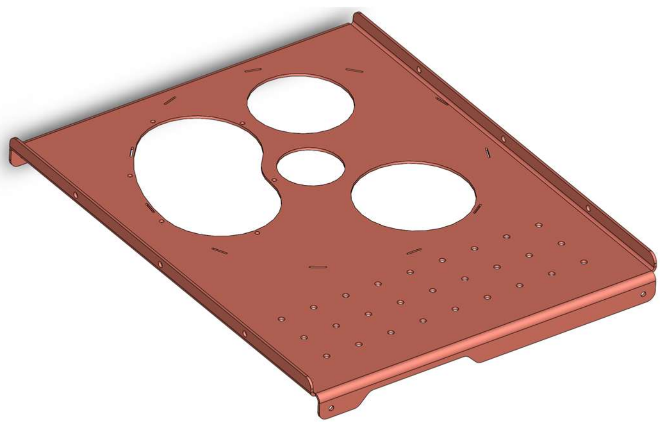

Figure 8. Cup guide panel. Large openings for the cups, tools and the revolver axle, small holes for mounting.

3.3 Revolver assembly

In the beginning of the revolver design, the idea was to machine a round piece from a 20 mm thick plastic sheet and then conical chambers through that, to hold the cups straight and firmly in place by the middle of the cups. The number of chambers was finalized to three: one for feeding the cups into the revolver, one for making the modifications, and one for ejecting the cups out of the machine. The possibility of four chambers was also evaluated, but no real benefits were identified from that approach. Actually, it is better to use both of the modification tools at the same time as they support and guide one another, and the revolver, and consequently the whole machine, is then smallest with the lowest number of chambers.

Multiple simple designs that are easy to manufacture exist for holding the cups, but the rotation mechanism was a bit trickier. Due to the machine steering heavily towards pneumatics the most suitable options would be to use either rotary or linear pneumatic actuators. Due to the aspects regarding rotary actuators, presented in chapter 2.6, linear actuators were preferred. The first iteration (Figure 9) was designed to utilize a variation of a barrel cam mechanism. When the yellow cam moves back and forth once with one end in the groove, the revolver fixed to it rotates a third of a full revolution, moving each cup to the next position. This design keeps the parts causing the rotation outside the diameter of the revolver, not interfering with the cups or their movements. Drawbacks of this design were that the assembly became large, limiting the space available for the notching tool drastically, and it clearly would have been difficult to manufacture cost-effectively.

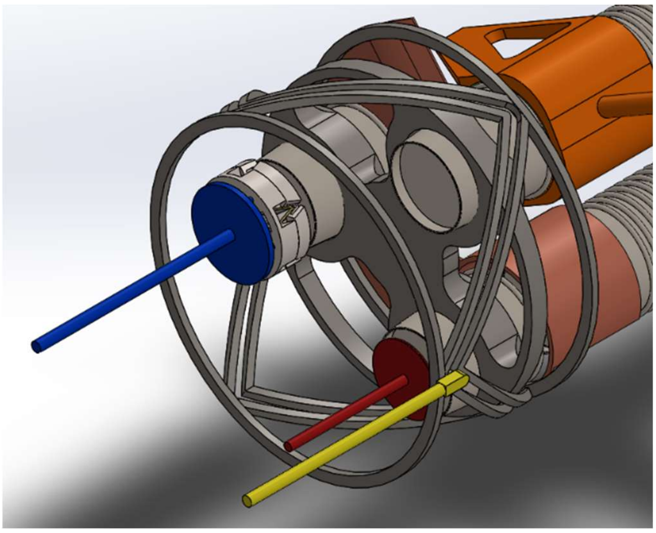

Figure 9. Initial revolver rotation design. Rotation guide on the outside edge

Because the cups are inserted and ejected at different points of the revolution from the chambers, one of the three chambers is always empty when the revolver rotates. This allows positioning a turning mechanism between the ejection and insertion points without it colliding with any cups during operation. The rotation groove could then be parallel with the revolver. This leaves more room for the notching tool and lowers the number of needed parts, for holding the cups and rotating them as the actuator extends, to one, since the groove can be within the bottom surface of the revolver (Figure 10). For this version, a more specialized actuator with a non-rotating piston rod would need to be used to prevent the cam from coming off of the groove, since it could no longer be held in place from the opposite side of the revolver panel.

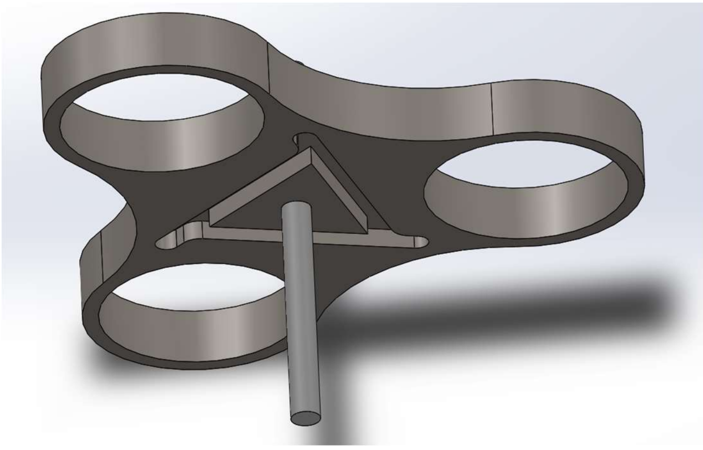

Figure 10. Second revolver iteration. Rotation guide switched to the center

The cam groove needs to be as precise as possible to align the centerlines of the cups with the tools. For a more cost-effective and less time-consuming prototyping ability, the groove was separated from the revolver and the manufacturing method and material of both parts was changed per the company request. The thickness of the revolver was lowered to suit this request, which meant losing the conical shape of the chambers as well. To make sure that the cups still stay aligned the chambers were enlarged to allow the rim of the cup to sit against the top of the revolver. The cup guide panel, originally designed to prevent the cups from coming off from the revolver with the hole piercing tool as it retracts, was redesigned to guide the top of the cup rims throughout the process from the insertion to the ejection to accommodate this change.

The final revolver assembly (Figure 11) consists of the revolver and the actuator. The revolver is comprised of two laser cut 3 mm thick metal panels. One holding the cups and the other guiding the actuator to accurate turn positions. The separate actuator guide is easy to replace or modify for altering the rotation system. Small mounting holes were designed around the cup chamber holes for attaching adapter plates if smaller cup sizes are processed with the same machine. The two are connected to a flange bearing with countersunk machine screws. A set of 28 mm long spacers ensure enough room for the actuator head to fit in between the panels. From the previous groove type guides, the actuator counterpart on the revolver was simplified to a triangular shape with indentations on each corner. As the actuator piston moves out, the roll attached to the end of it, slots into the indentation and the revolver begins to turn. When the actuator reaches its endpoint, the revolver has turned 120 degrees and the next indent is where the roll contacted the previous one in the beginning on the rotation. The hole piercing tool, when activated, locks the revolver in place, allowing the turning actuator to be retracted back to the starting position without disturbing the alignment of the cups. A draw-spring, attached to eyebolts in the actuator body and the cup guide panel, keeps the roll in the indent, and a stopper prevents the actuator from pivoting too far, ensuring that each rotation happens in the same direction. A layer of rubberized material should be added on the stopper, to minimize noise and damage for either the components, as they contact each other repeatedly during operation.

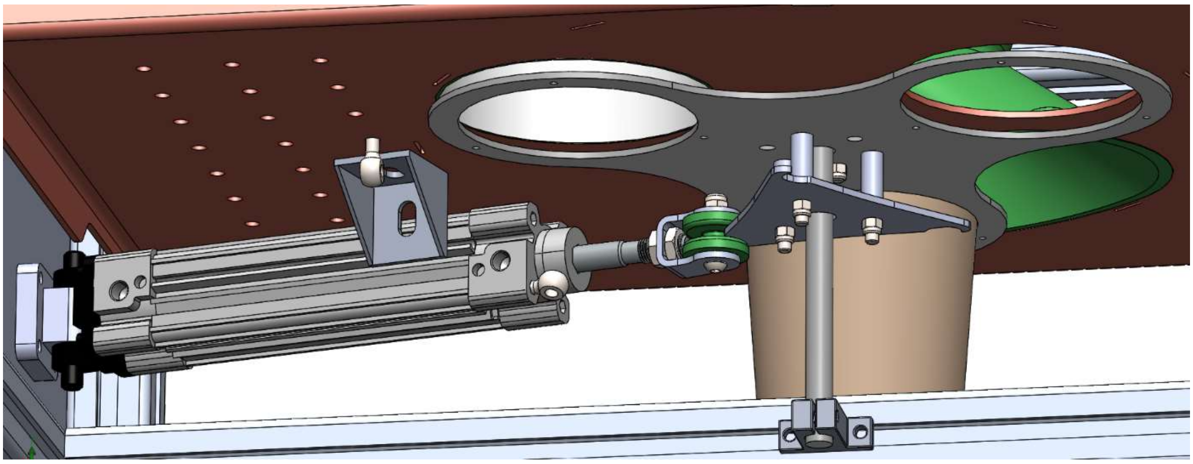

Figure 11. Final modular revolver assembly. Parts can easily be adjusted and replaced for prototyping and maintenance purposes.

3.4 Hole piercing

The holes are pierced through the cup floor without removing any of the material. Initially the idea was to use a cross tipped punch, but later on the design was simplified to a faceted tip for easier manufacturability. The latter design also better guides the hole edges from the puncturing tip to the final round shape. By designing the puncturing tool tip suitably, the hole edges can be forced to stretch slightly around the hole, giving the holes extra resistance against further tearing as the sharp cut edger are reshaped. Individual holes are made with a custom piercing tool since no suitable tool could be found readily available and the specific tool for this purpose (Figure 12) is simple to manufacture. The tool is turned from a round bar to smoothen the outer surface and to create a slight taper on the piercing end to ease the removal of the tool from the cup material after puncturing through it. On the opposite end there are two parallel sides milled or filed flat to provide a secure hold for a wrench during installation and removal. An M4 thread is located at this end for mounting the tool to the plunger plate.

Figure 12. Hole piercing tool head. From top down: mounting thread, wrench faces, hole rounding taper and cutting edges joining in the piercing tip

The tool head spikes are designed to be attached to a round 4 mm steel plate with multiple hole options, allowing the number and positioning of the spikes to be adjusted as needed. The extra holes also allow air to flow from the cup through the tool when it is inserted into a cup with a high velocity. This prevents air from pressurizing between the cup and the tool. The rapid rise in pressure could possibly rupture the cup, as the plate diameter is nearly equal to the diameter of the cup floor. The holes are on two diameters for making holes on different parts of the floor depending on the end use requirements. Ten holes are on both diameters and an additional four holes are designed on the outer diameter when six or three equally spaced holes are needed. When using a pattern of six holes two of the tool mounting holes are shared with the pattern of ten, on opposite sides of the base plate. With this hole patterning, equally spaced patterns of 2, 3, 5, 6 or 10 holes can be created with the same base plate, fastening the tool spikes on varying mounting holes (Figure 13). The base plate, with the piercing tools mounted is attached straight to the end of a pneumatic actuator piston, with a nut on both sides. Edges of the plate should be rounded to prevent damaging the cups if the two come in contact with each other during operation. This is the assembly with the least parts of the hole piercing assembly that testing can be started with.

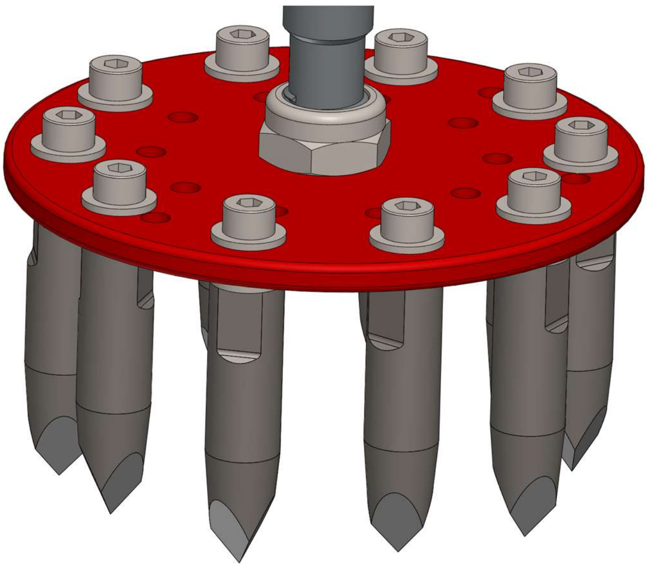

Figure 13. A ten-hole piercing assembly

During the design, the issue of the puncturing tools, especially with dulled edges, possibly tearing larger sections of the bottom was addressed. This could happen during the piercing if the holes would tear further than intended, causing them to merge with one another. This would result in holes larger than allowed, or in the worst case the whole middle section could be torn off by the tool heads. As the holes were required to be positioned near the edge of the bottom and the number of holes was predefined, the positioning did not give much leeway to arrange the holes further apart. Therefore, methods for lessening the pressure against the bottom were needed. Since pressure is force per surface area, and the force per tool head is defined by the tool shape in conjunction with the cup material for reliable cutting, only possibility was to minimize the contact surface area. To lower the contact area between the already sharp pointed tools and the cup, the only possibility was to lower the number of puncturing spikes reaching the cup surface simultaneously. This was achieved without any alterations needed for the tool parts and can be adjusted when necessary. Placing washers or spacers between the spike and the plunger plate moves the tip further from the plate, as the spikes are mounted to the plate with screws through the plate, from the topside (Figure 14). This way only one length of piercing tools needs to be made, but the tips of the tools can still contact the surface at slightly different points of the piercing actuator movement. This method creates slightly different sized holes due to the tapered tip, but the difference is negligible and has no effect on the cup's performance during use.

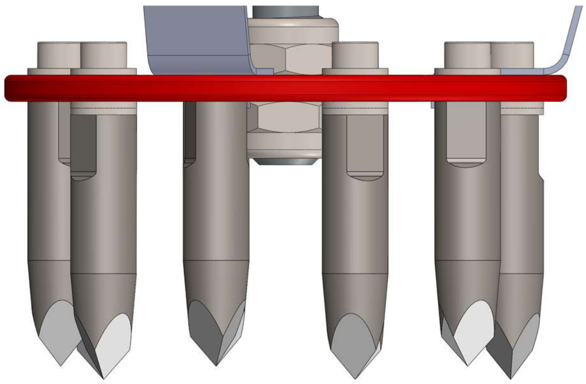

Figure 14. Piercing tool with spacers

On the top side of the mounting plate, guide leaves can be added (Figure 15). They are laser cut and bent from sheet metal with high spring back factor. They need to be firm enough to rotate the revolver centering the cup within with the tool, but not too firm to overpower the piercing force or cause bending in the hole plunger plate. The force can be tuned by altering the number of guides used. The alignment guides are mounted on the plate with the same screws as the puncturing tools heads, and they hold the correct orientation with a narrow section bent to fit inside the inner diameter holes. Precise final centering of the cup in the revolver with the tools is also done with the notching assembly presented in the next chapter, but it is only able to center the tool in relation to the cup. That is no issue if there was a cup in the chamber. This may not be true at startup, ramp down or if the feeder malfunctions missing a cup, leaving a chamber empty while the process is ongoing and the revolver rotating. Therefore, the centering guides on the hole piercing assembly can be left out from the initial testing of the machine if precautions are taken, and it is made sure that no empty chambers reach this step of the process, or the orientation is checked manually before actuating the tools.

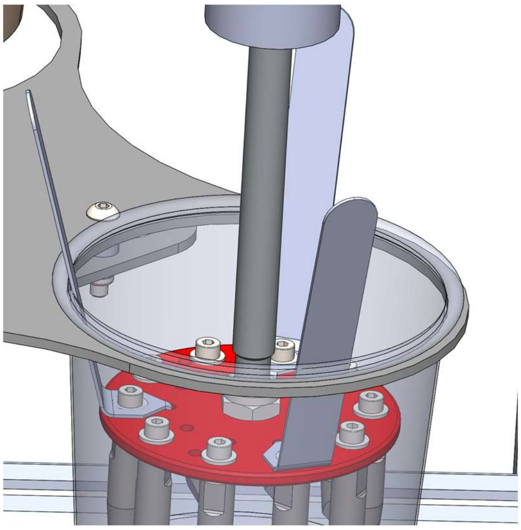

Figure 15. Revolver to tool -centering leaves attached onto the hole piercing plunger plate

3.5 Notching

To coincide with the ten-hole pattern selected for the initial prototype, the number of notches was selected to be five to interlace with the holes. For maximum reliability during use, the skirt material from the notches was decided to be cut off completely. One linear movement pushes the notching assembly (Figure 16) up against the bottom of the cup floor, and then pushes the notching heads diagonally up and out through the skirt. When the direction of the actuator is reversed the spring-loaded heads first pull themselves inside the notching frame and then the whole assembly is pulled away from the cup as the movement continues.

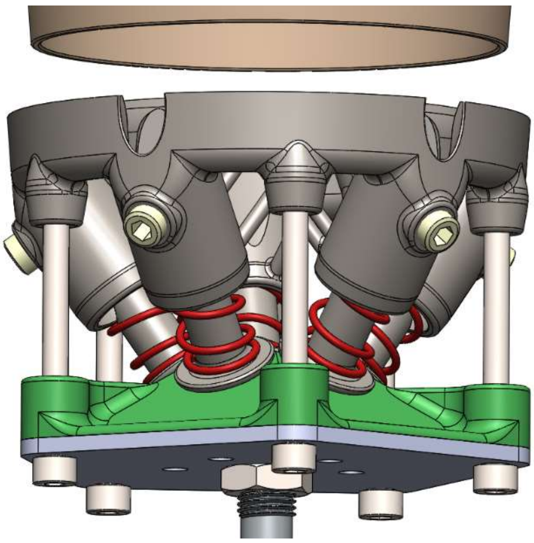

Figure 16. Notching assembly

The notching assembly can be divided in three subassemblies: the notching frame (figure 17), the toolheads (Figure 21), and the plunger (Figure 22). These assemblies move individually from each other but pose the limits for one another's movements. The frame holds the tool heads correctly aligned and the nylon M8 set screws maintain their orientation. Chamfered edges on the top side guide the cup skirt into the groove of the frame as the assembly arises, so that the cup is correctly positioned for notching. Screws keeping the plunger and the frame collinear and pulling the frame off of the cup bottom afterwards, thread on the frame as well. Top surface of the frame is pressed against the floor bottom when the holes are pierced from the top to provide support for the material, lowering the probability of the bottom tearing excessively.

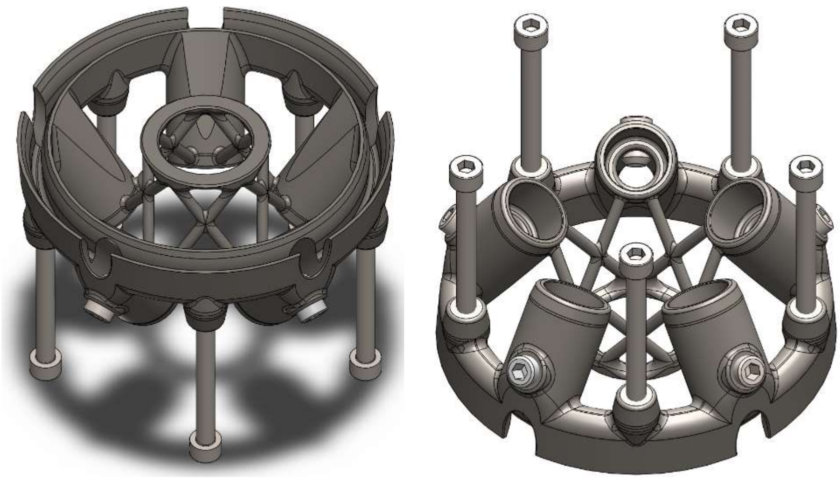

Figure 17. Notching frame assembly. Longer screws for attaching to the plunger assembly, set screws for aligning the tool heads

The notching frame is by far the most complex single component designed for the machine. During the initial idea evaluations presented in chapter 2.4 the base concept of the notch making system was found, and then developed further (Figure 18). Originally the tool heads were much more complex and the frame simpler, but as features needed to be added to the frame the complexity increased. More importantly the notching tool heads were simplified significantly during the same process. They are much more important considering runtime and maintenance costs, as they are the components needing to be sharpened, and replaced periodically. The frame should not need replacing nearly as often. If the tool channels wear unevenly, they can be rebored to a slightly larger diameter, as long as the tool heads are then updated accordingly.

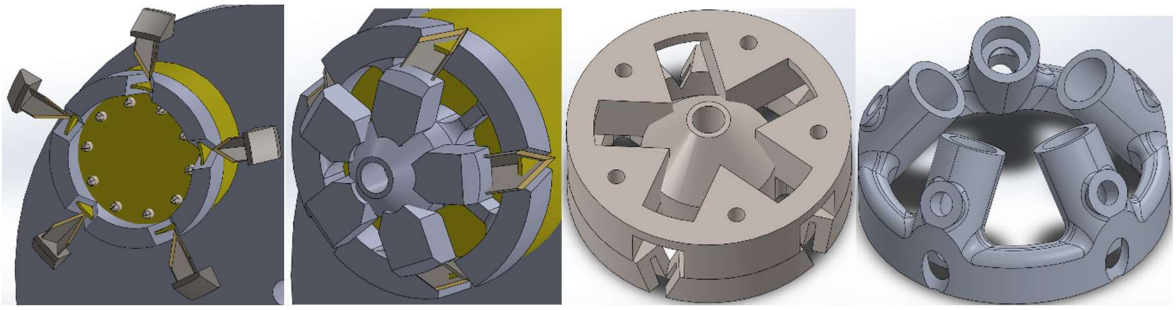

Figure 18. Notching tool frame early development

After all the frame functions were clear and designed, the emphasis shifted to manufacturing aspects. At First the design was developed with machining in mind, but soon it became clear, that even though it would be possible with the machinery available, it would be cumbersome and the resulting component heavier than necessary. Possibility for utilizing LUT additive manufacturing facilities for manufacturing the frame prototype came up during the refinement of the frame construction. The design at that point suited additive manufacturing relatively well already. Mainly a centering lip on the top of the outside edge needed to be lowered back to the cup floor supporting level, because otherwise it would have needed to be printed on nothing, and lots of support material would have been required during manufacturing, just to be removed later. After that, and optimizing the material thicknesses, adding some supports to tie parts more rigidly to one another, and finalizing the functional dimensions, the frame was ready for manufacturing. It requires no support material during manufacturing when manufactured top side against the build surface. Slight surface imperfections may occur at the overhanging sections, but they should cause no functional issues. After the initial manufacturing, the tool head channels need to be honed to final dimensions, and the threads created for the set screws and plunger connecting screws.

A machinable version (Figure 19) was designed for comparison, and as a backup alternative. The final version would have a mass of around 340 g if made of aluminum, and about 980 g if of steel. By no means is the design still easy to manufacture. From a DFMA viewpoint, there are many negatives compared to the additive manufacturing method: Multiple tools are needed, since the exterior shape can be turned but the inner parts need milling. The workpiece needs to be connected multiple times in different orientations for suitable machining directions. Overall, this version is significantly more complicated to manufacture, and in the end, it still would perform worse than the lighter alternative.

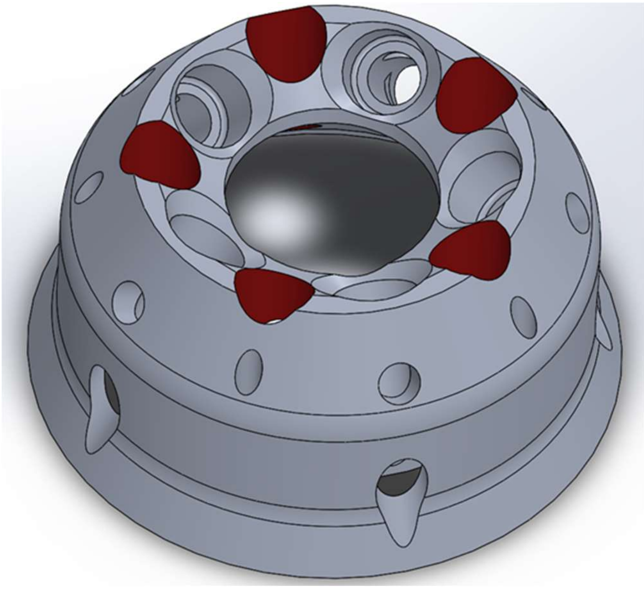

Figure 19. Notching frame optimized for conventional machining. Non-functional holes (highlighted in red) added for weight reduction.

An additive manufacturing version (Figure 20) would have a mass of around 160 g if made of aluminum and about 470 g if of steel. As a result, we can see that over a half of the mass can be saved by using additive manufacturing methods. The lighter version may not be exactly as strong, but it definitely decreases the stresses inflicted on all connected components, while moving back and forth on high speeds. Consequently, a larger portion of the force produced by the connected pneumatic cylinder can be used for the notching, since less force is needed to move up the notching assembly itself. Smaller reciprocating mass also causes less vibrations throughout the machine, minimizing vibration-based issues, such as screws or possible electrical connections shaking themselves loose.

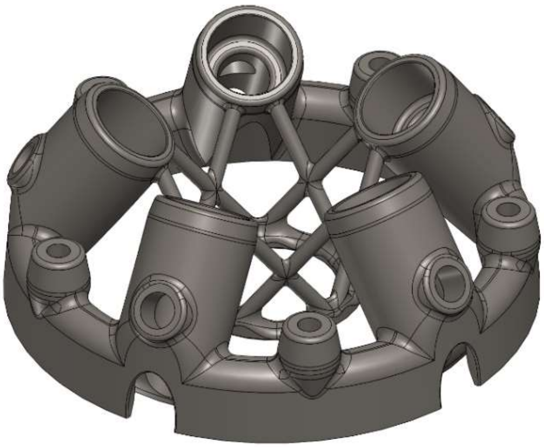

Figure 20. Notching frame optimized for additive manufacturing. No support material should be needed during manufacturing.

If additive manufacturing would not have been a possibility, a more complex assembly consisting of larger number of simpler components would probably have been the way to go, rather than trying to manufacture the frame with conventional machining equipment, at least in one piece. Alternatively, the whole assembly may have been needed to be redesigned for better compatibility with DFMA principles.

The notching tool heads (Figure 21) can be turned, much like the piercing tool heads. For the flange to be wide enough to keep the spring in place, 20 mm round bar needs to be used. The main shaft is designed to be 10 mm in diameter, but a suitable tolerance to the notching frame should be used. The tool heads are easier to reshape or redo, so they should be made to fit the frame, not the other way around. The flat section needs to be at least as wide as the tip of the M8 nylon set screw used to hold them in orientation. In the design the width is 8 mm, but not as wide area might not be needed if using narrower tip screws.

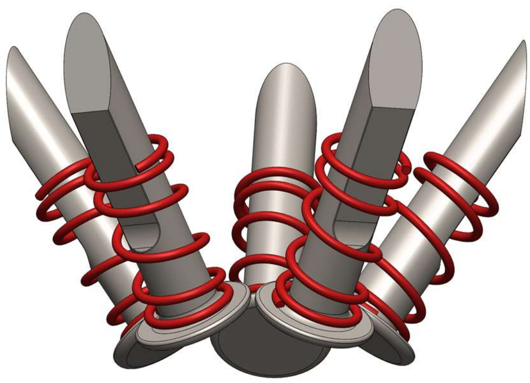

Figure 21. Notching toolhead assemblies

It is advised to manufacture the tool heads from a slightly softer material than the frame. This would result in wearing of the heads instead of the frame. The heads have a much cheaper replacement cost, and the tips wear down during production anyway. To minimize wear and possible heating of the adjacent components sliding against one another, some form of lubrication is needed. Environmentally hazardous lubricants should be avoided even in small amounts, since they may negatively affect the end use of the modified cups and accumulate where large quantities of the cups are used. A vegetable oil-based grease should stay in place better than a lower viscosity oil and therefore be a better option for this application. The porous structure resulting from the manufacturing method of the frame, may improve its lubricant retention capabilities. If the lubricant permeates into the pores, it may keep the part better lubricated as it wears compared to a completely solid material. However, the tribological characteristics of additively manufactured metal materials are yet to be comprehensively researched. The surface quality, for one, plays a significant role in tribology, and may wary significantly between manufacturing machinery and materials used.

The plunger, responsible for pushing the tool heads through the cup skirt and pulling the notching assembly away from the cup after cutting, consist of two parts attached to the end of an actuator with 125 mm stroke length. The base is a 3 mm thick laser cut steel plate. It provides a strong mounting and backing surface for an additively manufactured angled component. The plastic part aligns the tool heads correctly with the frame, for transferring the force from the pneumatic actuator to the cutting tips without bending the tool heads. It connects the plunger to the notching frame assembly screws mentioned earlier. As partially threaded screws are used instead of proper linear shafts, some play in the holes is needed. The positioning is not exact but both notching subassemblies should be as collinear as reasonably possible during operation. For initial testing, even entirely plastic plunger head may be used for testing clearances and alignment. Since the final notching frame allows free rotation of the holes and notches compared to each other without collisions, the top mounting nut does not necessarily need to be inset into the plastic, to prevent it from rotating. It may actually increase the risk of it becoming loose during production, which should be avoided.

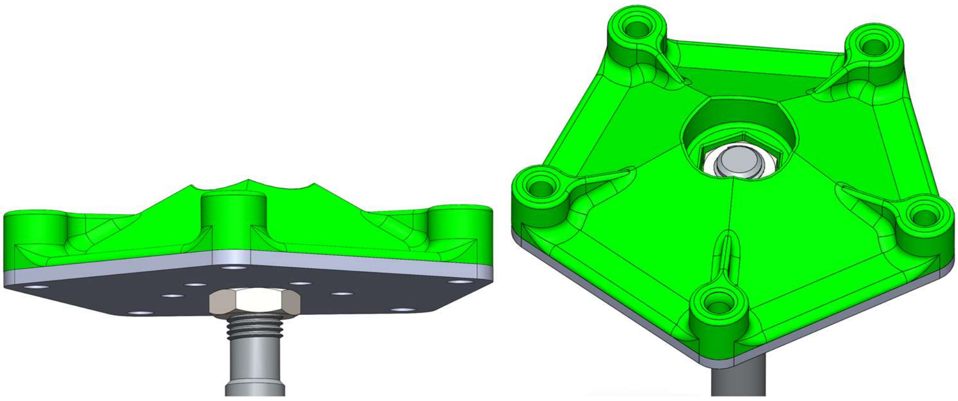

Figure 22. Plunger assembly comprising of a steel plate and plastic top part

3.6 Cup ejection

Initially a pneumatic cylinder was planned to be used for ejecting the cups horizontally from the vertical revolver. It could have in conjunction with a stopper or opposing spring, made sure that the cups are tightly restacked after modifications. Later as the machine layout was finalized to a vertical orientation, the limitations, and drawbacks of using a cylinder with one moving part compared to an air nozzle with none, became more prominent. Pushing the cups straight up from the revolver would not be enough and they would need to be moved aside as well, to not fall right back in the revolver as the actuator recompresses. With airflow the cups can easily be moved longer distances, through multiple corners in a suitably dimensioned pipe. This approach requires zero moving parts, as the nozzle can be positioned right below the level of the cup bottoms in the revolver assembly. Due to these aspects, pressurized airflow was chosen as the method for removing the cups from the revolver.

A simple open ended compressed air pipe might work for such lightweight workpieces, but a special nozzle, should be used for two reasons. First, to better direct the airflow, maximizing the moving force affecting the cup with the available volumetric flow and pressure. And secondly, to minimize the noise created. Noise is an important safety consideration when dealing with compressed air. Safety aspects of this machine are discussed in more detail in chapter 3.10. An example of a suitable nozzle for this application would be an *Air Mag* air nozzle by Nex Flow (Figure 23). (Nex Flow. N.d.)

Figure 23. Nex Flow Air Mag nozzle (Nex Flow. N.d.).

3.7 Pneumatic actuators

All the pneumatic actuators chosen for this design are ISO 15552 cylinders with a 32mm piston diameter, which is the smallest bore size these actuators are readily available in. The theoretical cylinder force on the advance stroke for these cylinders is 402 N and for return stroke 346 N, at 0.5 MPa of air pressure, as can be seen in the appendix I. This should be well enough for even the notching tool, which is the most demanding. If it is not enough as the blades wear, and therefore a greater force is needed the maximum operating pressure for these cylinders is 1.0 MPa, which more or less doubles the force.

For some of the actions, even smaller, round body, ISO 6432 pneumatic cylinders would suffice. The larger profile body, or optionally equally configured tie-rod type cylinders were chosen over the smaller alternatives for a few reasons. The stiffer structure is preferred, as all the cylinders are only mounted from the end furthest from the piston rod, and the precise linear movement of especially the hole and notch making tools is important for them to impact the cup well centered. Selection of accessories such as mounts, sensors, and rod options, is much broader for the larger ISO 15552 type cylinders. Such accessories are not necessarily needed for the current design, but the availability gives more flexibility and possibilities for refining the machine further during testing and production. Cost of the smaller ones would be lower, but the difference is rather insignificant in the in the scope of the whole machine, even though it is close to 50% per actuator. The prices are around 80 € for a 20 mm round body and around 120 € for a 32 mm profile body cylinder (Isojoen Konehalli Oy. 2021). Only two lengths of cylinders are needed: 50 mm for the notching tool and separation wedge, and 125 mm for the hole piercing and revolver rotation. The 125 mm stroke length cylinders are not even stocked by some vendors in the smaller type but are in the larger. On top of these aspects, the larger cylinders can be expected to last much longer in production, as they are not driven as close to their limits as the smaller cylinders would need to be.

3.8 Frame & enclosure

The frame (Figure 24) is constructed of aluminum extrusion T-slot profile, commonly used in prototyping and small industrial machinery. A 40 mm square profile was selected despite that even a smaller size would probably have provided sufficient rigidity. The oversized profile gives more mass to the frame to withstand the rapid movements of the modification tools without excessive vibrations or possible fatigue damage in the long run. This type of profile has the characteristic benefit of enabling nearly anything to be mounted anywhere on all sides of the profiles with corresponding T-slot nuts or bolts. Using the 40 x 40 mm size also has the added benefit that the center hole is 6.8 mm in diameter, perfect for threading to M8 sized thread. This makes it possible to attach adjustable leveling feet to the bottom ends of the vertical sections, for leveling the machine on an uneven surface for improved stability.

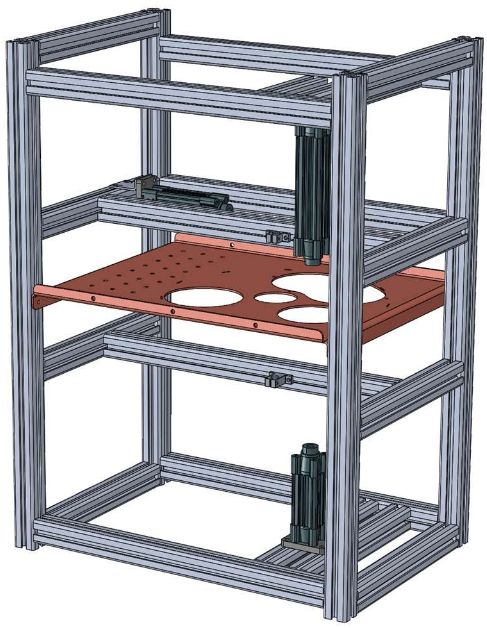

Figure 24. Machine frame structure consisting mainly of aluminum T-slot profile

The tool actuators and other components requiring precise positioning are attached on the vertical frame members running through the whole height of the machine. Therefore, their vertical placements can be freely adjusted to any height in the machine. The modification tools are also mounted on their own frame members on both horizontal axes so the horizontal positioning can be adjusted anywhere within the length of these profiles too. The separation wedge actuator has the horizontal adjustment on one axis with the aluminum sections and on the other in the mounts. The fine end position adjustment for all actuators can be done by adjusting the tool mounting nuts on the end of the piston rod, but the range is limited, so the other means are needed as well for sufficient adjustment range.

An enclosure is needed to ensure safety, contain debris, and to minimize the noise. The machine can be confined with no issues as no operator input is needed within the frame structure during operation. Mounting items on the aluminum extrusions is easy by design. Hence the enclosing panels can be selected from a multitude of sheet materials. Even a metal mesh with a small enough hole size to prevent fingers reaching the moving parts could be enough for the most imminent dangers. For dust and noise containment purposes more solid sheets are preferred. Dust can be contained with any solid sheet, but noise and possible shrapnel from tools colliding with each other, has higher requirements. Thin sheet metal would be an obvious solution, as many of the components designed, are be made out of sheet metal anyway. A considerable drawback with thin metal is its tendency to rattle with vibrations. Extra noise is unwanted when personnel are working in the space for extended periods of time.

The production process needs to be monitored from outside the enclosure, preferably from multiple angles, so transparent section or sections are needed. They can easily be cut from a sheet of acrylic or polycarbonate. Such panels are designed to be placed on one or both of the largest sides to allow for complete overview of all the process steps (Figure 25). For the remaining panels plywood is suggested. As renewable material it has clear sustainability benefits, but it also is acoustically better option for this use than reasonable thicknesses of sheet metal or plastic. The production process poses no hinderances to using wood materials either, even if wood is not that often used in industrial machinery, as the process is dry and at normal room temperatures. The middle section, or the whole panel, on which the revolver rotation actuator mounts is to be made out of metal. This is also the section through which the pneumatic lines and other needed utilities are recommended to be passed through the enclosure. It is in the middle of the machine and has good access to both sides of the partitioning cup guide panel.

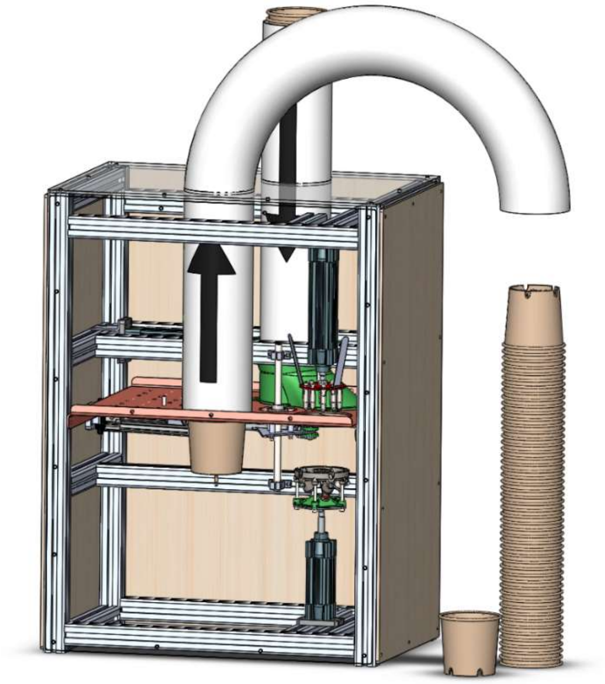

Figure 25. Enclosure concept with plywood and clear plastic panels.

Regardless of the material, the panels are attached on the frame using T-slot fasteners. If using stiff enough material, at least one of the larger side panels can be fastened only to the vertical frame members, allowing the panel to be easily slid up and off the frame by only loosening the fasteners, for easy access to the insides for maintenance. The inside of the enclosure is only to be accessed while the machine is inactive and disconnected from compressed air, and possible electrical network.

During commercial production, a lot of waste is created from the cut off notch sections. If not able to exit the enclosure the debris would pile up within and start disrupting the process fairly quickly. There is a couple of options to tackle this problem. Either removing them actively with a vacuum, or allowing them to passively fall down and collect within or below the enclosure, where they could then be removed manually. A simple option would be to make the enclosure bottom panel out of metal mesh with roughly 30-50 mm hole size. This would allow free passage of the cardboard scraps but prevent human access to the machine internals. By extending the vertical frame members from the bottom, enough room would be created to place a box under the mesh panel. Offcuts would rain into the box, and it could be emptied when necessary. With some channeling, the debris from multiple machines could even be collected in the same container. This approach would nullify the efforts made elsewhere on the enclosure, trying to minimize noise from the machine as the bottom would be mostly open.

An active extraction approach could be added without leaving large openings in the enclosure. A vacuum cleaner hose could be added tightly sealed through the side or bottom panel of the enclosure near the notching tool. This would not only extract the removed cardboard sections, but the more hazardous dust resulting from the cutting and puncturing of the cups as well. The hazards of dust are discussed in more detail in the safety chapter 3.10. To achieve a powerful enough airflow to effectively remove the excess material, nearly equal amount of air needs to be supplied into the enclosure as is removed. This is easily achievable by making openings in suitable places in the enclosing panels. Filters are recommended to be installed to any openings on the machine to minimize dust and noise escaping. Some internal partitioning may also be needed for the extraction suction not to interfere with the cup ejection airflow.

3.9 Process control

Action sequence during operation is according to the diagram in figure 26. During production, the process is a continuous four step loop. Actions listed in the same circle can and should happen simultaneously for optimal production efficiency. First the notch and hole making cylinders extend to lock the revolver in place. If a cup is in this chamber, it gets modified, but even on startup at least the hole piercing cylinder needs to extend to align the other two chambers with the inlet and outlet pipes. In the second step the revolver rotation cylinder is retracted back in to prepare it for the next rotation, separation cylinder is pulled in, freeing one cup to drop into an empty chamber below, and airflow is turned on for the cup ejection nozzle. In the third step all but the revolver cylinder are returned to their original positions: Separation cylinder extends dropping the cup pile above down the height of a skirt of a cup. Notch and hole making tool cylinders retract freeing the revolver to be rotated again. The cup ejection airflow is to be shut off at this point too. Lastly, in the fourth step of the cycle, the revolver cylinder extends, turning the revolver 120° moving the cups in the chambers to the next step in their processing.

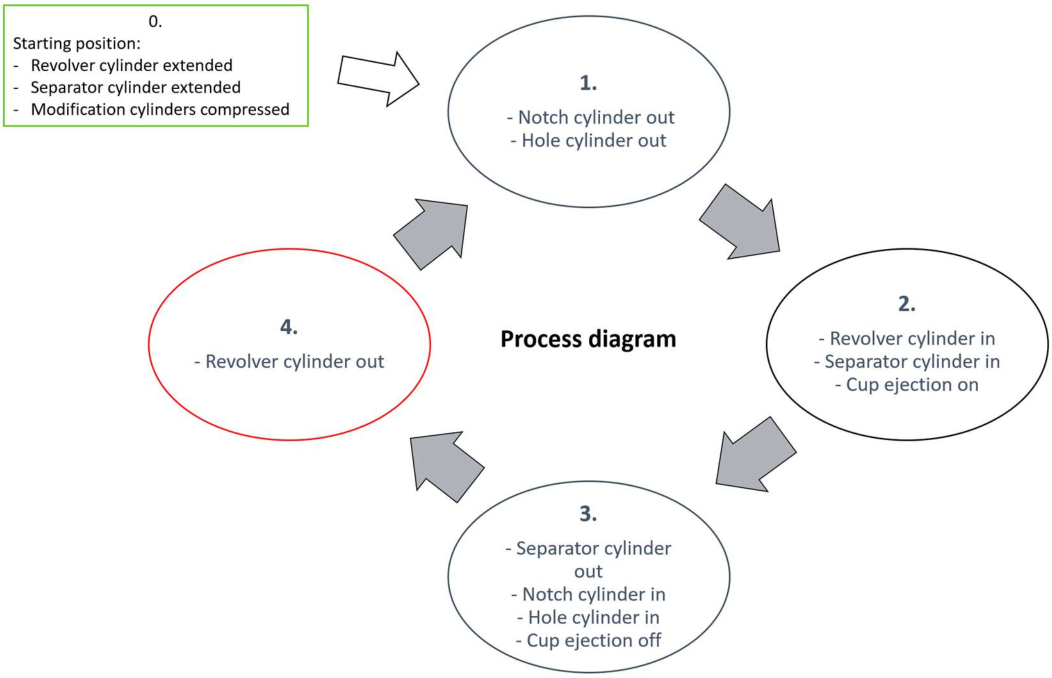

Figure 26. Machine production process diagram

The operation of the machine is not dependent of the cups within. A risk that is present if running the machine empty on high speeds, is the possibility of the hole piercing spikes colliding with the notching tool frame. When a cup is inserted on every cycle, the cups center these tools on the same axis, but if not, and either the mounts or piston rods allow lateral movement of the tools in an unfavorable direction, more than the design allows, slight scraping may occur. Test running the system on low speeds or occasional cup misfeeds, should cause no issues as long as the cylinders are firmly mounted and properly aligned with one another.

When doing initial manually operated test and adjustment runs on the machine, the actions happening concurrently in the same step according to the process diagram (Figure 26) can be activated consecutively in any order. Only when cups are in the machine, the notching tool should be already against the cup floor when it is pierced from the opposite direction. During normal operation both these cylinders can be activated simultaneously on equal speed, as the hole making actuator is longer. The most reliable solution is that the alignment flaps of the piercer assembly roughly center the revolver chamber with the tools, before the notching frame contacts the cup, since the notching frame has significantly less allowance for aligning itself with the cup than the piercing assembly.

Due to the achieved simplicity of the final process, the cylinders and the ejection nozzle can be controlled with either pneumatic or electrical valves. Main benefits with a purely pneumatic system is that it minimizes fire hazards, and keeps all the variables easy to adjust manually, in the limits set by the chosen components. This on the other hand is also the most limiting aspect of such system. If using electrical valves and other control components, a much more accurate adjustment and process monitoring is possible. Pneumatic control system can work well for testing the subassemblies and the whole system, but for large scale production electronic control with digital processing is advised.

With electronic, processor-controlled system, much more functionalities can be cost-effectively incorporated. As previously stated, the timing of the contact point of the tools is important, and where this issue can be overcome in a pneumatic system by the adjusting the movement speeds, in electronically controlled system the timing of all actions can be controlled on a millisecond level. This is highly beneficial in optimizing the timing of the system. For example, the actuator movements can be sequenced precisely in the desired order, and the ejection nozzle on-time can be optimized to transport the cup exactly the desired distance, but not staying on any longer wasting air and thus energy.

Adding sensors to the system can provide functionalities not possible with purely pneumatic switch systems, most importantly conditionals. If a sensor is added in each the revolver chambers, the system is able to monitor the presence of cups and then act accordingly. If no cup is inserted into the chamber on any cycle the system could reactivate the cup separation wedge again before continuing with the process. In case of an issue like this, the system could then try activating the actions in question again a set number of times and if the issue persists, and no cup is inserted properly the machine could continue operation for one cycle, if the revolver positioning had been slightly off on the previous cycle for example. If the issue has not been solved, the machine could then shut down the process in a controlled manner and signal the operator. Similarly, the ejection could be monitored, preventing the already occupied chamber from turning to the cup feeding point and causing major issues, in case of an ejection malfunction. The machine could also stop the action when the machine runs out of cups to process, and automatically continue again when cups are restocked in the infeed pipe. This prolongs the lifespan of the components and minimizes needless energy consumption as no empty cycles are run.

Process monitoring and data collection is another important entity completely ignored if not using an electronic control system. The most basic form of such are various counters, registering values such as number of cups processed, and cups missed on feeder/ejector actuations. Clearly some sensors can be added to pneumatically controlled system, but the benefits are more limited. Where real benefits start to emerge is when the gathered statistics are cross-referenced with one another and with external data such as cup production batches, operation speeds, elapsed time since last maintenance and so on. The machine could even adjust its operation parameters according to the sets of data collected and input by the user.

Even quality monitoring could be done automatically, especially when production numbers increase, and comprehensive manual inspection becomes cumbersome. A machine vision camera system is perfect for monitoring this type of process where the outcome is the presence of a clear visual pattern, and an issue is variation of the specified pattern or the complete lack thereof. Understandably this data could also be automatically collected, analyzed and actions taken like in the earlier example. An important production factor that could be easily determined from this are service intervals. By collecting accurate data on when and what kind of quality issues arise, the corresponding components could be replaced beforehand in the future.

Another possibility with an electronic control system is the possibility to predefine process values for various configurations. As varying hole and notch patterns and material thicknesses may be used, the ideal process values such as piercing speeds, forces and time delays need to be adjusted accordingly. The preset of variables could either be set and all changes made with a push of a button or by inputting the exact values for each batch. Possibly with suitable programming the machine might even be able to to find the optimal values for any configuration on its own. The possibilities are endless.

3.10 Safety

Operational safety is of utmost importance, when designing any type of industrial machinery. The safety assessment and development is done based on the European Union machinery directive. The machine is required to coincide with the directive, even though it is only planned for internal use, not for sale. A CE-marking is also needed to display that the machine is affirmed to comply with the relevant European Union legislation, part of which is the machinery directive. Fortunately for this machine, a suitable, safe construction is rather simple to achieve. Even though the movement speeds should be optimized for maximal production output, the forces needed are rather small, the pieces handled lightweight, and no operator access is needed during the process near the moving parts. To make sure that the pneumatically actuated parts are only accessed while inactive, the main air feed line could even be routed in a way that it always needs to be disconnected to open the access panel of the enclosure, for example. (Directive (EU) 2006/42/EC).

Considering final design, only input and output openings are needed. For the larger cups to fit, the openings need to be so large that a human hand and arm can fit through as well. To prevent the operator from accessing moving and/or sharp components during production, input, and output pipes longer than an arm's length must be used. Longer pipes increase the production flexibility as well. On the input side, a tube supports a larger number of cups for longer continuous production without an operator feeding more constantly. On the output side the longer pipe gives more flexibility for the repackaging location, as the cups can be transported even long distances with the compressed airflow method proposed allowing the repacking area to be located further from the hazardous production area. Ergonomic aspects need to be addressed if the cups are fed into the machine and repacked afterwards by hand.

Fire hazards are another safety concern, when handling flammable materials, such as cardboard. Especially, when flammable materials are present in large quantities of microscopic particles, such as dust mixed with air. When notching the cups, three layers of carboard are cut on each of the five notches. Multiplying that with the expected production numbers of thousands per day, the amount of offcut waste and finer dust is substantial. Two aspects of the design limit the severity of a fire risk significantly, the enclosed structure, and fully pneumatic actuators. The only openings on the enclosure are the cup inlet and outlet pipes. Much less dust is probably exiting from the infeed pipe in the first place compared to the outlet pipe. A brush-like strip could be installed on the inside surface of the pipe on the enclosure end to better seal the extra space in the pipe. This would limit amount of dust exiting while still allowing the cups to move freely through.

Minimizing the dust and debris coming from the outlet pipe is a greater challenge. Obviously, the outlet is after the dust and debris creation step in the production process, and pressurized airflow is directed out of the pipe sporadically, propelling the unwanted particles down the pipe with the finished cups. This pipe cannot be sealed like the inlet pipe since cups must travel freely through with only the airflow propelling them. All the other matter carried through the pipe is much smaller in size compared to the cups, the scale difference is roughly tenfold (<1 cm offcuts versus >10 cm cups). Possibly the waste could be directed off the pipe by making openings larger than the waste, but smaller than the cups in one of the elbow sections, making the smaller items continue forward and the cups only having the possibility to turn to another direction. Alternatively, the last sections of the ejection pipe could be substituted with guides made of metal wire. The wires can direct the cups, but let the air and debris disperse elsewhere. Depending on how well the enclosure contains the debris and dust on its own a dust extractor may be needed, either in the outlet pipe, or even better, right at the source. This way it can be removed completely from the process as soon as it is created, to be reused or recycled properly. Especially important when the production is scaled up.

Not only does the dust pose a fire hazard, it’s also a direct health risk when inhaled. Carboard dust is comparable to wood fiber dusts and can cause the same health hazards, even after a short exposure. Possible hazards range from mild irritation of eyes and skin to asthmas, allergies, and even various cancers. The negative effects can be minimized by shortening the exposure time, enclosures, dust extractors, good ventilation, regular cleaning, and as a last resort, with respirators. (Finnish Institute of Occupational Health. 2020.)

A negative outcome from choosing pneumatic actuators over electrical or hydraulic actuators, is the higher amount of noise. Not only does the pneumatic actuators operate at high speeds, but the valves venting the pressure out cause possibly hazardously loud sudden noises. Mufflers/silencers should be installed in all outlets of valves, cylinders, fittings et cetera, that vent straight to the atmosphere to minimize noise. As the silencers disperse the exhaust stream, they minimize the amount and velocity of dust and debris in the air, maximizing user safety and comfort.

3.11 Commissioning

For initial testing the individual functions, the subassemblies can be assembled into the machine frame as well as to a separate test bench. Each function can be tested independently, and there is plenty of adjustment for each mounting point, as the actuator stroke lengths are fixed. All actuator attachments should initially be mounted in the middle of the piston rod threads and then the cylinders mounted according to their extend positions. Only for the separation wedge actuator, both end positions matter, since it affects the cups moving both directions unlike the other actuators that only "work" when extending. This way fine adjustments can be made from the nuts on the piston rod with thread left in both directions. Rotator actuator extended position must be adjusted accurately to stop the revolver in line with the openings in the plate each time. Position in the collapsed state is not a defining factor as the revolver orientation is held in place by other means then. Notching assembly must be set to slightly contact (<1 mm of compression of the cup) the cup bottom. Hole piercing actuator must be set to pierce past the cup floor far enough to leave round holes with the scraps pushed away from the opening without the tool heads coming to contact with the notching assembly. Of the two, notching assembly should be adjusted first, as the hole piercing assembly has more flexibility in terms of the positioning. Only compatible hole patterns and sizes and notching assemblies are to be used.

Assembling the subassemblies into the frame should be started either from bottom up, or from the horizontal guide plate roughly in the middle of the machine. Multiple components must install to or move through this panel and the sheer size would pose challenges if trying to install after other assemblies. The guide funnel, ejection pipe and rotation actuator accessories also mount to this plate, and hence cannot be installed before it. The revolver distance needs to be set to minimum from this panel, while the cup rims can still fit in between, and the revolver can freely rotate. The separation wedge must be installed and adjusted before the top mount of the revolver can be attached to the wedge guide aluminum profile. After the cup guide panel and the revolver are installed, the installation order is more relaxed since the rest do not interfere with installations of the others as much.

Starting with fundamental components and assemblies and adding guides and such as needed is advised. Some features may we unnecessarily overengineered. The parts guiding the hole punch into the revolver centering the cup with the tools, may not be needed at all if the revolving mechanism proves to be adequately accurate. When starting to add more and more of the functions to the same construction it is important that the tools are out of the revolver and no other actuators move while the revolver rotator actuator extends. Otherwise, some components will be damaged.

3.12 Cost estimation

Calculating the cost of the complete machine precisely is impossible since not all details are finalized, and many components remain unknown in the design. The company's wish to procure or manufacture the proprietary components designed for this system themselves leaves those components out these calculations. Finding out the cost of the metal parts made using additive manufacturing methods would have been especially challenging as such services are scarce and the price is very dependent on the component in question, so references are more or less nonexistent. Some estimation can be given for the components that can be purchased straight from catalogues. The presented prices are with full value added taxes included, if not stated otherwise, as mainly stores aimed for consumers have their prices widely visible, and in such catalogues, taxes are included in the prices.

Shorter, under 200 mm long, 32 mm diameter pneumatic cylinders cost about 120 € regardless of the length. The flange mounts are quite expensive at nearly 80 € a piece, so it might be more cost effective add them to the list of laser cut pieces, since the available ones also seem needlessly heavy-duty for this application. The pivot mount for the revolver rotation cylinder will cost roughly 70 €. An *Air Mag* nozzle for the cup ejection costs about 55 € depending on the size and connection thread (Suomen Virtaustekniikka Oy. 2021). The valves controlling the pneumatic actuators and nozzles are a significant expense and range anywhere from 50 € to 150 € a piece. Even the number of valves is not defined at this stage of the design, and neither is the control system, so accurate cost estimates are not yet possible. (Isojoen Konehalli Oy. 2021.)

Two options for sourcing the parts for the frame were compared: a German consumer-oriented retailer Motedis GmbH and a local industrial retailer Item Profiili Oy. The offer from Item Profiili Oy included the aluminum profiles and the fasteners for assembling them together, but no fasteners for the enclosure panels or anything else. The offer without taxes (appendix II) was for a little over 700 €, but they rectified it a bit afterwards to have four more of the standard fastenings and as many fewer of the more expensive, automatic type fasteners. This lowered the final offer to around 650 €. From Motedis GmbH the same profile sections with similar fasteners would cost about 160 €, excluding taxes and shipping as was the case with the other offer (Motedis GmbH. 2021). The list in appendix III includes the aluminum sections cut to length at 10.80 €/m, 40 automatic profile fasteners, 30 internal and 30 external corner brackets, and T-slot nuts and screws for fastening them together, leveling feet and also lots of additional hardware for mounting the enclosure panels, valves, pneumatic lines and so on, that may be necessary during the testing and final assembly of the machine. Even with all these additional items the total cost is just over 300 €, less than half of the Item Profiili Oy's offer. Some of the fasteners are sold in bags of 100, so there are enough of these for a couple of machines in this list already.

From these main components the amount totals to the 2 000-3 000 € range, highly depending on the number and type of the pneumatic valves needed and selected procurement channel of the frame materials. When the other components such as the revolver axle, bearing and mounts, enclosure panels and especially all the parts specifically designed and manufactured for this contraption, and labor costs are taken into account, the assessment becomes even more vague as the number of unknown variables keeps increasing. Most of the components to be manufactured: the laser cut sheet metal pieces and the turned toolheads, are straightforward and on the inexpensive side, but the additively manufactured plastic and metal pieces are total unknowns regarding cost. Realistically the end cost could be somewhere in the 4 000-6 000 € range, if the current design is functional and significant redesigns and/or component changes are not needed.

4 ANALYSIS & DISCUSSION

The initial requirements and limitations posed by the company only focused on the end result, the modified cup. The machine design was based on achieving the functional cup requirements. The design was constantly refined throughout the process, taking into account the company preferences and propositions received during the biweekly meetings. All initial requirements were fulfilled, and most of the additions and notions that arose during the process, could be accounted for in the end result. Some minor issues do still exist in the design, but they were discussed with the company and declared acceptable at this stage of development.

4.1 The modified cup

The final modified cups the machine produces are ideally according to the figure 27 and they fulfill all the company's requirements. They have 10 mm holes through the floor, with no protrusions on the inside. The number of holes can be adjusted between one and ten, without any changes to the coinciding notching assembly. Likewise, five clean-cut notches are made in the skirt. The width of the notches is 10 mm, and the height is under one millimeter less than the full height of the skirt, as requested. If more notches are required, another notching assembly needs to be manufactured accordingly. Downwards the number may be altered to four, three or possibly even two with this design. Using only two notching tool heads in the five-slot assembly might prove to be too imbalanced to function properly, and only with five tool heads will the notches be equally spaced. All cup dimensions should be verified comparing the machine model and an actual produced cup before manufacturing any of the main components, as the dimensional drawing used might have been incomprehensive or inaccurate.

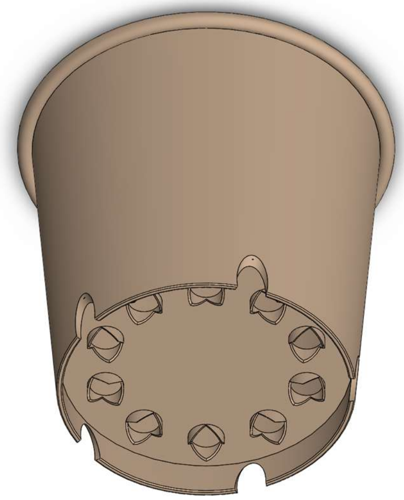

Figure 27. Finished cup from below with five notches in the skirt and ten holes in the floor

Holes and notches made to the cups by the machine will not be as clean-cut as in the figure above. For the holes, the rough edges should cause no issues during re-piling since the diameter of the holes is smaller than the height of the skirt. A more probable issue is the rips merging and causing holes too large and the scraps possibly protruding below the bottom edge, causing issues down the line. Notch edges should be cleaner as long as the tool heads are sharp. Given that some material is cut off, no issues should arise during repackaging as the possible scraps have room to fold back to their original position when the cup is pushed into the next in line. In the end use some issues may be caused if the notches are improperly cut, as the proximity of the top of the notch to the bottom of the floor is vital. However, as long as even some of the notches are the full height, no considerable issues should ensue. If such poor performance is noticed from the machine, actions to overcome the issues should be taken to maintain a satisfactory production quality.

4.2 Finished machine

The finished machine measures 440 mm in width, 650 mm in length, and 860 mm in height. It is similar in size to an office printer (Figure 28). Even multiple such machines can easily be operated in a normal sized room. An industrial sized production facility is not needed before significant upscaling of production. Only utilities needed are standard 230 V electricity and compressed air.

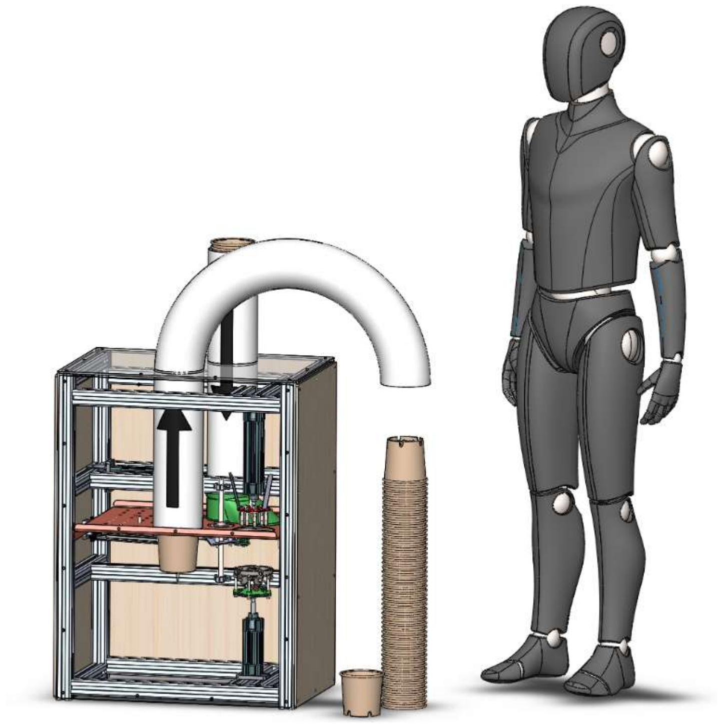

Figure 28. Finished machine prototype model, 180 cm character for scale

The concept machine consists of four of the five subassemblies the design process was initially divided in :

1. cup separation and revolver feeding system,
2. rotating revolver mechanism,
3. cup floor piercing system, and
4. cup skirt notch cutting system.

In addition to these there is the fifth, cup ejection step of the process, but it entails only a nozzle and a yet to be specified valve controlling it, with no moving parts so it is not considered as a separate subassembly at this point. Considering the number of subassemblies, the fact that only about 15 individual components needed to be designed from the ground up is a definite success regarding the initial goals set for the design process. Nearly half of these are simple laser cut components and the rest additively manufactured and turned.

4.3 Future development

After this prototype design is tested and proved functional, production capability is needed for smaller cup sizes as well. The options are to either use adapters and smaller sizes of tool assemblies, and to adjust this machine to fit every size, or to design and manufacture a scaled down version, based on this machine for each size. Production numbers play a vital role on selecting the better option out of the two. If the production numbers are low and one machine is enough to fulfill the production quota for all sizes, then it is probably most cost-effective to use only one machine and set it up for each size as needed. If the production numbers are greater from the get-go, or expected to increase in the near future, it is definitely better to build specific machines for the different sizes. The setup time and effort needed between sizes would be significant and all taken from the value-adding production time. Using the frame and actuators specified in for the largest size, would also make the machine inefficient and unnecessarily expensive if used with the smaller sizes, where smaller actuators and less structural materials would be needed. The low number of cup sizes also supports the multiple machines approach. Specific machine for each of the more popular sizes and then possibly another to be used for a couple of the more infrequently needed sizes. Even if the production numbers only necessitate running a single machine at a time, the increased reliability, flexibility, and possibilities for servicing the machines during production on another machine, support not relying on one machine for the whole operation. If the frames of all the machine sizes were to be created with equal external dimensions, the machines could be attached to each other for better stability, and even enclosed as one unit.

If the output from a single machine needs to be maximized, a few things need to be addressed. If using this construction, the control system should not be purely pneumatical and all the cup movements need to be assisted, not only relying on gravity, like the cup feeding is in the initial design. Both of these would require the measuring/testing of the maximum speed with which the machine functions without issues. This could mean that for example over 99% of the cups from the separator fall into place faster than the rate at which the machine operates, but as even one feeding issue in hundred cups is way too frequent, considering the required production numbers, the system would need to operate on such low speed to accommodate even the slowest cup movements. The issue is similar with the pneumatically controlled actuator movements. If only the speed can be controlled and the actions get the signal to activate from other actuators as they have finished their movement, some time is lost in the process. When using a more sophisticated control system, all the actuators can always move with their maximum speed that still produces reliable results. The precise sequencing can be done based on millisecond scale time delays and sensors constantly monitoring various aspects of the machine, such as the presence of a cup in specific chambers.

Another approach could be to add more chambers to the revolver. It would be a smaller cost increase compared to building several whole machines. The principle is displayed in figure 29, where four chambers for each step of the process are incorporated to a revolver comparably to single ones in the smaller version. Four cups would be inserted, four modified and four ejected simultaneously. Because all the actuator movements are purely linear, only the same number of actuators would be needed for such construction, as are needed for only three chambers. The sufficiency of the actuator forces would need to be reevaluated, and the actuator diameters updated accordingly, when needed.

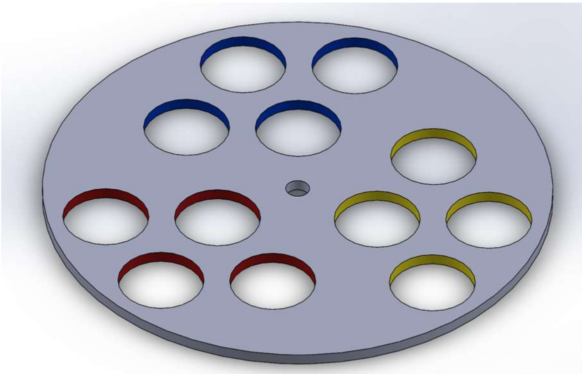

Figure 29. Twelve-chambered revolver concept. Each color represents one action similarly as one chamber is one action in the smaller version

Combining multiple machines to a single unit or at least placing them side by side, has clear benefits regarding the cup handling before entering and after exiting the machine. The cup stacks can be unpacked from the boxes they arrive in and unwrapped from the plastic and fed into the machines in one place, whether these steps are done manually or with automatic machinery. The finished cups from multiple machines could be directed into a single ejection pipe, carrying them to be repackaged without needing to route a pipe separately from each machine. When several cup sizes are processed at once, it may be simpler to have discrete pipes for each size rather than reseparating them in the other end.

If Bionido Oy wants to incorporate simple company identifiers into the cups during production, it could possibly be done with no additional printers or other equipment. The positioning and action of the hole and notch making tools allows various embossing and perforation possibilities. One option is to add the logo protruding from the middle of the notching frame. When the frame is pressed against the cup floor the protrusion would crease the floor accordingly, leaving a lasting imprint in the otherwise unaffected middle section of the cup floor. A clear imprint might require an opposing die attached on the hole piercing assembly. The dies would need to line up with each other, which may be challenging to achieve as the tool assemblies on both sides of the cup are allowed to rotate freely in the current design. Another possibility is to attach a set of pins in the shape of the desired print on to the middle of the hole piercing assembly. Concurrently with the main hole piercing, miniscule holes would be created in the middle of the cup floor in the shape of the company logo for example. The outcome might not be clearly visible in the cups right after processing, but during use, as the cups come in contact with various substances discoloring all the cut edges more than the intact surfaces, the print would become clearer.

4.4 Design issues

Despite the fact that multiple development iterations were performed during the process, some minor issues still persist with the design. All of the options incorporated design cannot be utilized with the current construction. Out of the two hole-patterns on the plunger, only the outer can be used without the hole piercing heads colliding with the notching assembly. Neither can the hole making, and revolver assembly centering leaves be mounted on the inner diameter properly. The enclosure is not finished to a high level of detail and there are issues with securely mounting some sections. Only propositions for removing the cut off scraps and dust were presented, no actual designs. The top axle mount of the revolver is not of standard dimensions. Either a lower mount can be machined, or some other way of mounting is needed.

When downscaling the machine, or even only the tools, for the smaller cup sizes, issues with at least the notching assembly are to be expected. The diameter of the smallest cup floors is so much smaller than on the largest size used on this design, that similar notching assembly may not fit inside the skirt. The skirt height compared to the floor diameter scales down in somewhat linear manner, but the material thickness does not. This means that neither the cutting forces, nor the notching frame material thicknesses can be decreased in scale. Possibly a similar notching assembly can be designed to work straight from outside in, conversely to this design where the tool heads move diagonally out and up. The revolver can handle any cup size smaller than the one used with adapter plates, but the separation wedge and cup feeding funnel need to be rescaled. Same tool heads for the piercing can be used with a smaller plunger plate, if the hole diameter is suitable.

Since, all systems and functions of the machine are not yet designed in detail, their safety aspects were not assessed yet either. Safety of all the already designed systems and ones yet to be finalized, needs to be thoroughly evaluated before production is started. The safety considerations made during this research mainly focused on the operational aspects. Therefore, extra attention must be paid regarding safety during maintenance, transportation, and other similar more occasional situations. These considerations could not be made during this research, since the components have not yet been manufactured and sourced, so all their space requirements, dimensions, and hazards are still undetermined.

One other unknown factor is the operation rate of each of the production steps designed into the process compared to each other. It may well be that for example the holes cannot be made with as high speed as the cups could be fed to and ejected from the machine. If some issues like this realize themselves in the initial testing phase and simple solutions for speeding up the said step cannot be found, partial redesign may be needed. Unfortunately, the revolver-based structure adapts quite poorly to using multiple tooling points for single insertion and ejection points or vice versa, compared to a linear production line approach.

5 CONCLUSION AND SUMMARY

The goal of this design process was to come up with a machine that can efficiently take in stacks of cardboard cups, modify the cups for a specific use, and then extract them back into similar stacks, with emphasis on DFMA, simplicity and adjustability. At the beginning of the design process, multiple plausible solutions were envisaged and presented for creating the required holes in the floors and notches in the skirts of the cups and for handling them step-by-step through the machine. As the design progressed, issues arose with the initial ideas, either when interacting with the other subassemblies or regarding manufacturability, assembly, or production reliability. Therefore, the design process advanced iteratively, and multiple revisions of each component were designed for improving outcome. After all the redesigns and frequent feedback sessions with the company and university examiners, the resulting machine prototype model was satisfactory for all parties.

Gravity, assisted by a pneumatically actuated wedge, separates the individual cups from the stack, one by one into the first chamber of a rotating revolver. After another pneumatic actuator rotates the three chambered revolver a third of a revolution, the cup reaches the modifying point of the machine. At this stage, a third pneumatic actuator pierces several holes through the floor of the cup, from inside the cup. Simultaneously a fourth pneumatic actuator pushes a notching assembly against the floor, supporting the floor during the hole piercing. As the actuator continues to extend further the notch tool heads cut out sections of the shirt, creating openings nearly the full height of the skirt. After the piercing and notching movements have completed, the actuators retract, and the revolver is rotated again. At the third and final stage the finished cup gets pushed up out of the revolver and into an outlet pipe with pressurized airflow blown through a specialized nozzle. The empty revolver chamber then gets rotated third of a revolution forward once more, putting it back in line with the infeed pipe and the separation wedge, allowing the chamber to be refilled restarting the process cycle. Since the revolver has three spots for cups, three cups can be in the process simultaneously. As cup is being inserted into the first chamber, another cup is being modified in the second, and a third is being extracted from the machine.

All the components are expected to be easily sourced from variety of vendors or manufactured withing acceptable tolerances with the specified, available manufacturing methods. A version 2.0 should be designed based on this prototype, better optimizing the lengths and locations of the aluminum profiles and other aspects, after the actuators and other vital components have been chosen and their true dimensions acquired for the production operation. The whole assembly is expected to work as intended after testing and adjusting within the limits designed into the assembly.

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SMC CP96 ISO Cylinder datasheet

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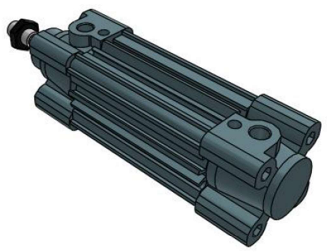
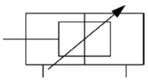


CP96S(D), ISO 15552 Cylinder, Double Acting, Single/Double Rod with Air cushion on both ends and Bumper cushion

CP96SB32-50C

Datasheet

- Double acting, standard type, single or double rod with Air cushion on both ends and Bumper cushion
- Bore sizes (mm): 32, 40, 50, 63, 80, 100
- Standard stroke up to 2000mm
- Auto switch capable



Double-acting cylinder with cushioning adjustable at both ends, single piston rod

Standard specifications

Magnet	None
Mounting	B (Basic)
Bore Size	Ø32 mm
Stroke	50
Rod Boot	w/o Rod Boot
Rod	Single Rod
Auto Switch	No Switch
Lead Wire or Prewired Connector	0.5m [Or None in the Case of No Switch]
Number	2 pcs. [Or None in the Case of No Switch]
Rod End Options	None
Temperature Resistance	None
Heavy Duty Scraper	None
Tie Rod	None
Fluororubber Seal	None
Coil Scraper	None
Made of Stainless Steel (-XC68)	None
Made of Stainless Steel (-XC65)	None
Pressure medium	Compressed air
Maximum temperature of pressure medium	70 ºC
Minimum temperature of pressure medium	-20 ºC (no freezing)

Datasheet - CP96SB32-50C

Maximum operating pressure	1.0 MPa
Minimum operating pressure	0.05 MPa
Proof pressure	1.5 MPa
Maximum ambient temperature	70 ºC
Minimum ambient temperature	-20 ºC (no freezing)
Number of pneumatic connections	2 pcs.
Pneumatic input connection	G 1/8
Pneumatic exhaust connection	G 1/8
Mode of operation of drive	Double acting
Theoretical cylinder force, advance stroke (at 0.5 MPa)	402 N
Theoretical cylinder force, return stroke (at 0.5 MPa)	346 N
Maximum piston speed	1,000 mm/s
Piston rod end	Male thread
Male thread of rod end	M10 x 1.25
Minimum piston speed	50 mm/s
Weight	0.600 Kg

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Viitteemme	Mikko Seppälä		
Merkki			

Nro.	Tuote	Määrä	Yks.	Nettohinta	Yhteensä
0.0.492.91	Profiili X 8 40x40 kevyt	11,25	M	23,28	261,90
	Pituus / Leveys / Yksikkö / Määrä / Merkki				
	850 / 0 / mm / 4 / pos 1				
	550 / 0 / mm / 7				
	350 / 0 / mm / 4 / M8/M8				
	350 / 0 / mm / 7				
	150 / 0 / mm / 1				
0.0.026.07	Vakio kiinnitys 8	8	SET	1,68	13,44
0.0.672.84	Automatik kiinnitys 8 40	29	SET	11,04	320,16
8051	Katkaisu alumiini <40	23	ST	3,20	73,60
8401	Työstö, alumiini	0,3	TIM	75,00	22,50
0.0.480.48	Uramutteri V 8 St M8	10	ST	1,28	12,80

Toim.aika: Noin 5-10 työpäivää tilauksesta.

Tuotteet välimyyntivarauksin,
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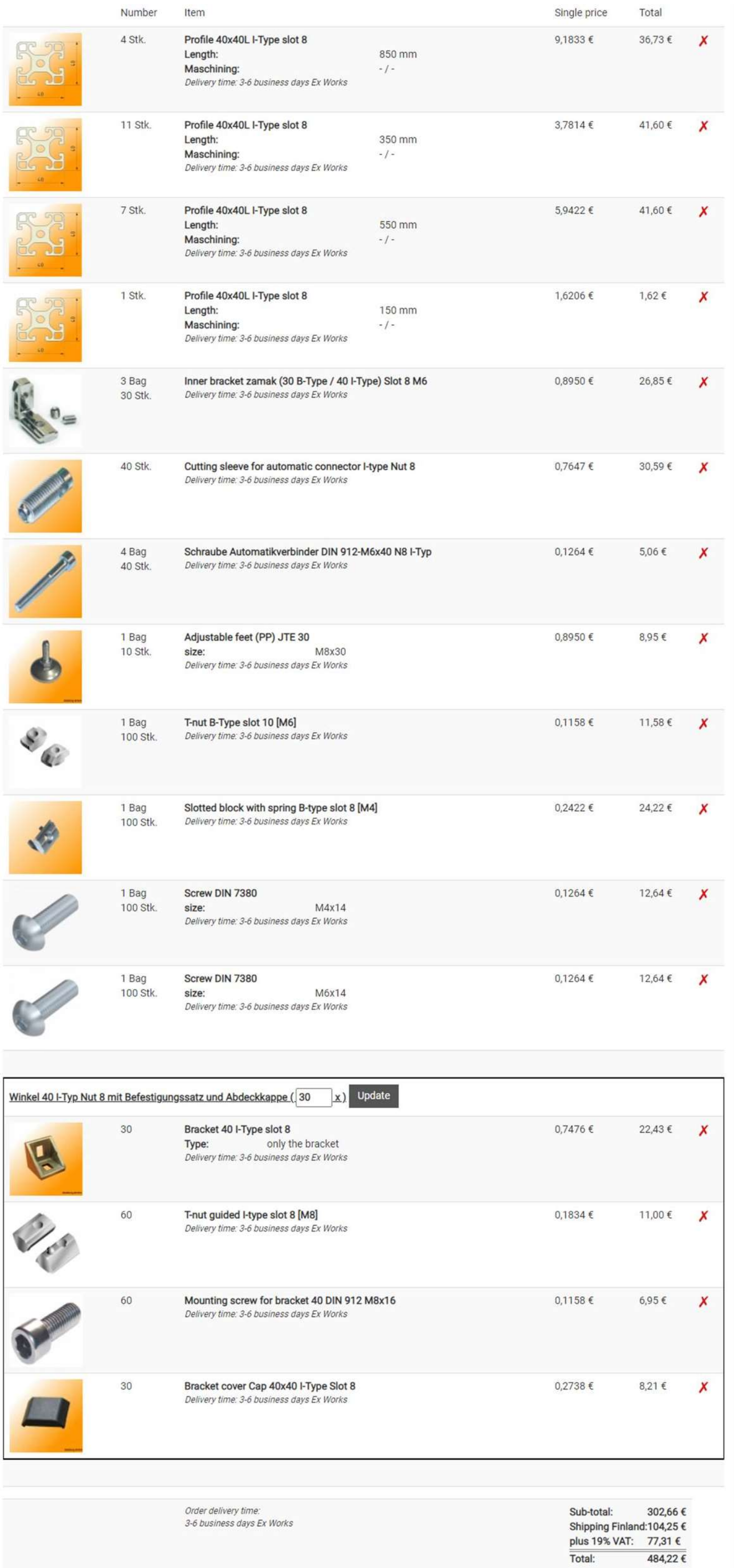

	Number	Item	Single price	Total	
	4 Stk.	Profile 40x40L I-Type slot 8 **Length:** 850 mm **Maschining:** - / - *Delivery time: 3-6 business days Ex Works*	9,1833 €	36,73 €	✗
	11 Stk.	Profile 40x40L I-Type slot 8 **Length:** 350 mm **Maschining:** - / - *Delivery time: 3-6 business days Ex Works*	3,7814 €	41,60 €	✗
	7 Stk.	Profile 40x40L I-Type slot 8 **Length:** 550 mm **Maschining:** - / - *Delivery time: 3-6 business days Ex Works*	5,9422 €	41,60 €	✗
	1 Stk.	Profile 40x40L I-Type slot 8 **Length:** 150 mm **Maschining:** - / - *Delivery time: 3-6 business days Ex Works*	1,6206 €	1,62 €	✗
	3 Bag 30 Stk.	Inner bracket zamak (30 B-Type / 40 I-Type) Slot 8 M6 *Delivery time: 3-6 business days Ex Works*	0,8950 €	26,85 €	✗
	40 Stk.	Cutting sleeve for automatic connector I-type Nut 8 *Delivery time: 3-6 business days Ex Works*	0,7647 €	30,59 €	✗
	4 Bag 40 Stk.	Schraube Automatikverbinder DIN 912-M6x40 N8 I-Typ *Delivery time: 3-6 business days Ex Works*	0,1264 €	5,06 €	✗
	1 Bag 10 Stk.	Adjustable feet (PP) JTE 30 **size:** M8x30 *Delivery time: 3-6 business days Ex Works*	0,8950 €	8,95 €	✗
	1 Bag 100 Stk.	T-nut B-Type slot 10 [M6] *Delivery time: 3-6 business days Ex Works*	0,1158 €	11,58 €	✗
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	1 Bag 100 Stk.	Screw DIN 7380 **size:** M4x14 *Delivery time: 3-6 business days Ex Works*	0,1264 €	12,64 €	✗
	1 Bag 100 Stk.	Screw DIN 7380 **size:** M6x14 *Delivery time: 3-6 business days Ex Works*	0,1264 €	12,64 €	✗
Winkel 40 I-Typ Nut 8 mit Befestigungssatz und Abdeckkappe (30 x) Update					
	30	Bracket 40 I-Type slot 8 **Type:** only the bracket *Delivery time: 3-6 business days Ex Works*	0,7476 €	22,43 €	✗
	60	T-nut guided I-type slot 8 [M8] *Delivery time: 3-6 business days Ex Works*	0,1834 €	11,00 €	✗
	60	Mounting screw for bracket 40 DIN 912 M8x16 *Delivery time: 3-6 business days Ex Works*	0,1158 €	6,95 €	✗
	30	Bracket cover Cap 40x40 I-Type Slot 8 *Delivery time: 3-6 business days Ex Works*	0,2738 €	8,21 €	✗

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