GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

DESIGN AND MANUFACTURE OF A MECHANICAL DOOR OPENER

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Madrid

Julio de 2019

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Fdo.: Sofía Alía Rivero Date: 13/06/2019

I authorize the submission of this project

PROJECT SUPERVISOR

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Madrid

Julio de 2019

DISEÑO Y FABRICACIÓN DE UN ABRIDOR DE PUERTAS MECÁNICO

Autor: Alía Rivero, Sofía.

Director: Flachsbart, Bruce.

Entidad Colaboradora: ICAI – Universidad Pontificia Comillas.

RESUMEN DEL PROYECTO

Introducción y Motivación

El diseño mecánico del abridor de puertas se hizo teniendo en cuenta las puertas batientes de los espacios comunes. La creación de este producto surgió como resultado de un problema de la vida cotidiana, que quería resolverse para hacer la vida de los seres humanos más fácil. Este obstáculo previamente mencionado es abrir puertas batientes que se abren tirando desde el interior sin el requisito de usar las manos. Existen varias razones por las cuales se desea evitar el uso del manillar de la puerta. Por un lado, pueden encontrar útil este dispositivo aquellas personas que no puedan usar sus manos debido a causas como discapacidades en las extremidades superiores, ir cargado con los brazos ocupados o incluso haberse lavado las manos recientemente. Por otro lado, este producto podría evitar la transmisión de enfermedades infecciosas por el contacto con el manillar. Para cumplir con su objetivo, este producto esta destinado a ubicarse principalmente en áreas públicas, que son las más expuestas a este tipo de amenazas. Los espacios comunes ideales para su operación son hospitales, restaurantes o baños públicos.

Figura 1, puerta batiente [Fuente: https://www.amazon.com/, vrss 2pcs 200 mm de largo de acero inoxidable Pull para tirador de puerta duradero y ligero]

Antecedentes

En cuanto al mercado actual de abridores de puertas, se encontraron dos dispositivos ya existentes los cuales serán detallados a continuación:

- Step-N-Pull es un diseño simple que se adjunta a la parte inferior de la puerta. Consecuentemente, el producto funciona al proporcionar un agarre para el pie del usuario. El borde permite un agarre firme que se puede usar para abrir la puerta tirando con el pie, evitando de esta manera el uso de las manos en dicha operación. Su funcionamiento se muestra en la siguiente figura.

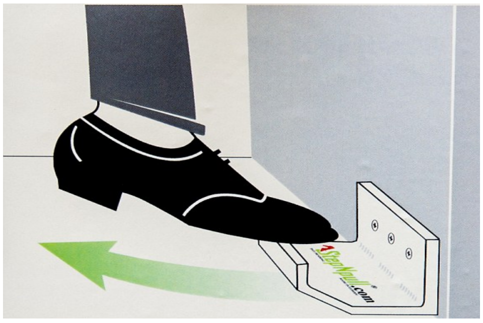

Figura 2, Step-N-Pull [Fuente: https://www.stepnpull.com/shop]

- Los abridores de puertas neumáticos. Este es un dispositivo que está conectado a la parte superior de la puerta. Funciona transformando la energía eléctrica en movimiento mecánico. Combina operadores de puertas con una unidad de control y un compresor de aire. Este dispositivo permite la apertura automática y completa de la puerta sin utilizar las manos. Sin embargo, requiere una fuente de alimentación energética. Este producto se puede observar en la siguiente figura.

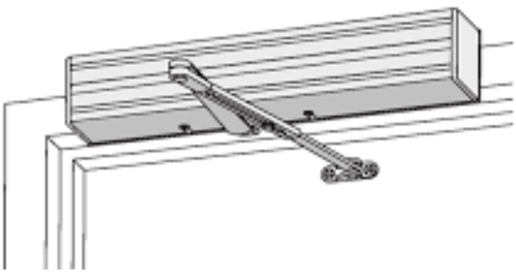

Figura 3, abridor de puertas neumático [Fuente: https://www.doorware.com/site/product.cfm?id=217028]

Tras completar la investigación de los productos ya existentes, el proyecto inicial resultó ser una combinación de los dos modelos previamente explicados. El diseño se basó originalmente en una carcasa que contenía todo el mecanismo y se adjuntaría a la parte inferior de la puerta, como el primer producto. Además, el dispositivo incluiría un sistema de retardo temporal para la seguridad del operador, inspirado en el dispositivo neumático.

Objetivos

Aunque el principal objetivo del proyecto era crear un abridor de puertas totalmente mecánico y sin necesidad de un suministro de energía eléctrica, aparecieron otros retos esenciales durante el diseño del aparato. Uno de los requisitos más importantes fue la introducción del mecanismo único de retardo temporal mencionado anteriormente. La principal razón de la incorporación de este sistema de retardo es el hecho de que una vez que el usuario presiona el pedal, el dispositivo debe esperar hasta que la persona retroceda antes de empujar la puerta para evitar accidentes. Otra ambición crucial durante el proceso de diseño, fue determinar la mejor manera de proporcionar el impulso a la puerta batiente. Las ideas para desarrollar esta función fueron variando desde brazo de palanca, a una rueda, hasta una rueda semicircular cubierta de goma. Por último, fue determinante la decisión de contener todo el mecanismo en una única caja con una unidad instalable. De esta manera, se evitarían las conexiones externas con tuercas y tornillos, que podrían dañar la puerta al fijar el dispositivo.

Metodología

Durante el desarrollo del proyecto hasta conseguir el producto final se ha llevado a cabo un proceso iterativo de prototipos consecutivos, como se explicará más adelante. Cada prototipo fue evaluado tras su montaje para optimizar sus puntos débiles y corregirlos con vistas al siguiente modelo hasta alcanzar el producto más perfeccionado posible. Algunas de las herramientas imprescindibles que se utilizaron en este procedimiento fueron, el software CREO Parametric que fue el programa más utilizado para crear el diseño CAD de los diferentes modelos y, por otro lado, un software de estimación de costes llamado aPriori. Este programa se utilizó para pronosticar los gastos de fabricación del dispositivo y así mejorar su rentabilidad. El resultado obtenido de este análisis de costes del producto final fue de 21.2€ por dispositivo.

Se desarrollaron varias técnicas de fabricación para la construcción de los distintos prototipos. El método más popular debido a su capacidad para crear casi cualquier geometría fue la técnica de impresión 3D. En particular, Fused-Deposition Modeling, FDM, que es la mejor opción para la impresión en 3D, ya que es el proceso más rápido con una precisión adecuada para la construcción de las piezas diseñadas. El material utilizado para este método es un filamento de plástico PLA que existe en distintos colores. Por otro lado, la técnica de corte por láser también fue necesaria para la creación de partes transparentes del prototipo debido al material acrílico utilizado para este método. Así mismo, el láser fue útil para cortar las piezas que requerían alta precisión y un acabado de superficie suave. Hubo otras técnicas realizadas como el mecanizado o el moldeo por inyección, que no se utilizaron para la creación de los prototipos. Sin embargo, estos métodos también se experimentaron durante el proyecto con vistas a la fabricación del dispositivo final en cantidades industriales para su comercialización.

Resultados

Durante el diseño del primer boceto del producto, se ideó que el abridor de puertas StopNswing tendría una placa de apoyo en la parte superior que presionaría el brazo de palanca al ser apretado por el usuario. Este brazo de palanca curvado alcanzaría un pequeño gatillo, proporcionando un retardo temporal que permitiese al usuario dar un paso atrás antes de abrirse la puerta. Una vez acabado el intervalo de tiempo establecido, el brazo de palanca se liberaría y sería lanzado por fuertes muelles previamente comprimidos impulsándose contra el suelo y abriendo la puerta de golpe. La siguiente figura representa un simple boceto del mecanismo explicado anteriormente con las partes mencionadas.

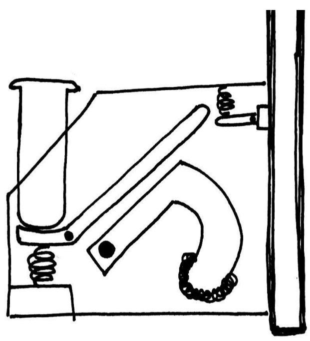

Figura 4, primer boceto del abridor de puertas mecánico

El primer prototipo funciona de manera similar al boceto explicado anteriormente, operando con un brazo de palanca presionado por un pedal y lanzado con el impulso de muelles comprimidos. Sin embargo, este modelo incluye un mecanismo de retardo temporal como parte del sistema de engranaje interno. Consiste en un mecanismo hecho de engranajes de diferentes tamaños y formas cuya función sería retener un gatillo durante algunos segundos. Esto sucede cuando se presiona el pedal, lo que hace que los engranajes entrelazados entre sí giren simultáneamente mientras que ambos se bloquean con una clavija rígida. Una vez que la fuerza causada por los muelles comprimidos en el brazo de la palanca sea lo suficientemente grande, el gatillo liberará el engranaje principal para transmitir dicho impulso al brazo, abriendo de esta forma la puerta. Las siguientes imágenes muestran la operación anteriormente detallada con un modelo de CAD. Además, se creó un prototipo de cartón que se muestra a continuación para probar dicho diseño. Este prototipo expuso los defectos existentes en la anterior idea y condujo al desarrollo del segundo modelo.

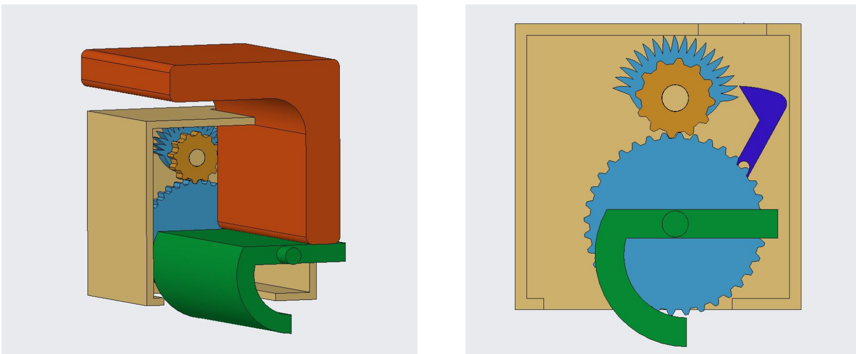

Figura 5, modelo de CAD del primer prototipo

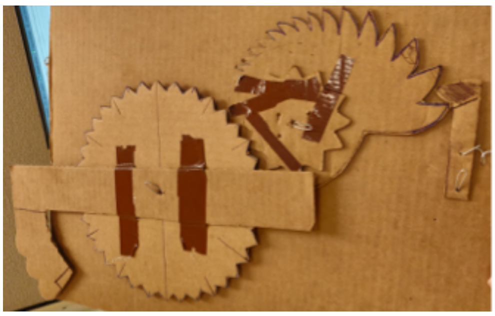

Figura 6, primer prototipo de cartón

Después de comprobar que el mecanismo del primer modelo era prácticamente imposible de analizar matemáticamente debido a la complejidad del diseño de los engranajes, se comenzó el desarrollo de la segunda idea. El diseño CAD del segundo modelo se muestra a continuación y su funcionamiento se explicará haciendo referencia a la imagen. Tiene un pedal identificado como elemento verde claro que termina con un sistema de encaje de cremallera y piñón. Cuando se aplica fuerza a este pedal, hace que un engranaje de rueda dentada, elemento naranja, gire y mantenga comprimido un muelle de torsión colocado en su mismo eje. Este mecanismo queda trabado mediante varios trinquetes que actúan como sistema de bloqueo, elementos verdes oscuro, unidos a una rueda semicircular, elemento azul. El muelle en espiral almacena la energía para liberarla transformándola en un momento torsor. El gatillo, parte que se conectará al sistema de retardo temporal, soltará repentinamente la rueda semicircular cubierta de goma proporcionando el impulso adecuado abrir la puerta. Sin embargo, se puede observar que este modelo no contiene un sistema de retardo de tiempo dado que debido a la complejidad de dicho sistema se diseñará y probará aisladamente en el siguiente paso del proceso. Este prototipo se imprimió en 3D y se puede ver en la siguiente figura.

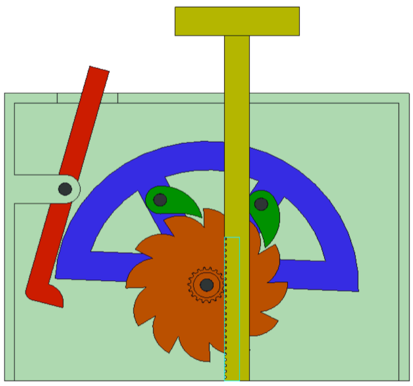

Figura 7, modelo CAD del segundo prototipo

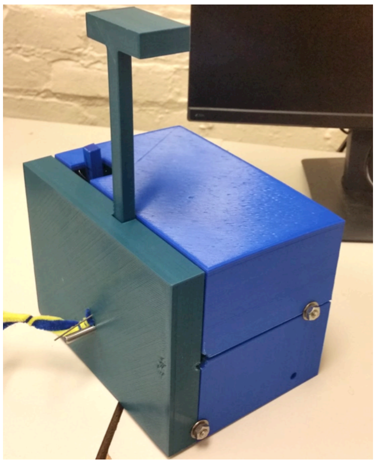

Figura 8, segundo prototipo impreso

Durante el segundo proceso de iteración, antes de crear el tercer y último prototipo, se realizó un procedimiento de diseño experimental para diseñar un mecanismo de retardo temporal adecuado para la incorporación al aparato. Este prototipo de retardo consistió en un bastidor ajustable imprimido en 3D para alojar distintas tiras de goma, dicha pieza es el elemento azul que se muestra en la figura expuesta a continuación. El bastidor se diseñó para permitir hasta un máximo de nueve lengüetas de goma que podrían intercambiarse y ajustarse en longitud. Por otro lado, el mínimo número de tiras fue cuatro para garantizar el hecho de que hubiera un retraso. La longitud expuesta de las lengüetas se determinó por las limitaciones de espacio del prototipo. El rango de rigidez de las tiras de goma se eligió con una dureza de 95A y 40ª en el durómetro. Por lo tanto, estas fueron las tres variables elegidas para realizar el experimento, el número de pestañas, la longitud y la dureza del material. Además, se colocó una cadena entre dos engranajes con un cilindro con peso constante para producir la rotación del mecanismo. También, se adjuntó en el otro lado de la cadena un pequeño clip responsable de ralentizar el movimiento y provocar el retraso.

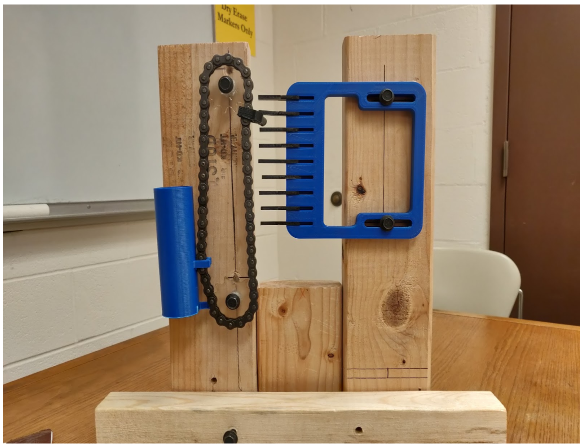

Figura 9, segundo mecanismo de retardo temporal

Los resultados del análisis no mostraron ningún valor significativo después de realizar las seis combinaciones posibles de variables. Aunque parece que hay dos efectos principales válidos en el siguiente gráfico, sus valores no fueron mayores que el valor de 2 sigma, por lo tanto, no se consideran significativos. En consecuencia, surgió la necesidad de crear un sistema de retardo temporal nuevo. Sin embargo, el diseño general de dicho mecanismo ya estaba diseñado, sólo necesitaba mejorarse.

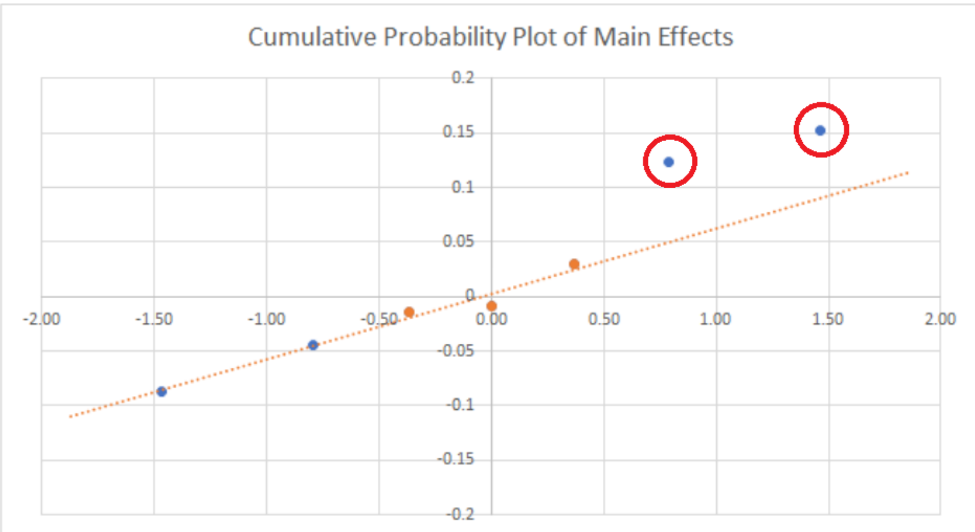

Figura 10, gráfica de probabilidad acumulada de efectos principales

Finalmente, para la creación del último prototipo que se muestra en la figura localizada debajo, se realizaron algunas mejoras al modelo anterior para optimizarlo. El mecanismo de retardo temporal mencionado en el párrafo anterior se mejoró e implementó en la operación completa del dispositivo. Este prototipo funciona de la siguiente manera. Mientras el pie del usuario presiona el pedal, el sistema de piñón y cremallera gira haciendo girar el engranaje de la rueda dentada que levanta la rueda semicircular hasta la parte superior, como se muestra en la imagen. Una vez que la rueda alcanza el gatillo y el muelle de torsión, que se coloca en el eje del piñón, está completamente comprimido, el sistema de retardo actualizado empieza la cuenta atrás mientras la rueda queda bloqueada. Una vez finalizado el tiempo deseado, se suelta el gatillo de bloqueo y se descarga la energía almacenada del resorte en el eje de la rueda en forma de momento torsor. De esta manera, la rueda semicircular se lanza contra el suelo generando el impulso necesario para realizar el proceso de apertura de la puerta.

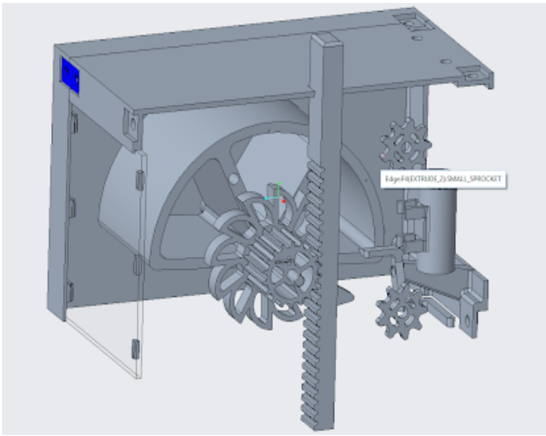

Figure 11, modelo CAD del prototipo final

En este párrafo se detallan los principales avances realizados para construir este último prototipo. Se mejoró la cubierta del aparato y se implementó una ventana hecha de acrílico para observar el mecanismo interno sin tener que desmontar todo el dispositivo. El sistema de cremallera y piñón se optimizó para mejorar el engrane entre ambos. Además, se mejoró la configuración y colocación del muelle de torsión. Por otro lado, las partes pesadas del modelo, como la rueda semicircular, fueron rediseñadas y reimpresas para hacer un dispositivo más liviano. Para terminar, se incluyó en el dispositivo el sistema mejorado de retardo temporal. Todas estas mejoras se pueden observar en la siguiente figura del prototipo real.

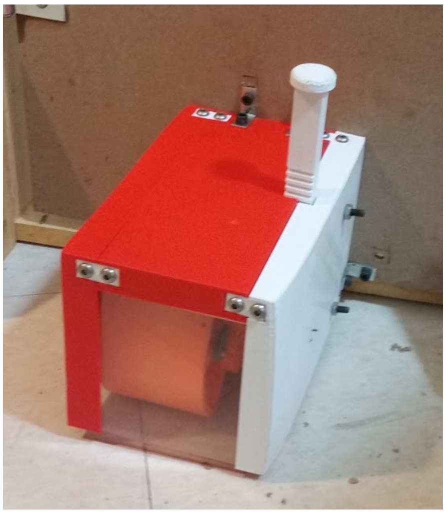

Figure 12, prototipo final

Conclusiones y Futuros Desarrollos

Finalmente, se construyó una puerta de prueba hecha de madera para evaluar este prototipo final. En la imagen anterior se puede ver cómo se adjuntó el modelo a esta puerta simulada utilizando soportes de metal, tornillos y tuercas. Aunque uno de los objetivos iniciales del proyecto era crear una unidad instalable para fijar el dispositivo, la falta de tiempo no permitió su implementación. Sin embargo, para la comercialización del producto, la incorporación de un sistema de unidades instalables sería crucial. Al probar el prototipo, resultó ser exitoso y cumplir su objetivo correctamente. Sin embargo, el tiempo de demora resultó ser un poco escaso. El sistema de retardo temporal siempre fue el reto más difícil y desafiante durante el desarrollo del proyecto. Aumentar el tiempo de espera antes de llevar a cabo el proceso de apertura de la puerta sería un requisito esencial a mejorar antes de la comercialización del dispositivo. En conclusión, el producto final por lo general funcionó adecuadamente. Sin embargo, quedarían un par de detalles por perfeccionar antes de sacar el producto al mercado como sería un sistema de retardo perfeccionado.

DESIGN AND MANUFACTURE OF A MECHANICAL DOOR OPENER

Author: Alía Rivero, Sofía.

Director: Flachsbart, Bruce.

Collaborating Entity: ICAI – Universidad Pontificia Comillas.

RESUMEN DEL PROYECTO

Introduction and Motivation

The mechanical door opener design was made with swinging doors in mind, specifically for common spaces. The ideation of this product came up as a result of a daily life problem, which wanted to be solved for making human beings life's easier. This previously mentioned obstacle that needed to be overcome, was to open swinging doors pulled from the inside without the requirement of using ones hands. There exist several reasons why people do not wish to touch the door handle. On one hand, those people who are not able to use their hands due to causes like disabilities on the upper limbs, having full hands or even having recently washed their hands, might find useful this device. On the other hand, this product could avoid infectious diseases transmission. In order to fulfill its goal, this product must be mainly located in public areas, which are more exposed to this kind of threats. For instance, hospitals, restaurants or public restrooms would be the ideal areas for its operation.

Figure 13, swinging door [Source: https://www.amazon.com/, VRSS 2Pcs 200mm Long Stainless Steel Pull Door Handle Plate Durable and Lightweight]

Background Research

In regard of the current market of door openers, two already existing devices were found:

- Step-N-Pull is a simple design that is attached to the inside part of the door. Therefore, the product works by providing a handle grip for the user´s foot. The lip enables a firm grip that can be then used to open the door by pulling, allowing the users to leave their hands free. Its operation is shown in the following figure.

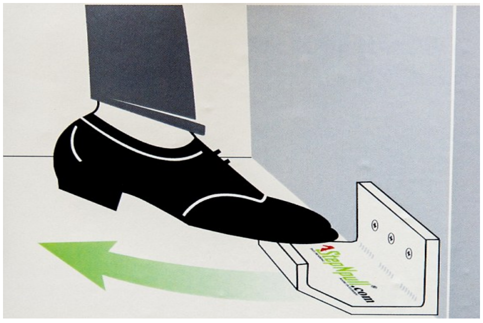

Figure 14, Step-N-Pull device [Source: https://www.stepnpull.com/shop]

- Pneumatic door opener, it is a device that is attached to the top part of the door. It works by converting energy into mechanical motion. It combines door operators with a control unit and an air compressor. This device enables completely hands free automatic opening. However, it requires a power supply. It can be observed in the consecutive figure.

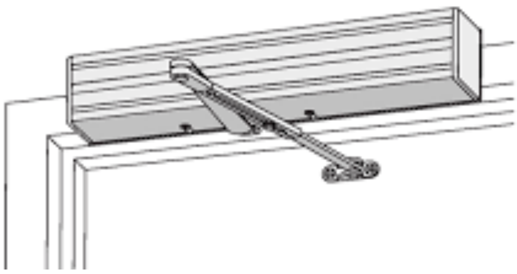

Figure 15, Pneumatic Door Opener [Source: https://www.doorware.com/site/product.cfm?id=217028]

After completing the background research, the initial product resulted to be a combination of the two previously explained models. The design was originally based on a case that contained the whole mechanism, which will be attached to the bottom part of the door, as the first product. Besides, the device would include a time delay system for the operator’s safety, taken from the pneumatic device.

Main Goals

While the main goal of the project was to create a fully mechanical hands free door opener, which did not require any energy supply, there were some other key challenges ahead. An essential requirement was the introduction of the unique time delay mechanism mentioned above. The importance of this systems remains in the fact that once the user has pressed the pedal, the device must wait until the person step back before pushing the door. Another central ambition during the design process was to determine the best way of providing the impulse to the swinging door. The ideas for developing this function varied from a lever arm to a wheel to a semi-circular, rubber-covered wheel. Last but not least, it was crucial to contain the whole mechanism in a single case with an installable unit, avoiding in this way external connections, which could damage the door when attaching the device.

Methodology

For the design of the final product it has been used an iterative process of consecutive prototypes, as it will be explained further on. Each prototype had been evaluated after being created in order to optimize its weaknesses for the creation of the following one and reach the most successful product affordable. Some powerful tools have been used in this procedure; for instance, CREO Parametric software has been the most useful method for creating the CAD design of the different models. On the other side, cost-estimating software called aPriori was also used for forecasting the manufacturing costs of the device in order to improve its profitability. The outcome obtained of this cost analysis for the final product was a manufacturing cost of 21.2€ per device.

Several manufacturing techniques were developed for building up the prototypes. The most popular method due to its ability to create almost any geometry was 3D printing technique. In particular, Fused-Deposition Modeling, FDM, which is the best option of 3D printing since it is the fastest process with a suitable accuracy while building up the parts. The material used for this method is a PLA plastic filament, which can be colored. Moreover, laser-cutting technique was also necessary to create clear parts due to the acrylic material used for this method. Also, high-accuracy parts, with smooth surface finishing needed, also required being laser cut. There were some other performed techniques as machining or injection molding, which were not used for prototype creation. However, these methods were also tested with large-scale manufacture process of the final device in mind.

Results

During the ideation process, for the first rough outline made, the StopNswing door opener would have a kick plate on top that would depress the lever arm. This curved lever arm would catch a smaller trigger, providing a time delay that allows the user to step back. After the safety delay, the lever arm launched by strong compressed springs would swing down and slam the door open. The following figure represents a simple sketch of the mechanism previously explained with its parts.

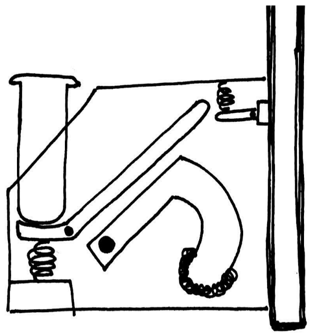

Figure 16, first door opener sketch

The first prototype works similarly to the previously explained sketch, operating with a lever arm pushed by a pedal and launched by some strong springs. However, this model includes a time delay mechanism as a part of the inner gear system. It consists on a mechanism made of different sizes and shapes gears that would hold a trigger for some seconds. This happens when the pedal is pressed making the main and rare gears turn simultaneously while both get locked by rigid peg. Once the force caused by the compressed springs on the lever arm is big enough, the trigger would release the main gear to deliver the impulse of the arm, opening the door. The following pictures show the operation formerly detailed with a CAD model. Besides, a cardboard prototype shown below was created to test the design, which exposed the defects of the idea and led to the ideation of the second model.

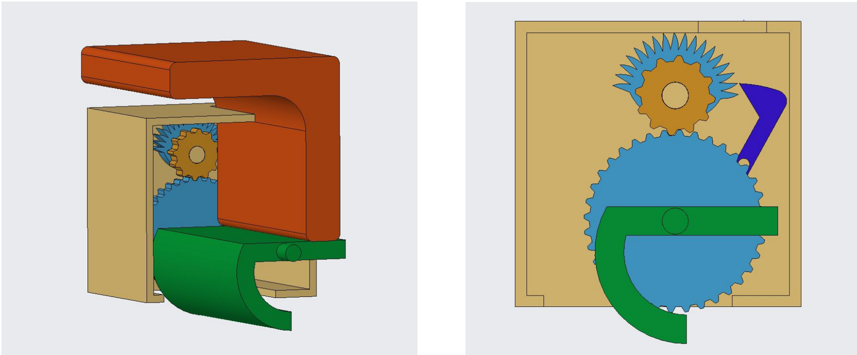

Figure 17, first prototype CAD model

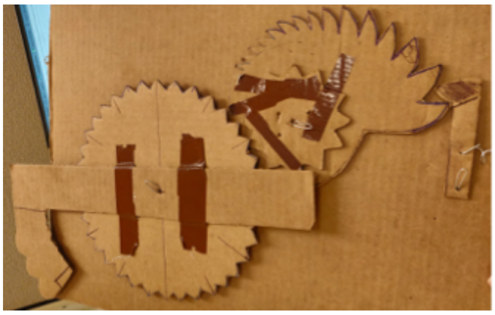

Figure 18, first cardboard prototype

After realizing that the first prototype model was virtually impossible to analyze mathematically because of the complexity of the gears design, the second prototype idea was developed. This second CAD model prototype is shown hereunder and its operation will be explained making reference to the picture. It has a pedal, light green item that ends with a fitting system, rack and pinion. When a large force is applied to this pedal, it makes a sprocket gear, orange item, rotate and keep a torsional spring placed in its shaft compressed. Several ratchets, dark green items, attached to a semi-circular wheel, blue item, are responsible for this locking mechanism. The compact spring stores the energy in order to release it as a mechanical motion. The trigger, part that will be connected to the time-delay system, will suddenly release the rubber covered semi-circular wheel. It will provide the right impulse to the door in order to open it. Nevertheless, it can be noticed that this model does not contain a time delay system due to the fact that it will be carefully designed and tested in the next step. This prototype was 3D printed and it can be seen in the following figure.

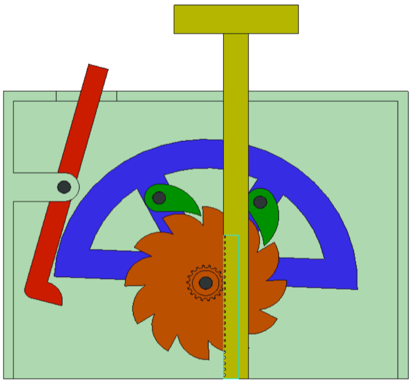

Figure 19, second prototype CAD model

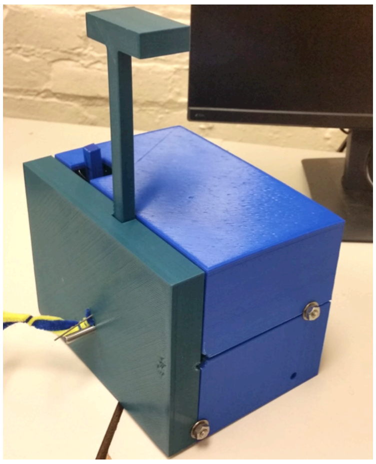

Figure 20, second printed prototype

During the second iteration process, before creating the third and final prototype, a design of experiment procedure was performed to design an outstanding time delay mechanism to incorporate. This time delay prototype was primarily accomplished by the printing of an adjustable rack to house the rubber strips, which is the blue item shown in the following figure. The rack was designed to allow for up to a maximum of nine rubber tabs that could be swapped out and adjusted in length. On the other hand, the minimum was of four tabs to ensure there was in fact a delay. The exposed length of rubber's maximum value was determined by the space constraints of the prototype, as there was at most 1 inch of clearance for tabs with ⅜ in. kept in the rack for support, and a minimum of ⅜ in. required to engage with the peg. The range of stiffness of the rubber tabs was chosen with a maximum of 95A and 40A durometer hardness. Therefore, these were the three chosen variables for performing the experiment, number of tabs, length and material hardness. Furthermore, a chain was set between two gears with a cylinder with constant weight to produce the chains movement. Also, a little clip responsible of slowing the motion and making the delay was placed on the other side of the chain.

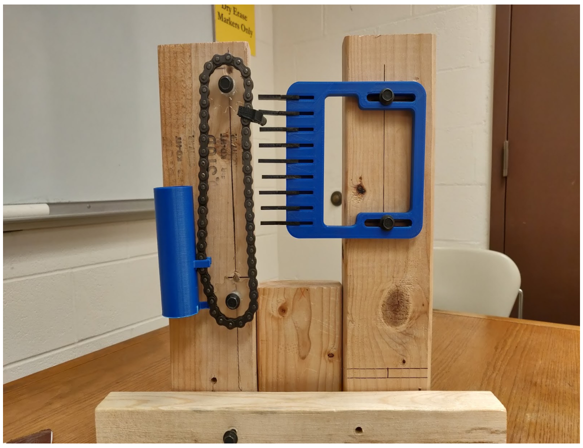

Figure 21, second time delay system model

The results of the analysis did not show any significant value for the test after performing the six possible combinations of variables. Even though there appear to be two valid main effects in the following graphic, their values were not larger than 2-sigma value. Consequently, this caused the need of the creation of an upgraded time delay system model for the final prototype. However, the overall design of the mechanism was already devised, it only had to be improved.

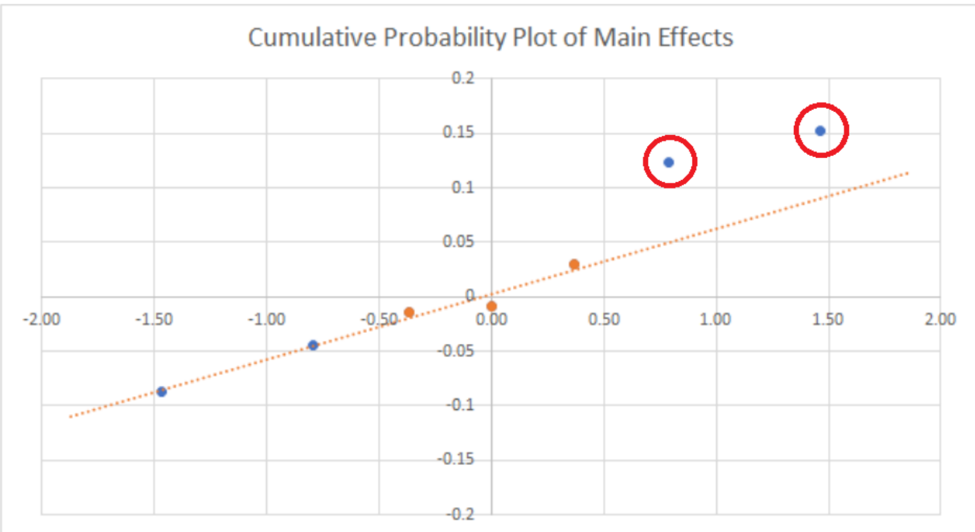

Figure 22, cumulative probability plot of main effects

Finally, for the last prototype shown in the figure below, some upgrades were made to the previous model in order to optimize it. Similarly, the previously mentioned time delay mechanism was also fixed and this time included to the whole device operation.

This prototype works in the following way. While the pedal is pressed by the users foot, the rack and pinion system turns making the sprocket gear rotate, which lifts the semi-circular wheel to the top part as shown in the picture. Once the wheel reaches the trigger and the torsional spring, which is placed in the pinion gear´s shaft, is fully compressed, the optimized time delay system starts the countdown. After the desired amount of time has been finished, the locking trigger is released and the torsional spring stored energy is discharged on the wheels shaft. In this way, the semi-circular rubber covered wheel is launched to the floor powering the door opening process.

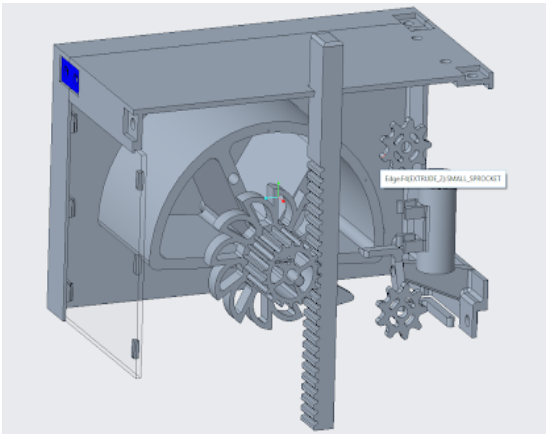

Figure 23, final prototype CAD model

Regarding the changes performed for building up this last product prototype, here are explained the main progresses done. The housing was improved and an acrylic window was implemented to observe the intern mechanism without having to disassemble the whole device. The rack and pinion system was optimized to improve the fit between both. Moreover, the torsional spring configuration and placement was upgraded. Besides, the heavy parts of the model were redesigned and reprinted in order to make the product lighter. Last but not least, an enhanced time delay mechanism system was included in the device. All these improvements can be noticed in the following figure of the real prototype.

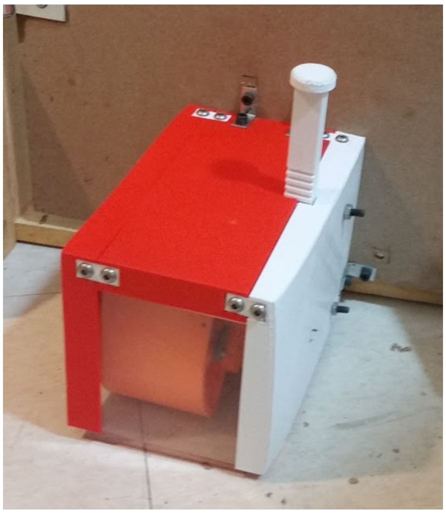

Figure 24, final prototype

Conclusions and Future Direction

Finally, a fake door made out of wood was built to test this final prototype. In the former picture it can be seen how the model was attached to this mock up door using metal brackets, bolts and nuts. Even though one of the initial project objectives was to create an installable unit for attaching the device, the lack of time did not allow it implementation. However, for the market of this product, the incorporation of an installable unit system would be crucial. While testing the prototype, it resulted to be successful and deliver its goal properly. Nevertheless, the delaying time turned out to be a little poor. The time delay system had always been the most challenging and difficult part to develop during the project. Therefore, increasing the amount of time before pushing the door would be another requirement before commercializing this device. Overall, the final product worked quite acceptable and is almost ready to operate perfectly.

CONTENTS INDEX

INDEX OF FIGURES

1. Introduction

The mechanical door opener device was designed with swinging doors in mind, in particular, for common spaces. The handle of the door is never wanted to be touched in public areas. What if you could just use your foot? The StompNSwing Door Opener would have a kick plate on top of the device that will open the door automatically, with a process entirely built of mechanisms. In this way, the problem would be solved easily. It would avoid using the hands to pull the door from the inside in order to open it. Instead, the foot would be used for pressing a pedal that activates the procedure of turning the door. It is important to highlight the fact that this product would be applicable to swinging doors pulled from the inside, avoiding, this way, the power required by the operator.

Figure 1, swinging door [Source: https://www.amazon.com/, VRSS 2Pcs 200mm Long Stainless Steel Pull Door Handle Plate Durable and Lightweight]

2. Background Research

2.1 Existing products

Analyzing the main current problem and searching for different solutions led to the creation of the first prototype of the desired device. Some of the ideas that provided inspiration to design the initial sketches were:

- Step-N-Pull, a simple design that is attached to the inside part of the door. Therefore, the product works by providing a handle grip for the user's foot as it can be seen in Figure 2. The lip enables a firm grip that can be then used to open the door as it is done with the hand, but allowing the user to leave their hands free. The architecture of this product is shown in Figure 3. As it can be noticed in the following figures, this device is attached to the doors using bolts and nuts, which will damage the door for life.

On the other hand, the commercial name for the project device, Step-N-Swing, also resulted from this handle grip device.

Figure 2, Step-N-Pull [Source: https://www.stepnpull.com/shop]

Figure 3, Step-N-Pull existing product [Source: https://www.stepnpull.com/shop]

- Pneumatic Door Openers convert energy, typically air, into mechanical motion. They combine at least one door operator with a control unit and an air compressor. This product works by pushing an actuator that activates the air compressor. This remote compressor pressurizes a cylinder above the doorframe, which then opens the door with a lever arm. This enables automatic opening that is completely hands free, but requires pneumatic piping and supplied electricity. This device is shown in Figure 4. Moreover, this device typically includes a damper, which slows the motion of closing the door. This product is the most popular one in the current market. It can be found in almost all the automatically opened doors.

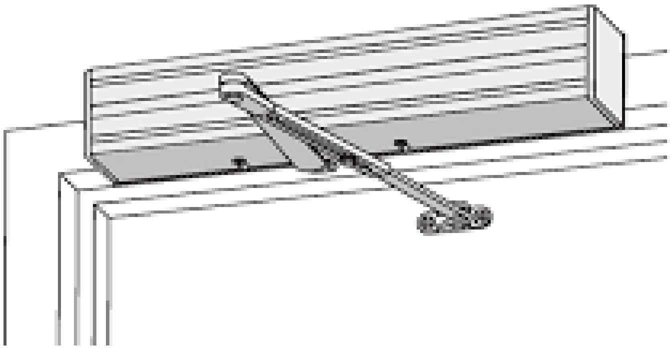

Figure 4, Pneumatic Door Opener [Source: https://www.doorware.com/site/product.cfm?id=217028]

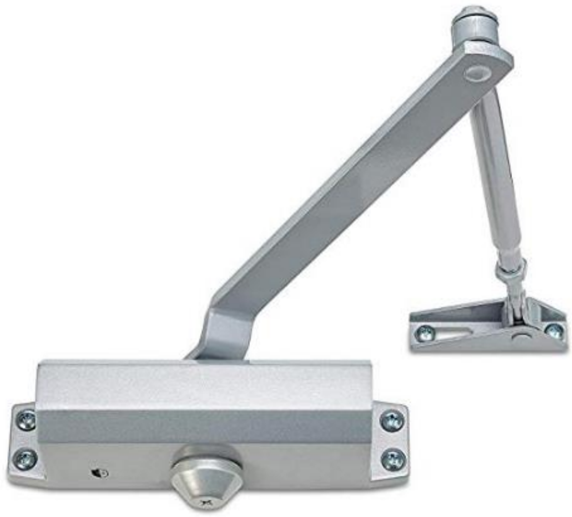

Figure 5, existing product [Source: http://www.sopl.us/blog/the-history-of-door-closers]

The following table shows the range of prices in today´s market for both products depending on its quality. The goal of the project would be to create an accessible, helpful product that fulfills some outstanding requirements like being entirely mechanical in order to attract the customer.

Prices	Step-N-Swing	Pneumatic Door Opener
Lower	26.38€	26.38€
Higher	105.53€	290.20€

Table 1, products prices range

After completing the background research, some ideas were taken from the previously explained devices for the creation of the first prototype. The initial model turned out to be a combination of the two previously explained concepts. The product would be attached to the bottom part of the door and powered with the foot strength like the Step-N-Pull. Besides, it would require a time delay mechanism as the Pneumatic Door Opener to let the user step aside. The time delay mechanism idea was inspired by the damper operation system of the Pneumatic Door Opener. However, the device would only work mechanically, without any electricity supply, which will be one of the bigger advantages when compared with the Pneumatic Door Opener device.

3. Manufacturing Techniques

3.1. 3D Printing

3D Printing is a manufacturing technique used to quickly fabricate a scale model of a part for an assembly using computer aided design data, CAD file. There are several advantages and limitations with these methods as compared to more traditional subtractive processes.

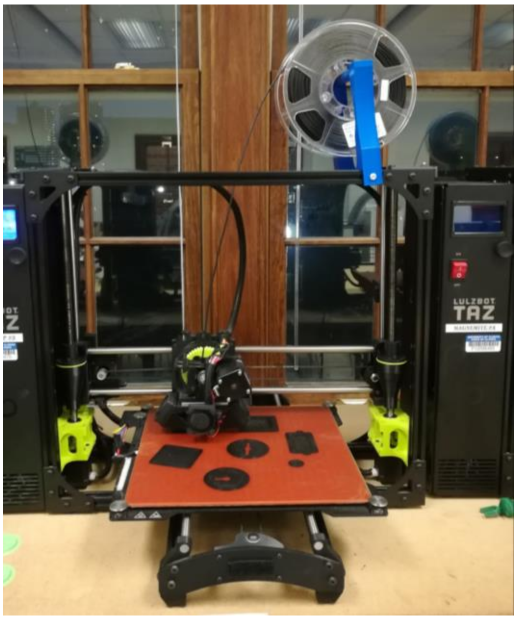

Figure 6, 3D printer used for FDM process

In 3D Printing, the machine reads in data from a CAD file, and lays down successive layers of liquid or powdered material, and in this way builds up the model from a series of cross sections. The primary advantage to this type of construction is its ability to create almost any geometry. Construction of a part using 3D Printing typically takes from minutes to hundreds of hours, depending on machine and model size. Often this process is used to make prototypes since design changes are quick and easy, and sometimes used in limited production.

There exist four different categories of 3D printing, which will be explained in the following paragraphs.

Selective Laser Sintering (SLS) is the first kind of 3D printing method. It is known for not requiring support structures as the powder supports the part being printed. Moreover, parts produced with this method have high strength, stiffness and chemical resistance. It is the fastest additive method. Nevertheless, with SLS thin parts may warp due to heat, making it a risky choice for parts requiring high precision. Also, it is very demanding in terms of environment, as humidity poses the risk of moving the powder, thus making it necessary to maintain a dry environment. It has grainy finish and often porous, which also results in the user having to remove powder from the various pores during the finishing process. It has lack of colors as material is usually white, and there is no option for clear parts.

Stereo lithography Apparatus (SLA) is a 3D printing method, which is able to achieve highest resolution and smoothest surface among additive methods. It uses less support structures than some methods such as MJP, later explained, usually 70% volume, decreasing material costs. Unlike SLS, it offers the option to make semi-clear rigid parts. It is the cheapest method in additive options. Although lesser in volume than MJP, the support structure must be cut and thus opens up a safety hazard. Likewise, since resin is a fluid, it gets trapped within the smaller gaps and holes of the part, making removal difficult. In addition, it is made of brittle material and it requires a curing process, increasing the amount of time required to fully make parts. Thin surfaces are susceptible to warping.

Multi-Jet Printing (MJP) is the best method for creating thin parts since the support structures completely prevent warping. It has availability of multiple colors, which makes it a good choice when colors are an important part of the prototyping process. Unlike SLS, provides a smooth surface finish. With specific methods and elastomers, it also opens up the option of making flexible parts. However, the material used in MJP is typically brittle and susceptible to breaking, cracking or crumbling easily. Furthermore, it requires completely solid support structure, thus increasing the material requirements and, in turn, expense.

Fused-Deposition Modeling (FDM) is considered to be the best option of 3D printing techniques due to the evidences explained in the following words. Some of the advantages that it presents are that it can be done in color with colored plastic filaments. As well as in large volumes, as it does not need as much surrounding machinery, only requiring a print head. It is typically the fastest 3D printing process. Otherwise, any overhanging structure requires large amounts of scaffolding. Also, higher resolution prints require smaller filaments and thus take exponentially longer to print. Finally, it is difficult to achieve a smooth surface due to factors such as staircasing effect, which is an error on the amount of material used compared to the volume specified by he computer aided design model. Inclined and curved surfaces show staircase effects more frequently than other surfaces. Thin parts tend to warp due to the heat of the extrusion process.

Taking into account the fact that FDM technique is the most valid for creating the prototype, some parts of the initial sketch were 3D printed with this method in order to analyze the accuracy of the procedure.

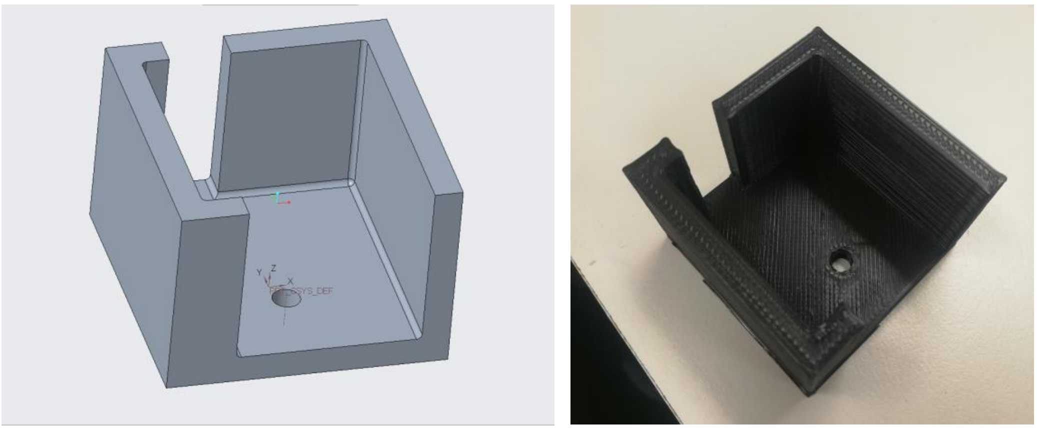

Figure 7, CAD model vs. printed part

By evaluating the procedure with the piece shown in Figures 7, several facts about FDM 3D printing method were proved:

- Exact size is not the same due to the tolerance limits of the 3D printers given the filament size.
- Surfaces that were rounded are not perfect curves due to the staircasing effect of the print layers. Most curves are an approximation at best.
- Corners have visible bump protrusions due to filament size and are not sharp corners like in the CAD file.
- CAD models are isotropic, having the same strength and properties in all directions. As our parts are 3D printed in FDM, there are large differences in stiffness and strength between the print direction and the direction of layering. Individual layers are quite strong, whereas the direction of the stacking of layers is going to be weaker.
- Defects from the support structure attachment points are likely, and similarly some parts may physically have warped from the heat of extrusion. FDM has a disadvantage among additive methods, as it tends to warp thinner parts.

Regarding the orientation of the printed part, it is crucial to select the optimal printing direction in order to facilitate the operation.

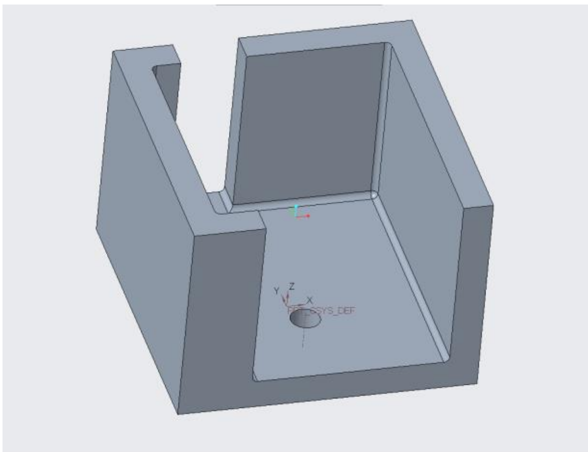

Figure 8, good printing orientation

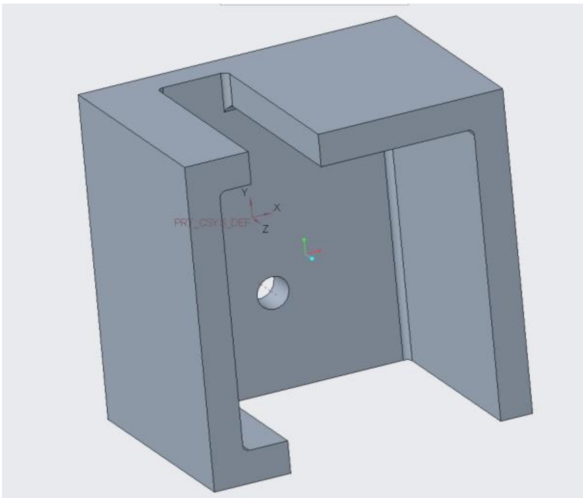

Figure 9, bad printing orientation

As seen above, the printing configuration of Figure 9 requires support structure for its overhanging wall and for the hole in the wall. The one benefit to this printing orientation is that it would require less material for a printing base at the start of the print. The printing position displayed in Figure 8 would be far superior. It would require no support scaffolding, as there are no overhangs. The only surplus printing material it would require would be in the few layers at the bottom for a larger print base. In addition, aligning the parts in a horizontal manner would decrease the setbacks faced due to the staircase effect, bettering the finishing of our rounded part. Besides, this good orientation would make a better shape for the hole. In the bad orientation, the printer can not follow the CAD surface completely and the hole surface will not be smooth.

Some of the differences that would be expected if the previously shown part was made using SLS printing instead of FDM would be:

- Primarily, the part would be void of support structures, as one of SLS's greatest advantages is its independence from support structures.
- The surface of the part would have a grainy finish, as well a porous surface. It would be necessary to remove the excess powder from the part and dispose powder in a 10mm radius around the part as well.
- The part would be stronger, stiffer and with a high chemical resistance.
- The material used would be a nylon powder, which means that we would be restricted to a white part.
- The part would be of a higher resolution due to smaller layer thickness.

The conclusion where this earlier measure leads is that FDM can create parts with great accuracy taking into account the fact that the two housing pieces shown in Figure 10 matched perfectly. The parts were also quite strong despite their relatively thin walls. In order to remove the excess support structures, the parts were subjected to rough handling and maintained their integrity.

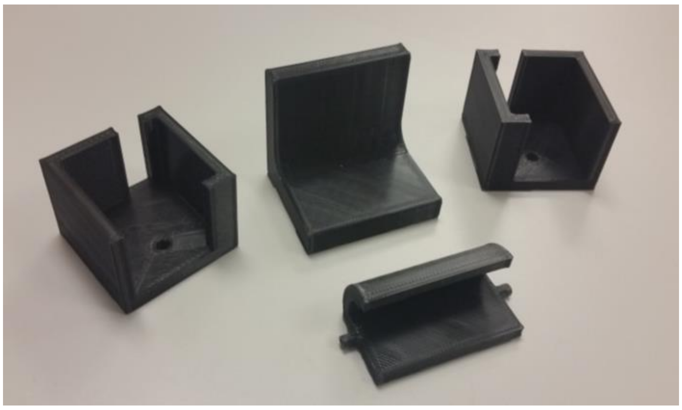

Figure 10, first FDM printed prototype

3.2. Machining

Machining is a procedure in which a piece of raw material is cut into a desired final shape and size by a controlled material-removal process. Machining is known to be a part of the manufacture of any metal products but it can also be used on materials such as wood, plastic, composites or ceramics. The roughing process will be used to machine the rough outline of the part, while the finishing process will be used to machine fine details and to improve the surface finish. Therefore, it is a useful technique for the manufacture of the different metal parts of the product. Consequently, this procedure was evaluated to test its accuracy by the creation of an example piece shown in Figure 12.

Figure 11, drilling machine [Source: https://centralaz.edu/divisions-programs/skilled-trades-technology/machining-technology-program/]

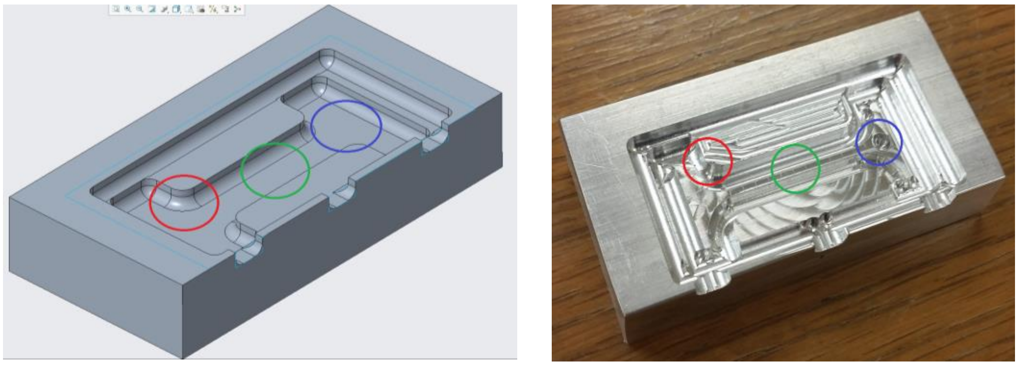

Figure 12, CAD model vs. machined part

While creating this piece, the exact details beyond the initial shape were heavily influenced by the available tools in the laboratory. The tools used for the experiment were a ¼ inch end mill and a ⅛ inch ball mill. The end mill was used for roughing and the ball mill was used for re-roughing and finishing. One of the design constraints stated that interior corners needed to have a radius greater than 0.0625 inches. As such the round size of the corners were increased, decreasing the sharpness of our block I. Another constraint required our design to have at least one curved surface. Therefore, during the design of a Block I, the corners were curved. These restrictions were imposed in order to analyze the accuracy of the process concerning the former hitches.

There appeared three main differences between the CAD design and the final machined part when it was created. The bottom surface was not flat and smooth enough as the CAD model, this can be observed in Figure 12, blue circle. The heights of those two inside parts are not the same, these were supposed to be the same in the design model. The reason of uneven bottom surface is that the roughing step was not finished. The depth of roughing should be deeper, green circle in Figure 12. As for the height difference, only one of the inside part got roughing step done. There is no mark of ball mill on the higher surface. Similarly there was an error in machining that led to corner defects on the interior, which can be noticed in the red circle of Figure 12. To eliminate the differences, the space for roughing might be bigger in the CAD design. And the corner radius needed to be optimized.

The two primary methods that could be used to reduce machining time on this part in particular is to either increase the volume that could be removed with the larger bit, or decrease the volume needed to be removed overall. In order to reduce the machining time by making more of the volume accessible with the larger bit, the stem, and upper and lower features of the shape could have been designed with a greater width. Similarly, reducing the depth of the shape's features could have reduced the overall volume of removal. Less variation of depth leads to a shorter machining time.

In conclusion, the capabilities of the machine greatly impact the range of design possibility. This is something that always has to be taken into consideration in the design process. If the design is rough, there are lots of unforeseen problems that can arise when trying to complete the manufacturing process. Hence it is important to know all the limitations of the machines available for this process.

3.3. Injection Molding

Injection molding technique consists on a manufacturing process for producing parts by injecting melted material into a mold at a certain pressure and temperature. These two parameters are established ahead by the manufacturer. It is an effective method for manufacturing plastic parts for the device in large amounts. For the purpose of using this procedure for creating the product, some testing pieces were built to analyze and evaluate the efficiency of the procedure.

Figure 13, Mini-Jector Injection Molding Machine used

During the injection molding process, solid resin is fed into the hopper and melted in the plasticizing or injection unit of the injection-molding machine. This melt is then forced from the injection unit into the closed injection mold. While the melt in the mold cools into a solid plastic part, the plasticizing unit melts resin for use in the next part. The final part is then ejected from the mold. Figure 14 shows a diagram of the injection-molding machine next to the actual machine.

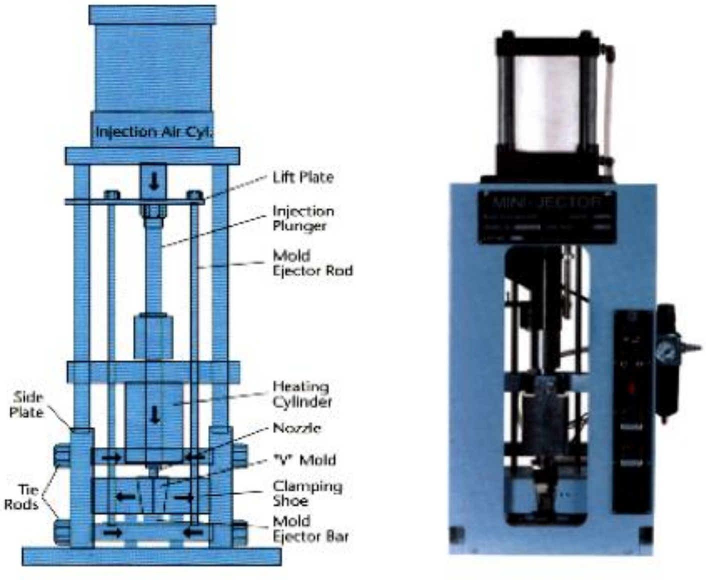

Figure 14, vertical injection molding machine with plunger

One piece selected to injection mold was the close replica of the I Block used for testing the machining procedure in the previous point. The small aluminum ingot was machined with a CNC and then injection molded with the Mini-Jector pictured in Figure 13. The Mini-Jector machine was also tested by injection molding a large spiral mold using varying temperatures and pressures, which will be explained in the succeeding paragraphs. In order to forecast the result of the procedure, an Autodesk software called Moldflow was run predicting the behavior of the technique by making a deep analysis. The performance of this analysis covers several points of the procedure as filling, cooling, flowing, warping, running balancing, best gate location and molding window of the injection molding process.

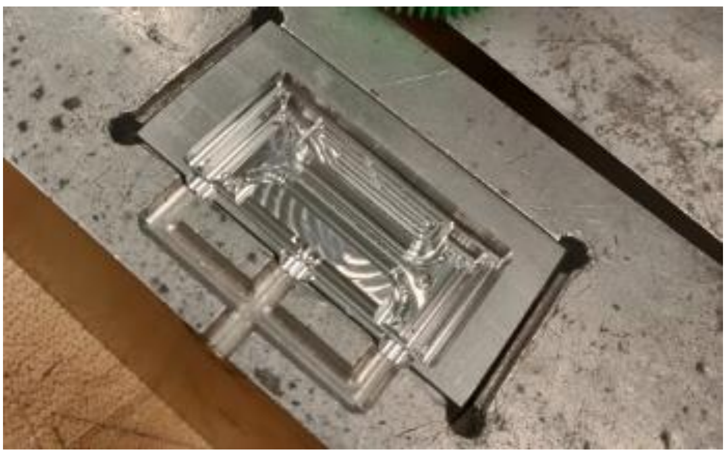

Figure 15, aluminum mold with sprue and runner

Figure 16, injection molded plastic part

After performing the Moldflow fill analysis, two primary defects were predicted to form, that of weld lines and air traps. Weld lines form when a molten plastic flow encounters an already solidified body of plastic, thus forming a weak joint, as the plastic polymer chains do not homogeneously mingle across the boundary. These boundaries mark the edges of where two flowing bodies meet, and these boundaries are points of weakness. As the tested part was continuous, but had multiple injection sites, weld lines were predicted to form between the different injection flows, this can be observed in Figure 17. However, weld lines were observed as barely seen circled below in Figure 18. In order to reduce this behavior, it is advisable to reduce the magnitude of the thickness changes of the part. This should be done to allow for more uniform flow, or simply using fewer gates to create fewer flow fronts.

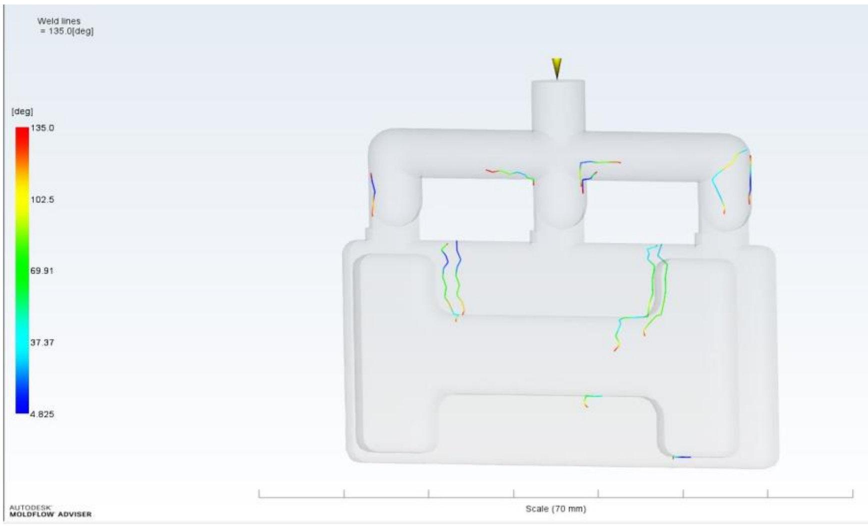

Figure 17, weld lines prediction

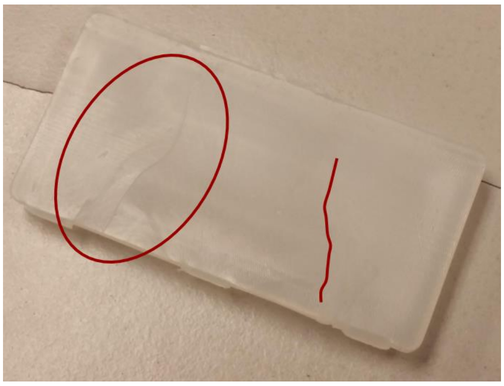

Figure 18, observed weld lines

Similarly, Moldflow predicted a large number of spots for potential air pocket formation due to the curvature of the part and indentation far apart from the parting line, which is shown in Figure 19. These defects would appear as external holes or blemishes on the surface, taking away from the appearance and creating points of weakness. These defects were however not visible on the final surface. To ideally reduce the potential number of air pocket formation points it would be advisable to decrease the amount of indentation depth and sharp curvature on the part. Likewise, a parting line more centered depth wise, longer air vents, or a higher injection pressure would better allow the mold to fill and displace the air.

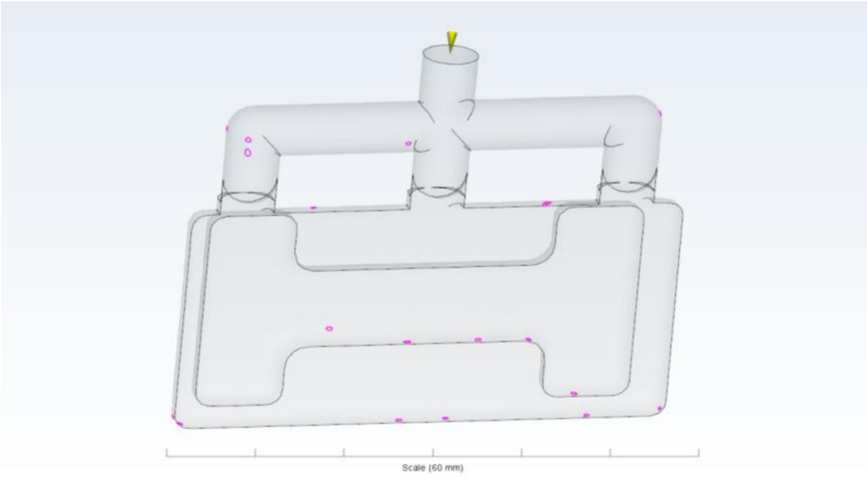

Figure 19, air pocket prediction

There was one defect that was evident that Moldflow did not, and could not predict. As Moldflow only looks at the filling of the part, it could not predict the slight plastic lip formed on the final part. This additional defect is likely due to the overfilling of the mold at high pressure, causing some plastic to force its way out along the edges. This could be solved by a better-secured mold, or by limiting the injection volume as to not overfill the mold.

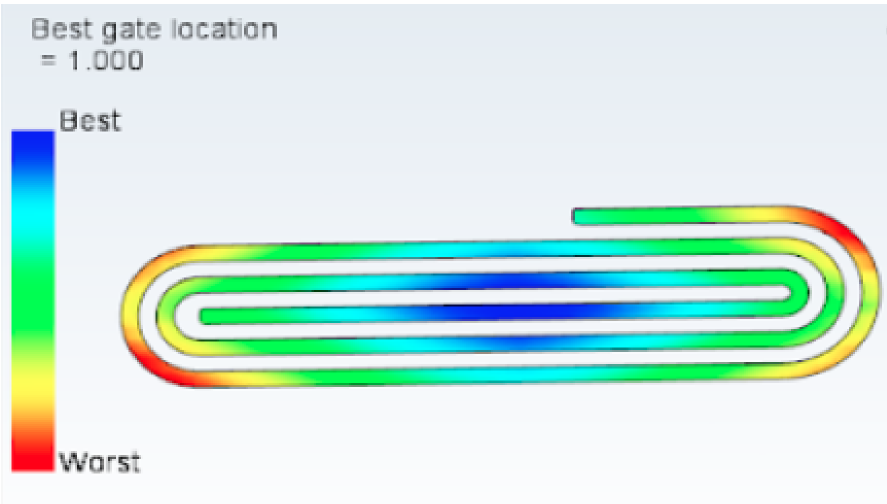

Figure 20, spiral CAD model

Figure 21, spiral mold injected

Consequently, several tests were practiced while varying two different parameters, pressure and temperature. The goal of this process was to evaluate the accuracy of the injected flow distance predicted according to both parameters to observe the technique´s development, as shown in Figure 21. These trials were performed with the spiral mold, which can be observed in Figure 20, making the measurement simpler. In the following graphs it is registered the experimental flow distance travelled depending on the values of both parameters.

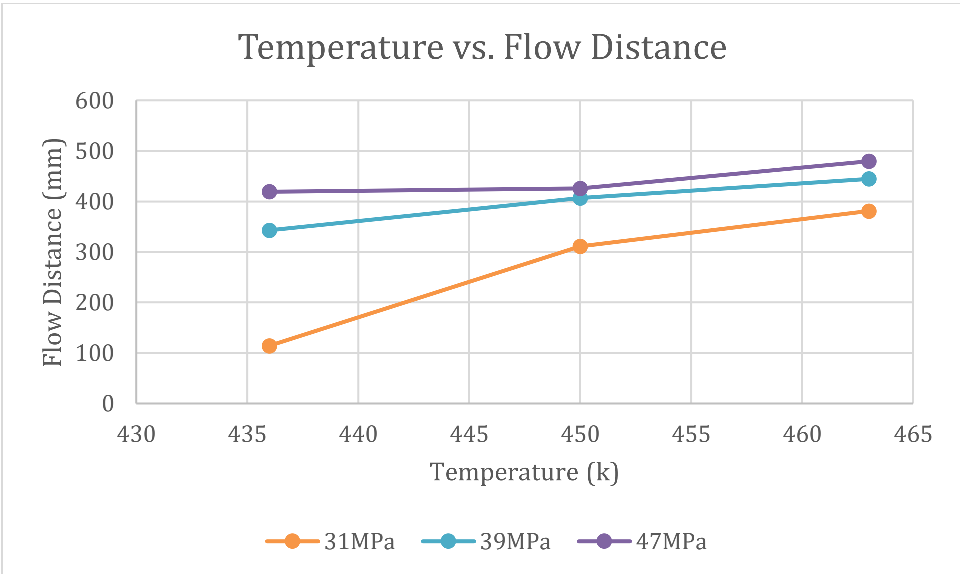

Figure 22, plot of Temperature vs. Flow Distance

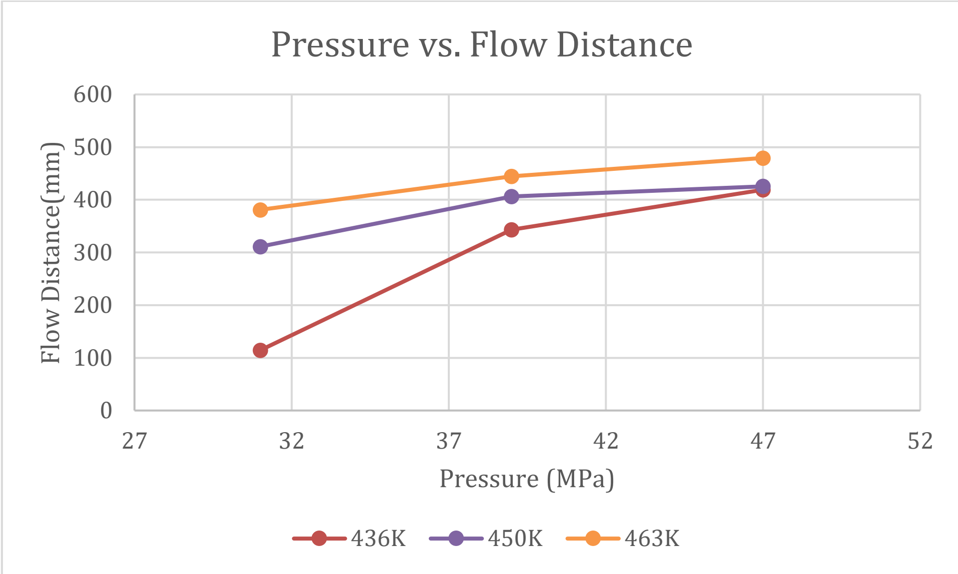

Figure 23, plot of Pressure vs. Flow Distance

As it can be noticed in the figures shown above, the varying pressure over the given range had a greater effect on flow distance. To compare the pressure and temperature effects on flow distance, the flow distance change rate is calculated for each condition.

When temperature or pressure is changed, the flow distance changes as well. Based on the plot of pressure vs. flow distance, the average initial flow distance is 0.2921m and the final flow distance is 0.4349m. The flow distance change rate is 1.03612m/MPa. Based on the plot of temperature vs. flow distance, the average initial flow distance is about 0.2688m and the final flow distance is 0.4413m. The flow distance change rate is 0.116613m/ºC.

Since the value of 1.03612m/MPa is bigger than 0.116613m/ºC, the varying pressure over the given measurement range had a greater effect on flow distance.

To compare the actual injection molded flow lengths, shown in Figures 22 and 23, with Moldflow predictions, the high confidence of fill lengths is compared to the total experimental lengths. The percent difference of each condition are listed below:

	436K	450K	463K
31 MPa	-42.13244151%	-42.14205181%	-58.93615897%
39 MPa	-37.44993575%	-53.67211986%	-83.65616564%

47 MPa	-50.62745399%	-75.62779059%	-40.85715808%

Table 2, percent difference of High Confidence of Fill Lengths and the experimental measurements

Based on the discrepancies between theoretical predictions and experimental outcomes, the pressure and temperature seems more accurate at predicting flow lengths. The main reason of this conclusion is that high confidences of fill lengths predictions are so conservative that leaves a large margin of error of distance covered that will be filled for sure. This can be noticed by the large values of percentage of difference obtained in Table 2. Moreover, the percent difference is negative due to the fact that the difference in length between the experimental values and the prediction is negative, since this conservative method always expects less to be filled than the reality.

However, the values over a 50% of difference in Table 2 are due to experimental failures in laboratory, which will be considered out layers of the experiment.

To conclude, the mold is not always perfect, as the walls may not have been machined properly, leaving small gaps for leakage of molten plastic of the pressure is adequate. This makes finding the perfect pressure more important, as a low pressure denies a complete part, while an excessively high pressure causes leakage.

While doing the experiment the Autodesk Moldflow Advisor analysis indicated that the edge was one of the worst areas to fill the mold, and as a consequence, the mold was never filled completely. Based on the graphs, the effect of pressure on the distance of fill decreases with the increase in temperature.

3.4. Laser cutting

Laser cutting is a manufacturing technology that uses a laser to cut materials creating flat pieces, and is typically used for industrial applications. Laser cutting works by directing the output of a high-power laser most commonly through optics. The CNC are used to direct the material or the laser beam generated. A commercial laser for cutting materials involves a motion control system to follow a CNC or G-code of the pattern to be cut into the material. The focused laser beam is directed at the material, which then either melts, burns, vaporizes away, or is blown away by a jet of gas, leaving an edge with a high-quality surface finish.

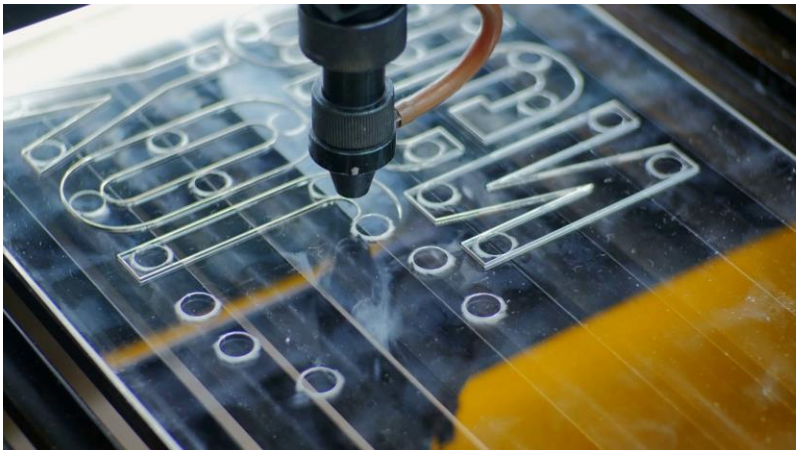

Figure 24, laser cutter [Source: https://www.videoblocks.com/video/laser-cutting-machine-at-work-acrylic-plastic-cutting-close-up-svmcm4h5gizzkc4gr*]*

Industrial laser cutters are used to cut flat-sheet material as well as structural materials. The main material used for this method was acrylic boards, which is known for being rigid, having excellent optical clarity and good impact strength. These pieces are cut by vaporizing the solid material. Consequently, laser cutting turned out to be a really effective method for producing pieces that required high accuracy. Therefore, this method was selected for producing the gears for the product likewise the elements that needed to be transparent.

4. Objectives

4.1. Problem Statement and Market Need

Taking into account the fact that this product will be created to avoid the use of the hands for pulling swinging doors from the inside, some of the purposes that encouraged this project are:

- Helping people who are not able to use their hands to open the door, for instance:

  I. Full hands; people who are carrying things or using their hands for other purposes as shown in the following figure.

Figure 25 [Source: https://www.gettyimages.es/detail/foto/mother-carrying-her-baby-and-a-grocery-bag-imagen-libre-de-derechos/481675222]

II. Disabled people; one armed people or people with any kind of paralysis in the upper extremities.

III. Recently washed hands; people who has just washed their hands and do not want to touch the door handle with their hands wet and clean in a public space.

- Avoiding the spread of infections or disease transmission in common spaces such as hospitals, restaurants or public bathrooms. This product could prevent many diseases transmissions by the use of the footwear to operate the device.

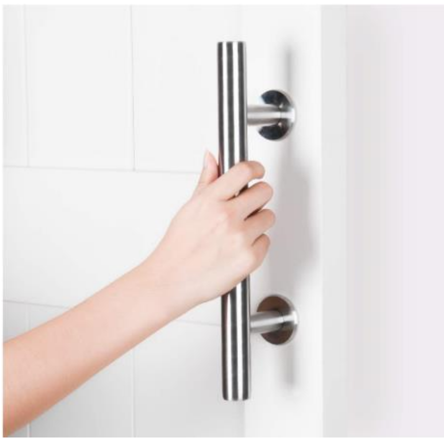

Figure 26 [Source: https://www.amazon.com/, VRSS 2Pcs 200mm Long Stainless Steel Pull Door Handle Plate Durable and Lightweight]

4.2. Project Goals

The main goal of this project is to create a hands free operation device that opens the doors completely. It must be fully made of mechanisms, without any kind of power supply. However, there exist some challenges that must be overcome in order to make the product work successfully. These objectives are:

- The introduction of a unique time delay system for the operator safety. This is a challenging and essential requirement. Once the operator has pressed the pedal, the device must wait until the person step back before pushing the door. This will avoid hurting the user. For this goal, it was initially designed the gear system mechanism, which will be explained forward with in prototype 1, Figure 30. It was also built a prototype of this mechanism out of cardboard, which is shown in Figure 27.

Figure 27, time-delay system prototype

- Figuring out the best way of providing the impulse to the door was one of the central ambitions of the product. For the first prototype, it was decided to use a lever arm launched by the force caused by several compressed springs to open the door. Nevertheless, it turned out to be quite difficult to make the calculations to obtain the required force and also to find the suitable springs for the device. Therefore, for the second prototype, it was introduced some rubber covered wheels turned by a torque to replace the lever arm and open the door. At the end, it was used the simpler method that produced the best motion of the door, which resulted to be the semi-circular rubber covered wheel.

- Creating an installable unit, which does not need external connections that damage the door, was also crucial. The primary idea was to design the product all contained inside a shell. It will have adaptable supports for attaching the device to the door with pressure, instead of using screws that hole and ruin the door.

5. Design development

5.1. Ideation

During the ideation process, different product ideas were considered for overcoming some real difficulties of the human being daily life. Some of these concepts were an horizontal motion window-cleaning machine, an electric three-wheeled tilting vehicle and a mechanical door opener. Finally, the door opener device was chosen to be the developed product taking into account how advantageous and handy it could be for our society. The subsequent paragraphs explain a brief summary of the SWOT Analysis made for the objective project.

The main strengths that this product presents are that it is fully mechanical, there is no external power source needed; its unique time delay for the operator safety; and the installable unit, external connections are not required. In addition, it has a low running cost and a low carbon footprint. On the other hand, the primary weaknesses of the device are the large amount of force needed for thicker fire doors; also, that it can not be used in conjunction with a door-latch or knobs; and the fact that it is not compatible with spring closing and other door dampers.

Differently, Step-n-Pull style doors, with door-bottom foot grip, require awkward maneuvering to use and pass trough. The design of this product is an opportunity for people of varying physical disabilities, as it only needs weight to activate. Besides, it works in a blackout, which is a good point for emergencies and it is a cheaper intermediate system compared to fully automatic pneumatic systems. However, there exist some threats in the creation of the design. For instance, finding the optimum angle for placement in order to maximize the conversion of user provided energy to useful mechanical energy. It would also be challenging to introduce an embedded counterweight for resetting the mechanism. Finally, minimizing the product size to decrease the chances of people tripping is a requirement.

In the first sketch, the StopNswing door opener would have a kick plate on top that would depress the lever arm. This curved lever arm would catch a smaller trigger, providing a time delay that allows the user to step back. After the safety delay, the lever arm launched by strong compressed springs would swing down and slam the door open. Figure 28 represents a simple sketch of the mechanism previously explained with its parts.

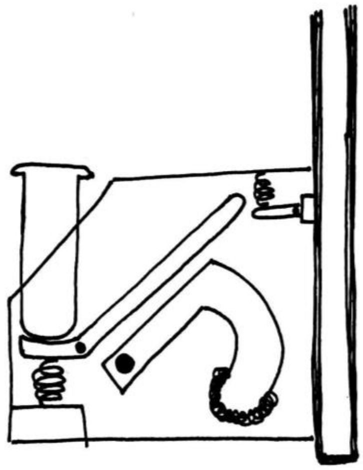

Figure 28, first product sketch

This product will be manufactured in a case, which will contain the whole mechanism in the inside. The product will be ready to be attached to the bottom part of any swinging door to start developing its goal.

5.2. Prototype 1

The first prototype, with the previously explained idea in mind, had a kick plate on top that would depress the lever arm. This curved lever arm would catch a smaller trigger, providing a time delay that allows the user to step back. After the safety delay, the lever arm launched by strong compressed springs would swing down and slam the door open as it was mentioned in the former part. However, the difference between this prototype and the sketch is that it includes a time delay mechanism, which would be included as a part of the gear system shown down below. The time delay system will be detailed in the following paragraphs. The design model can be observed in the consecutive figure.

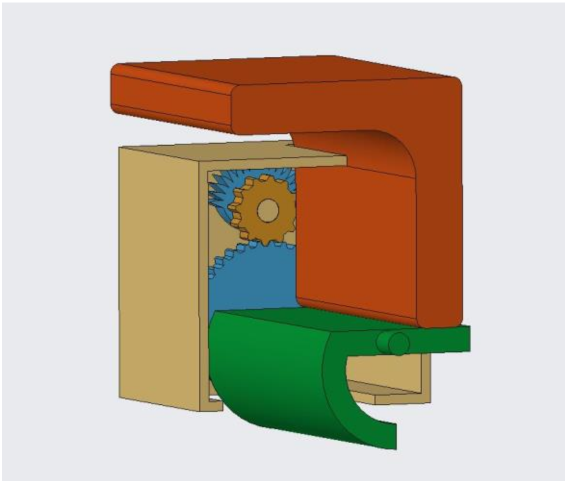

Figure 29, first prototype CAD model

The first safety delay system prototype is also integrated in the same formerly explained design as it was mentioned. It will consist on a mechanism made of different sizes and shapes gears that would hold a trigger for some seconds. This happens when the pedal is pressed making the main and rare gears turn while both get locked by rigid peg. Once the force caused by the springs on the lever arm is big enough, the trigger would release the main gear to deliver the impulse of the arm opening the door. This delay system mechanism is shown in Figure 30.

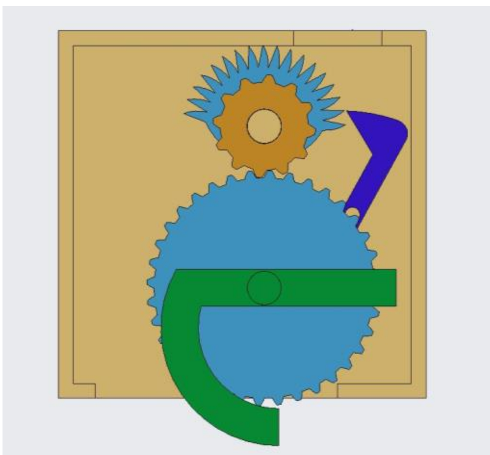

Figure 30, time-delay mechanism

This initial prototype was created using two different manufacturing methods. On one hand the housing, pedal and lever arm was 3D printed in order to test FDM 3D printing method as it was clarified above. The resulting pieces are shown in Figure 10. On the other hand, the time delay mechanism prototype was made out of cardboard due to the fact that it resulted to be really hard to make numbers to create a real prototype. This issue led to the development of a different kind of time delay mechanism, which will be explained in the next parts. This cardboard prototype can be observed in Figure 31.

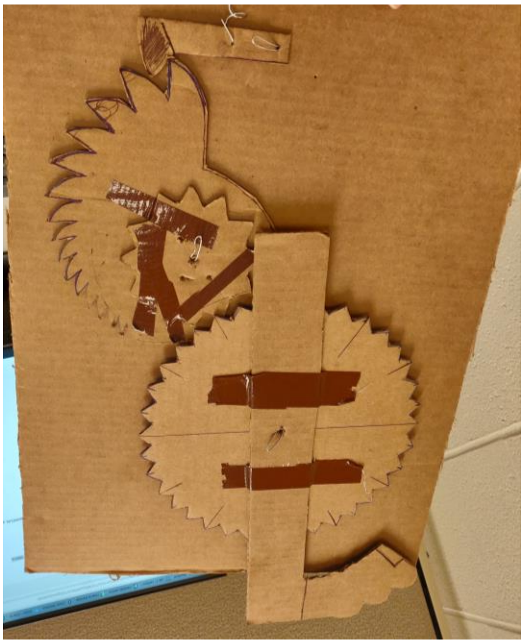

Figure 31, first time delay cardboard model

Even thought this prototype did not result effective, the outcomes were really advantageous. One important asset of this design was that the mechanism to open the door was clarified. Moreover, the compact time-delay mechanism was also decided to be part of the inner gear system. Nevertheless, it was found out to be a virtually impossible to analyze system, which guide the development of the product to the creation of a new prototype, prototype 2.

5.3. Prototype 2

This second prototype resulted from the feedback of the first one; its computer-aided design can be observed in Figure 32. It has a pedal, light green item that ends with a fitting system, rack and pinion. When force is applied to this pedal, it makes a gear, orange item, rotate and keep a torsional spring placed in its shaft and compressed. Several ratchets, dark green items, attached to a semi-circular wheel, blue item, are responsible for this locking mechanism. The trigger, part that will be connected to the time-delay system, will suddenly release the rubber covered semi-circular wheel. It will provide the impulse to the door in order to open it.

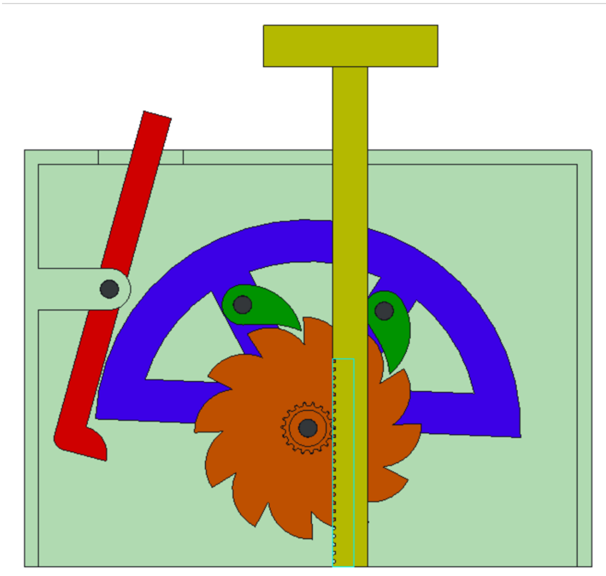

Figure 32, second prototype CAD model

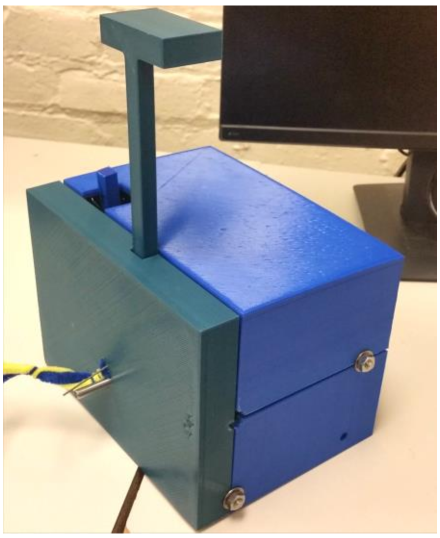

Figure 33, 3D printed second prototype

This prototype was created by 3D printing the whole design as it is shown in Figure 33. However, there were several parts that failed during the 3D printing process due to wrong placement or staircasing effect. Consequently, in order to avoid this failure and taking into account the amount of material and time that had already been lost, it was decided that those pieces were printed piecemeal. For instance, in Figure 33, the housing of the product can be noticed to be an assembly of three different parts. All the different parts were assembled using screws and nuts.

After the creation of the full design and analyzing the result, some successful changes were noticed. Using the semi-circular rubber covered wheel design as the element providing the impulse turned out to be a really effective adjustment. The reason for the previous fact was that this element resulted much easier to analyze and to make calculations with. Therefore, the impulse provided could be more accurate. On the other hand, even though this prototype did not include the time delay mechanism, an innovative trigger for releasing the movement was included in the design. Moreover, this trigger was drawn up with a setting for the introduction of the missing system. Besides, an improved plunger attached to the pedal part was also implemented. Last but not least, the ratchet design for compressing the torsional spring was an adequate development bearing in mind how well did this mechanism operate.

Furthermore, there emerged some setbacks while the creation of this prototype. On one side, the fit between the rack and pinion system arose to be defective. The large force that needed to be applied for pushing the pedal was the main cause of this problem. The initial depth and width of the teeth was not enough, hence both had to be increased. In addition, the torsional spring placement was not adequate. It enabled the movement of this item, which could not happen for a good compression. Accordingly, this setting had to be designed in a safer way. Also, the shell assembly improvement was a fundamental change to secure the operation as it is explained in the former paragraph. Finally, the most important advance was the implementation of the upgraded time delay mechanism.

To sum up, some of the required adjustments that needed to be done for the final prototype were redesigning and reprinting an improved rack and pinion system; enhancing the configuration of the torsional spring; creating a final housing out of clear acrylic to watch the intern mechanism; incorporating the time delay system mechanism and bettering the ribs to keep the rack in place.

5.4. Design of Experiments (DOE)

Design of experiments is a systematic method to determine the relationship between factors affecting a process and the output of that process. That is to say the method used to find the cause and effect relationships for different variables.

It was decided to make a design of experiment analysis with the part of the prototype that would create the time delay and to both manufacture and optimize it. This part was chosen as it both still needed to be designed and had the greatest number of meaningful variables that could be manipulated. It could affect the resulting time delay, and most important, it is responsible for the primary function of the product, providing the impulse to the door at the right time. A new time delay system mechanism was designed after the creation of the previous prototype and taking into account its outcomes. This fresh model can be observed in Figure 34 and will be explained later. The test was designed to vary some properties of the tabs to optimize the last time delay mechanism. A series of resistive tabs were applied to create a slowing, gravity powered, time delay. Three variables were chosen including the shear number of tabs, the respective durometer hardness, and length of the exposed tabs. These variables in particular were chosen, as it was not certain how the tabs in particular would interact with the rest of the moving system, and most other variables had predictable effects. Thus a testing setup was conceived in order to allow for manipulation of the main variables.

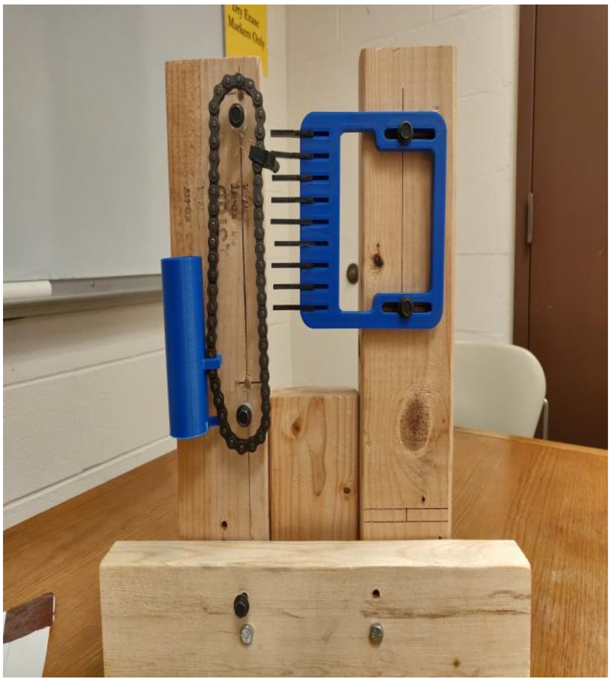

Figure 34, second time delay mechanism prototype

This time delay prototype was primarily accomplished by the printing of an adjustable rack to house the rubber strips, which is the blue item placed on the right side of Figure 34. The rack was designed to allow for up to a maximum of nine rubber tabs that could be swapped out and adjusted in length. As to the ranges, nine tabs were decided as the maximum, as it was the maximum number of tabs possible for the chain length while still maintaining adequate flexing distance in between tabs. On the other hand, the minimum was of four tabs to ensure there was in fact a delay. The exposed length of rubber's maximum value was determined by the space constraints of the prototype, as there was at most 0.0254m (1 inch) of clearance for tabs with 0.00953m (⅜ in) kept in the rack for support, and a minimum of 0.00953m (⅜ in) required to engage with the peg. The range of stiffness of the rubber tabs was chosen with a maximum of 95A and 40A durometer hardness. This was due to in part the selection available from McMaster Carr and avoiding great extremes due to ensure that the rubber was well within a range of resisting but not completely inhibiting the motion.

The resulting data that was collected from the experiment was the amount of time, in seconds, which it took the system to reset the peg to its apex position, after releasing at the start of the chain straightaway. This was measured using a stopwatch beginning from the release of the system until the peg reached a specified point above the tabs.

Test results:

Main:	E1	E2	E3	E12	E13	E23	E123	System Yave	Sys Std Dev.	Ave. Var.
	-0.014	-0.008	0.152	-0.045	-0.087	0.123	0.03	1.2085	0.14202113	0.02017
Noise:	E1	E2	E3	E12	E13	E23	E123		Sys 2 σ	
	-0.00721	0.006875	0.002465	-0.00724	-0.01273	0.01425	-0.01228		0.28404225	

Table 3, test results and calculations

Based on the result, main effects for three variables are:

Rank	Normsinv x-pos	Ranked Main Effects
1	-1.47	-0.087
2	-0.79	-0.045
3	-0.37	-0.014
4	0.00	-0.008
5	0.37	0.03
6	0.79	0.123
7	1.47	0.152

Table 4, ranked main effects

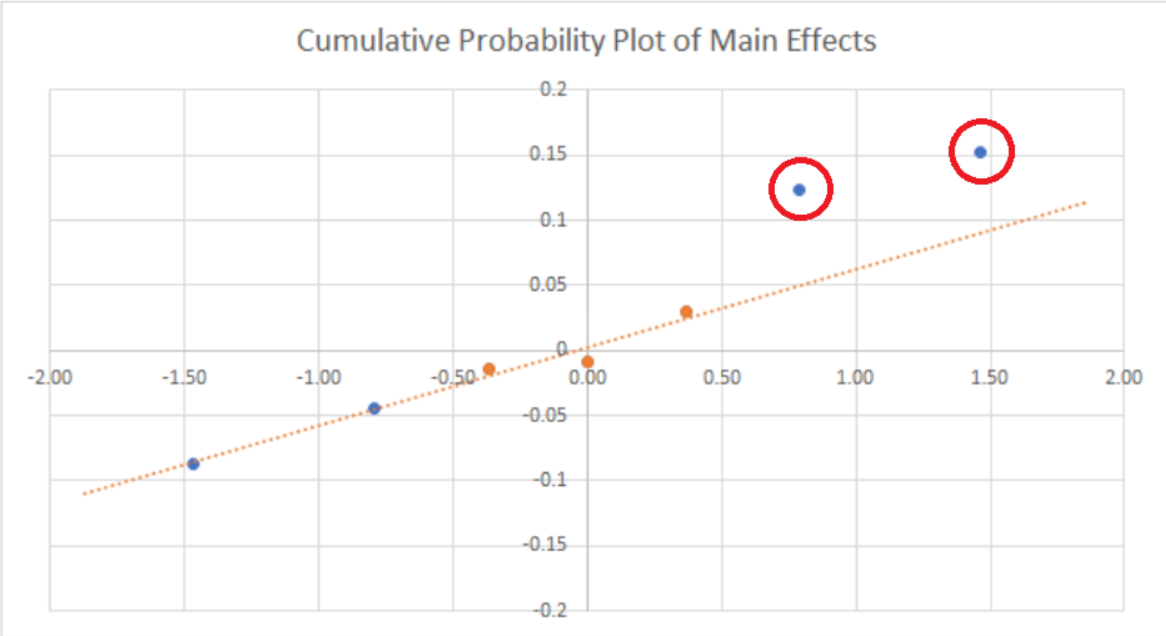

Figure 35, cumulative probability plot of main effects

Calculation results did not show any significant value for the test, taking into account the fact that no effect value was larger than 2-sigma value. However, based on the graphic analysis, Figure 35, the significant values of main effects are 0.123 and 0.152, corresponding to E3 and E23.

So the reduced characteristic equation to predict output value is:

$$y=1.2085+ 0.076x3+0.0615x2*x3.$$

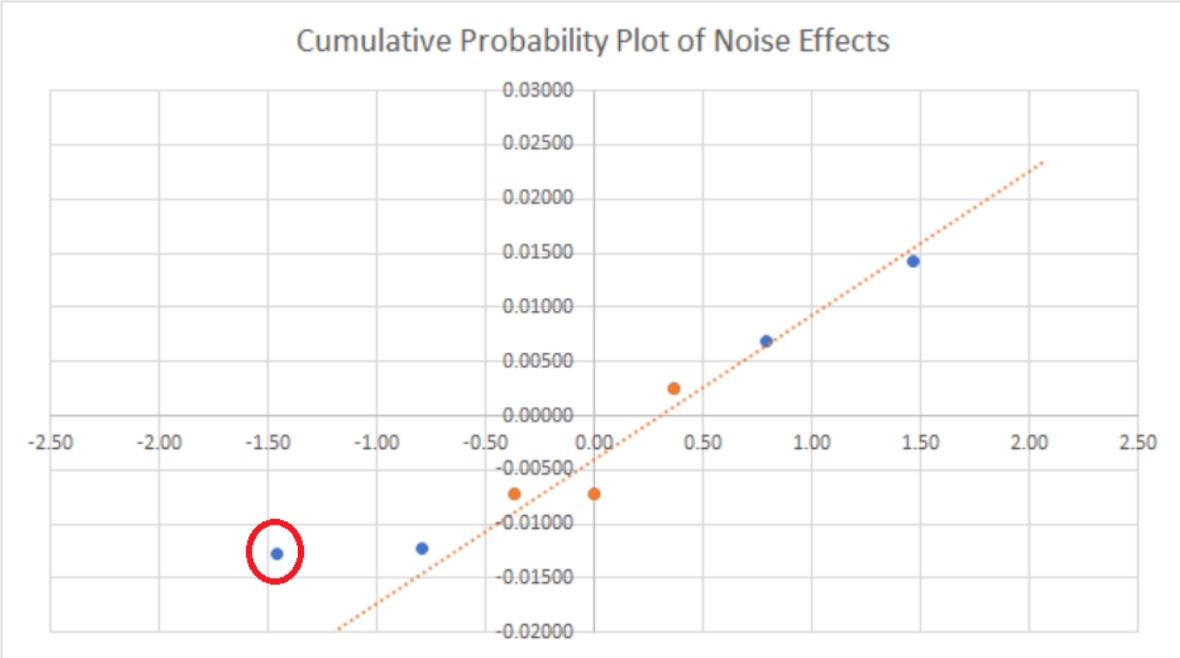

Figure 36, cumulative probability plot of noise effect

Similar to main effects analysis, the noise plot of Figure 36 shows the noise effects for the test. Based on the graph, there is one significant value corresponding to E13 with -0.0273 and the variance equation to predict variance is thus

$$y=0.02017- 0.01365*x1*x3$$

Thus to minimize variance x1*x3 should be maximized, and to maximize the delay time, x3 and x3*x2 should be maximized. This is best accomplished by thus setting the maximum values for all three control variables, being length, number, and hardness. This should result in a delay time of 1.346 seconds with a variance of 0.00652 seconds. With the given materials it is the best course to use the remaining rubber to create more tabs beyond the nine used in testing.

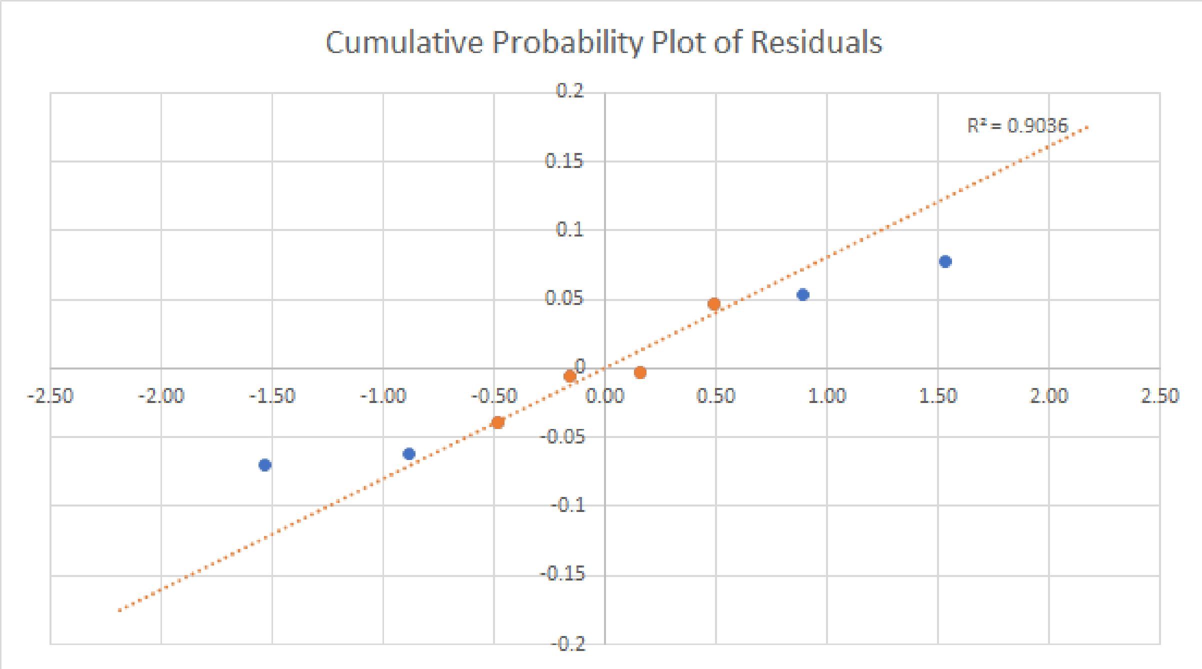

Figure 37, cumulative probability plot of residuals

As above graph shows, result points form roughly a straight line and this line of best fit had an R2 value close to 1 (>0.90). These analyses mean that the constructed model is good and the test results are valid.

In light of the results of the DOE analysis and the relatively high variance for such a small data range, the DOE was far from perfect. In light of the relatively small magnitude of the effects and the great variance observed, the system beyond just the tabs needs far more optimization and tuning. Similarly the maximum predicted delay is quite a bit smaller than the predicted amount. Although the system is still usable, it is undesirable. Therefore, testing and design of alternative delay methods should be researched and attempted posthaste. In regards to the DOE methods, the large variance is testament to the lack of precision of either the measuring of the output time or the overall setup of the variables, which could have been more finely controlled and replicated. To increase accuracy, better-defined marks as to starting and stopping locations, better alignment of the two primary delay components, and simply having multiple timers per run could have significantly improved the quality of the DOE data.

Overall, the optimization of the variables under the current system only marginally increases the delay time by an imperceptible 0.1s, and thus could be reasonably concluded to have negligible effect in improving the final product. This DOE knowledge can in fact be used to optimize the current setup, but another DOE should be performed with a different orientation of tabs for hopefully a better delay configuration and better-constrained measurements and setup. Overall these DOE results may lead to the scraping of the current tab-slowed delay design, and will negatively impact the expected result, as a minimum of 2.5s delay period is desired for the full functionality of the product.

5.5. Final Prototype

This last prototype, which can be observed in the figure showed below, operates likewise the previous prototype but with some decisive upgrades detailed in the following paragraphs. While the pedal is pressed by the users foot, the rack and pinion system turns making the sprocket gear rotate lifting the semi-circular wheel to the top part as shown in the picture. Once the wheel reaches the trigger and the torsional spring, which is placed in the pinion gear´s shaft, is fully compressed, the optimized time delay system starts the countdown. After the desired amount of time has been finished, the locking trigger is released and the torsional spring stored energy is discharged on the wheels shaft. In this way the semi-circular rubber covered wheel is launched to the floor powering the door opening process.

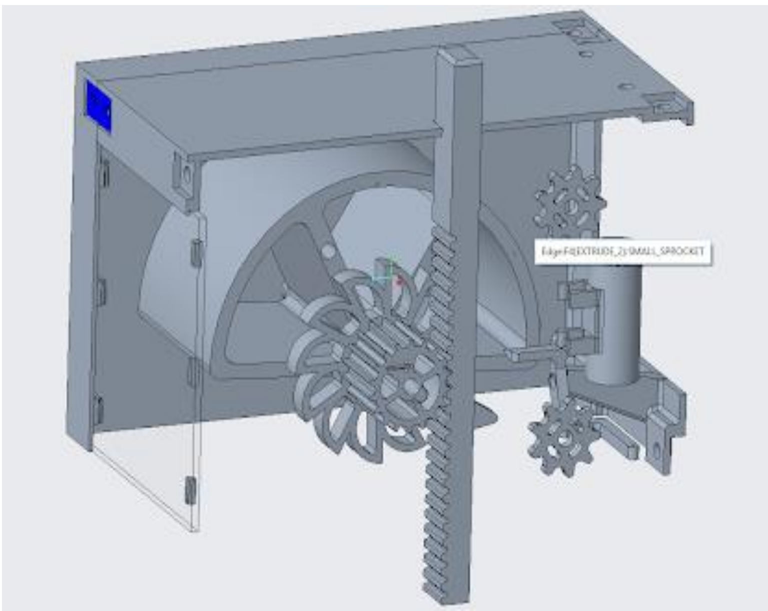

Figure 38, final prototype CAD model

Figure 39, final real prototype

For the final prototype, several changes were done in order to optimize the previous model and create a successful product. As it can be observed in Figure 39, the housing architecture was improved by dividing the design in 4 pieces. The top cover, left side cover and right side cover were 3D printed in red and white color, which is shown in Figure 39. The front part of the housing was made out of clear acrylic, this idea was thought only for the prototype model in order to allow the user to see through the case and observe the intern mechanism of the device without having to dissemble the whole product. This acrylic board was designed with some little holes for a better adjustment, which are shown in Figure 41, and laser cut for a smooth finish. These four pieces of shell were assembled with joining plates, bolts and nuts, which can be noticed in blue color in Figure 38. Also, the real 3D printed plates joiners are shown in Figure 40. Moreover, the acrylic board was attached by using snap fits contained in the 3D printed covers, shown in Figure 44, which is the reason of the creation of the little holes in the acrylic item.

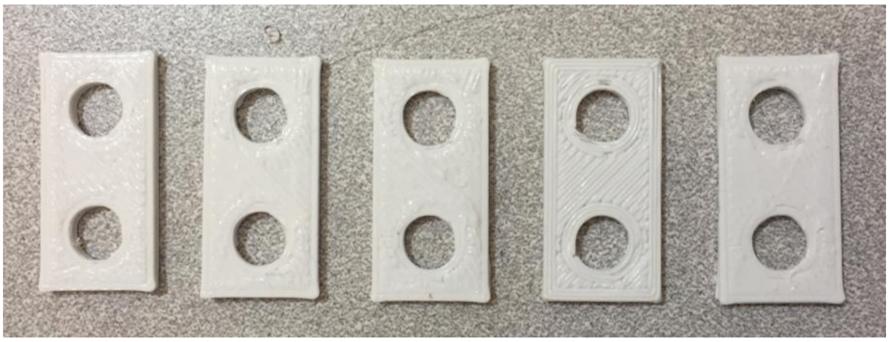

Figure 40, 3D printed plate joiners

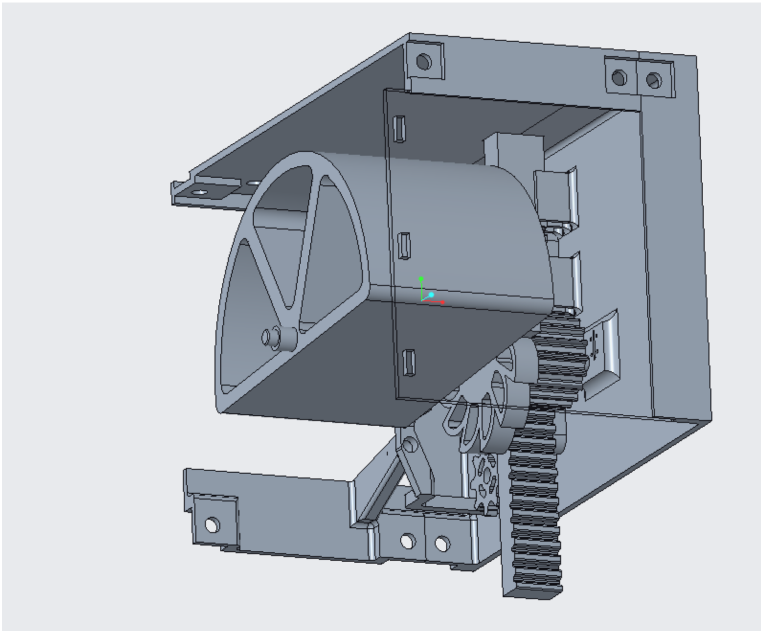

Figure 41, final prototype CAD model - Back View

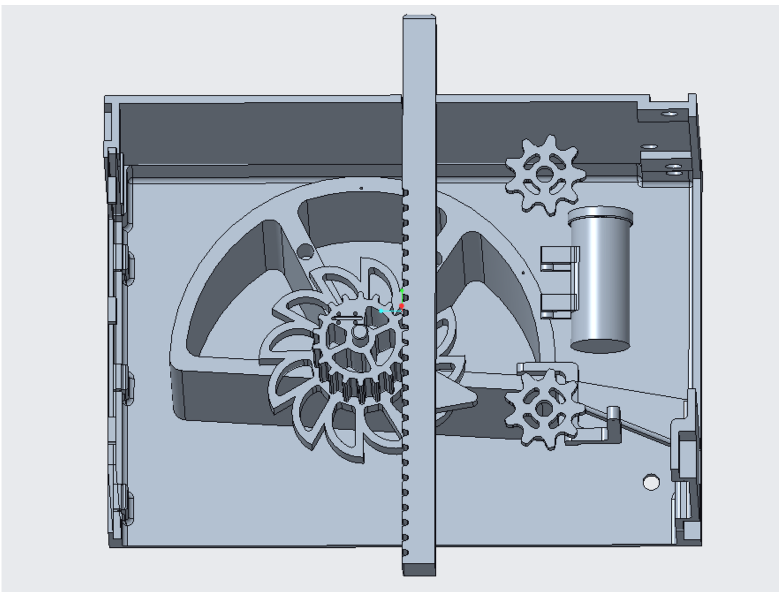

Figure 42, final prototype CAD model - Front View

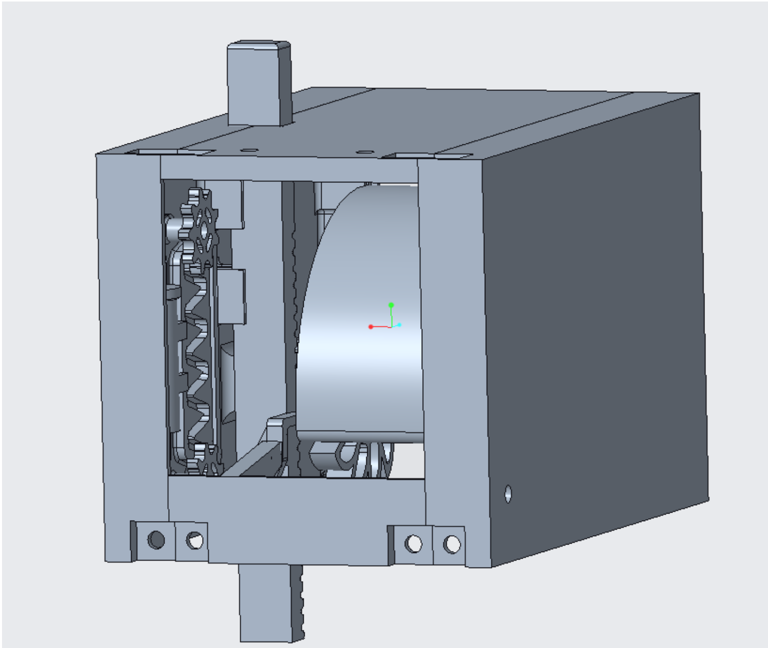

Figure 43, final prototype CAD model contained in the shell

Figure 44, 3D printed cover with snap fits on the side

On the other side, the torsional spring placement and configuration was improved. This item was properly fixed to the shell for the last prototype, making the energy storage better. The torsional spring, Figure 45, worked by twisting itself due to the force applied to the pedal. This mechanism operates in a way that when the rack of the pedal is pushed by the user it makes the pinion rotate because of the fit between both, therefore it makes the ratchet gear turn, compressing the torsional spring. Once the torsional spring is fully compressed it stores the energy due to two parcels, which can be observed in Figure 46. These pieces were 3D printed with the CAD model. Afterward, the time delay mechanism system starts doing its function by holding the compressed torsional spring until the time required has been completed. Then it releases the whole system in order to commit its goal, opening the door.

Figure 45, torsional spring used

Figure 46, 3D printed parcel

Likewise, the trigger operation was upgraded for an optimized release of the energy providing a bigger impulse. Last but not last, the rack and pinion system was redesigned and reprinted making both teeth deeper and wider in order to enhance the fit between both items. This is an extremely important mechanism in the system that needs to be highly reliable in order to develop the previously explained action with the torsional spring. Moreover, the semicircular wheel was redesigned and reprinted too reducing the amount of material used for this part, making it more light en effective. This former action was executed with several pieces of the prototype, not only with the wheel, in order to lighten the product as much as possible to avoid collateral damages while attaching the product to the door. These progresses can be noticed in the following figures.

Figure 47, rack

Figure 48, pinion and ratchet gear

Figure 49, semicircular wheel

Besides, the time delay mechanism was also implemented in this final prototype. A new model was created due to the counterproductive results obtained with the DOE test while proving the previous time delay system model, shown in Figure 34 and explained in the DOE part. The innovating prototype is shown in the following figures. This new design is based on the previous one; it uses tabs and a chain with a weight on its side, cylinder filled out with coins as seen in Figure 51, to produce the time delay. This cylinder was designed with clips on its wall in order to be attached to the chain without disrupting its motion and operation. However, for this model, a track was implemented as it can be noticed in Figure 53 in order to increase the time of the delay before providing the impulse. A 3D printed clip attached to the chain follows the path improving the delay. Once the path is fully completed, it releases the trigger, which holds the semi-circular wheel, liberating all the stored energy in the torsional spring. Finally, it transforms the stored energy on the required mechanical energy to impulse the door. This lastly explained time delay system prototype did not postpone the operation as much as it was expected, however, the results turned out to be really satisfactory. Therefore, this was the design used for delaying the final prototype.

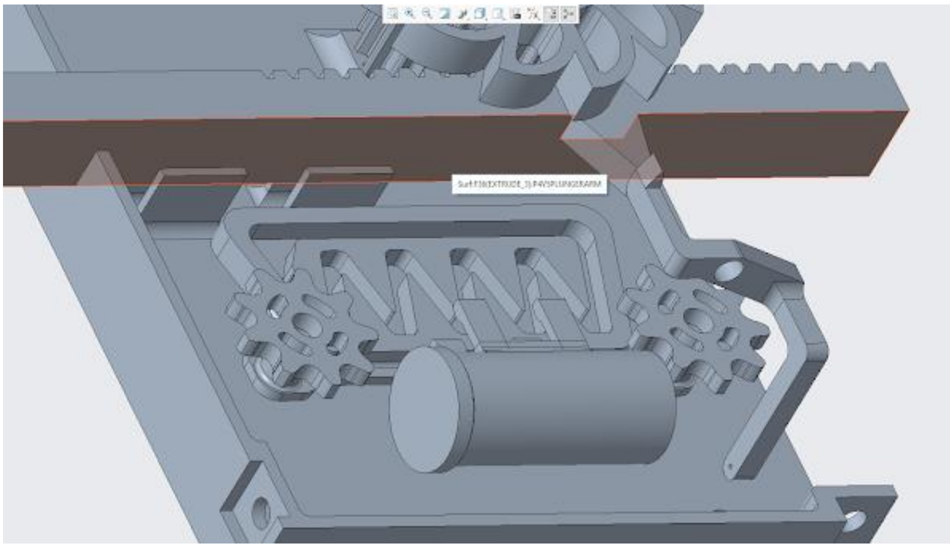

Figure 50, new time delay system CAD model

Figure 51, heavy cylinder

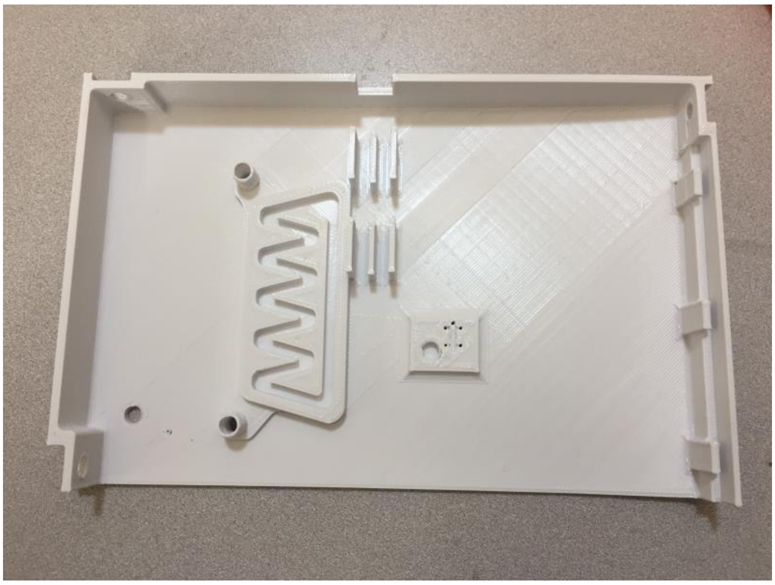

Figure 52, 3D printed right shell

Figure 53, new real time delay system

In order to test the created prototype, a fake door was built up out of wood as it can be noticed in the following figures. The product was attached to this fake door as it is shown in Figure 56. Even though the initial idea was to create an attaching system, which worked with pressure in order to avoid holing the door, it did not turned out at the end. Finally, the device was attached using bolts and nuts to the testing door since there was not enough time to design a completely new attaching system. However, for the commercial product, the goal would be to devise an attaching mechanism, which avoids the previous operation.

Figure 54, built door for testing

Figure 55, device attached to the testing door

Figure 56, product attachment system

Figure 57, user operation

The prototype cost was 26.38€, taking into account the fact that the chain cost 8.79€, the 3D printed material for creating the parts cost 14.07€ and the bolts and springs were 3.52€. Nevertheless, the cost of the chain would decrease when increasing the production. Besides, with higher production capacity, injection-molding parts are much cheaper than 3D printed parts. And finally, instead of using bolts and nuts, more snap-fit designs would be implemented in order to reduce costs.

For the development of the whole study and making several test with different manufacturing processes for the creation of the optimal final product, a budget of 131.91€ was provided. In the following figure it is explained the amount of money spent during the process. For building up all the prototypes, a significant expense was the 3D printing method. This was foreseeable taking into account the fact that almost the entire prototypes were made out of PLA printed material. However, the larger expenditure was making DOE test, which can be explained with the high cost of the parts used for creating the time delay prototype, chain or bolts. Overall, the total sum of money spent was 72.11€, leaving 59.80€ left for prospective changes. All these numbers are shown in the waterfall budget chart in the following figure.

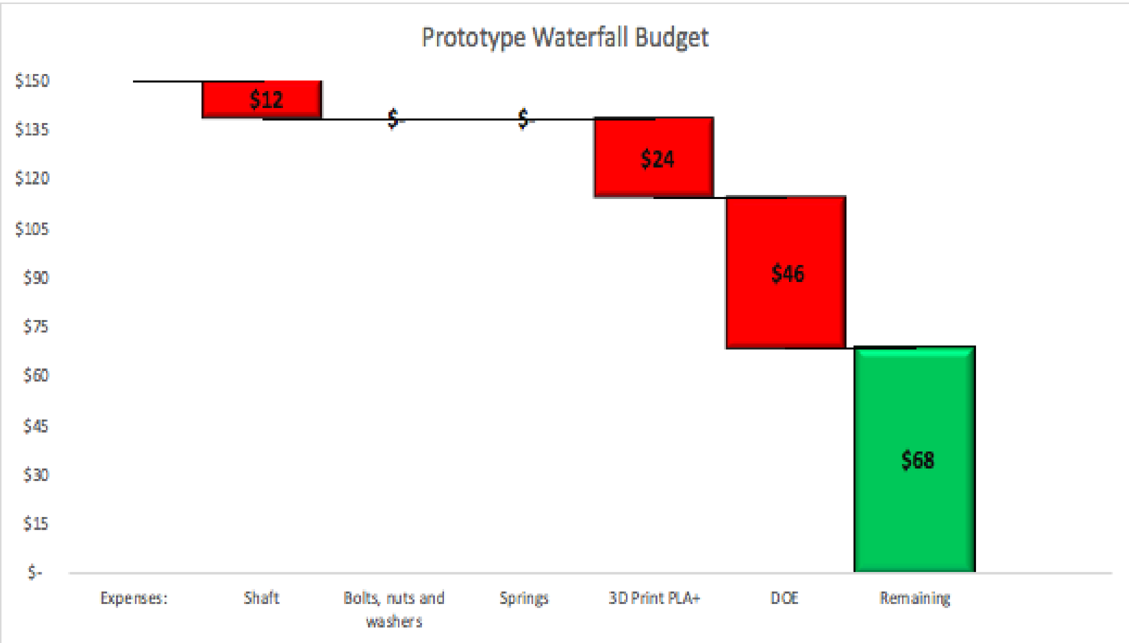

Figure 58, waterfall budget chart

6. Design for Assembly (DFA)

Design for assembly is a process by which products are designed with ease of assembly in mind. If a product contains fewer parts it will take less time to assemble, thereby reducing assembly costs. In addition, if the parts are provided with features, which make it easier to grasp, move, orient and insert them, this will also reduce assembly time and assembly costs. The reduction of the number of parts in an assembly has the added benefit of generally reducing the total cost of parts in the assembly. This is usually where the major cost benefits of the application of design for assembly occur. Taking this information into account, the designed product will be subjected to a DFA analysis, which will be developed later in order to optimize its production and cost of the device.

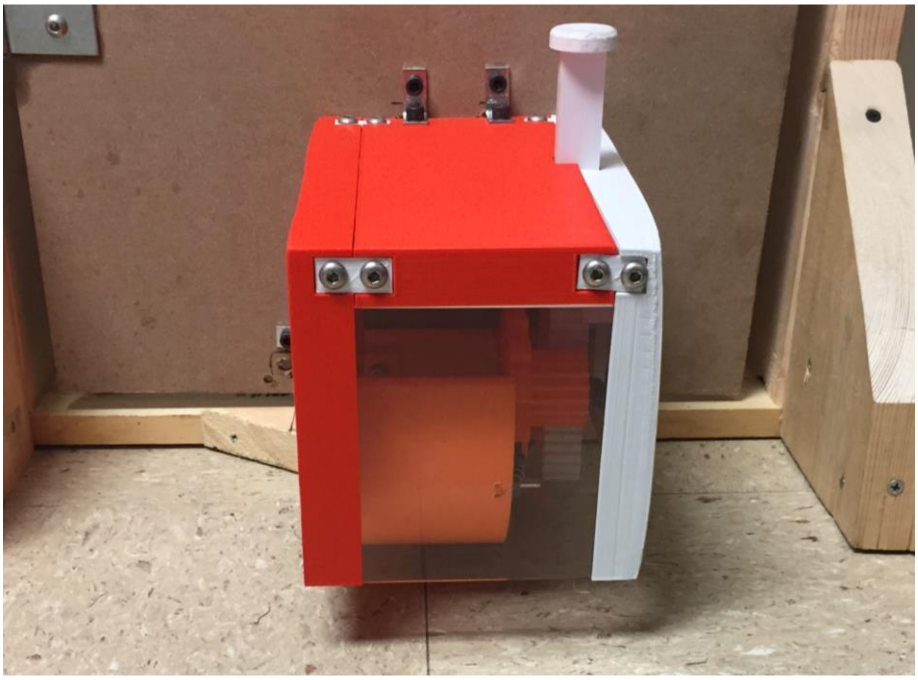

Figure 59, assembled prototype to be optimized

Table of parts of the final prototype:

Part	Amount	Theoretical Minimum	Alpha	Beta	Difficulties
Left Shell	1	Yes	360	360	Large
Right Shell	1	Yes	360	360	Large
Top Shell	1	No	360	360	Large
Rear Beam	1	No	360	360	Hold
Ratchet Gear	1	Yes	360	0	Spring
Pinion Gear	1	Yes	360	0	Align
Parcel	2	Yes	360	0	Align

Half Wheel	1	Yes	360	0	Hole Insertion Tolerance, Spring
Chain	1	Yes	180	0	Slippery, Flexible, Tangle
Sprocket Gears	2	Yes	180	0	Align, Tangle
Diagonal Track	1	No	360	360	Tolerance around track
Coin-Holder	1	Yes	360	360	Fragile, Force
Double-Sided Peg	1	Yes	360	180	Fragile, Force
Parcel Axle	2	No	180	0	Hole insertion, Small
Main Axle	1	Yes	180	0	Large, Aspect Ratio, Press Fit
Trigger Axle	1	No	180	0	Small
Trigger	1	Yes	360	0	Fragile, Sharp
Acrylic Plate	1	No	180	180	Fragile
Joining Plates	6	No	180	180	Hold
Small Bolts	12	No	360	0	Slippery, Small, Hold
Small Nuts	12	No	180	0	Slippery, Small, Hold
Parcel Springs	2	No	360	360	Spring
Main Torsion Spring	1	Yes	360	180	Spring
Trigger Spring	1	Yes	180	0	Spring

Table 5, prototype design for assembly data

Overall the initial design of the final prototype was created with a certain emphasis on ease of assembly and disassembly, but not necessarily a short assembly time. This lead to the creation of an astounding number of parts needed in the final assembly, many of which could be made unnecessary or redundant by design changes.

The first large improvement that could have been actualized was that of the elimination of the used joiner plates to assemble the different shell sections. With an ideal injection molding setup it would have been more ideal to use snap fits along the borders of the shells to join them, or simply make them as part of the same part in the first place. In general, this would reduce the number of parts significantly and drastically reduce assembly time as bolting together parts twelve times is incredibly inefficient.

In the design of the gears used in the prototype some of the components moved together in their function, thus in the final printing the ratchet and pinion gear they were joined into a single part for ease of assembly. This reduces the need of further alignment or other need of affixing that would significantly increase assembly time. This piece can be observed in the following figure.

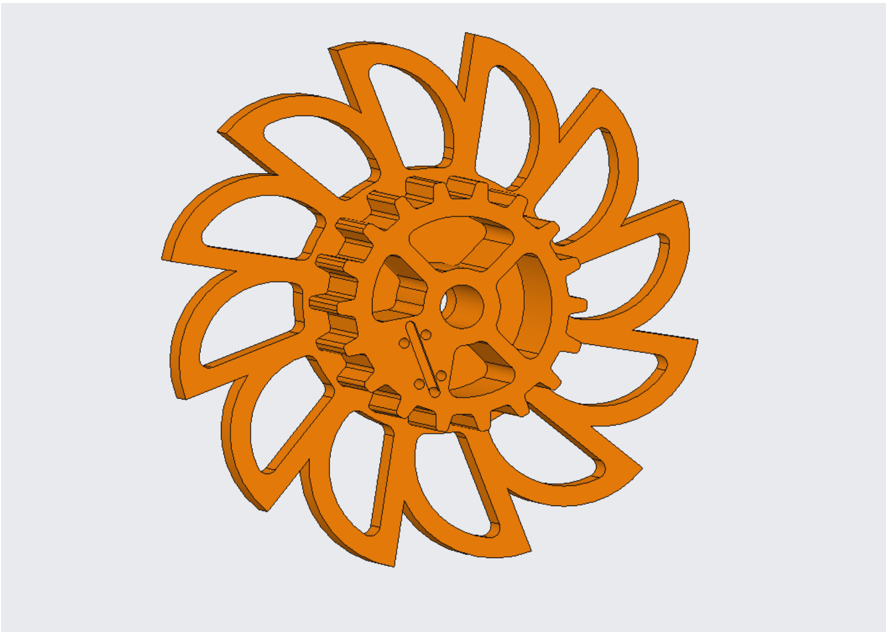

Figure 60, improved joined gear design

In the second prototype iteration there was a lot of difficulty in the mounting and placement of the parcel and trigger axles on their parent parts. These axles move and work with their parent components, thus a possible design optimization would be to construct plastic axle extensions as a part of those parent components such as the shells and half wheel.

The final major possible improvement was in the time delay assembly where the diagonal track and the right shell were to be permanently affixed together in order to maintain alignment of the peg in the track as well as with the plunger that actuated it. Thus the right shell was combined with the track in an assembly for printing.

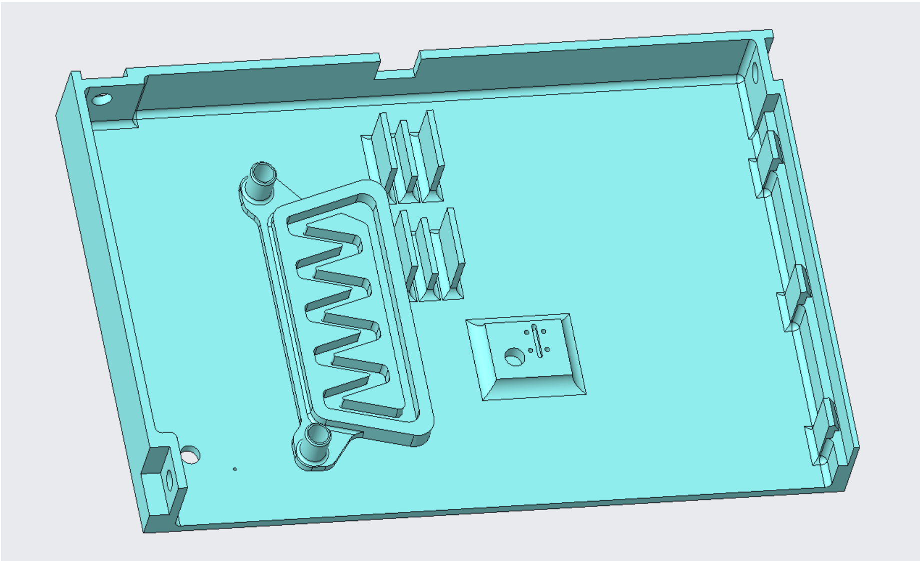

Figure 61, right shell and track assembly

In conclusion, using DFA methods reduced significantly the time to print and the time to assemble, and increase the overall efficiency of the prototype production with regards to material usage.

7. Manufacturing Costs

In order to improve profitability through a product cost management, aPriori software was used to make a manufacturing cost analysis. This software is focused on helping well-known manufacturing and product enterprises to optimize overall financial performance. The program works by introducing a CAD file and also introducing additional pieces of information of a product piece that would like to be manufactured. After filling several fields like volume of manufacture, material or desired manufacturing process, this software provides all the information of the manufacturing process including the price of each piece. If a change is made in the process or CAD file, aPriori upgrades all the information for the manufacture of that part in minutes or even seconds. Hereafter is shown the results of the aPriori analysis that was performed for the creation of the door opener.

Part	Parts per Product	Manufacturing Process	Annual Volume	Labor Time(s)	Material Composition	Piece Part Cost (€)	Total Capital Investment (€)
Pinion	1	Plastic Molding	10.000	31	Acetal, Copolymer	0.52	8,202.07
Spacer	2	Plastic Molding	10.000	4	Nylon, type 66 Min Filled	0.13	6,989.36
Right Shell	1	Plastic Molding	10.000	62	ABS, Fittings	1.66	26,111.12
Coin Cap	1	Plastic Molding	10.000	12	PET, Injection	0.22	7,619.3
Large Axel	2	Bar & Tub Fab.	10.000	21	Stainless Steel, Stock, 440B	0.22	0
Plate Joiner	6	Sheet Metal	10.000	5	Stainless Steel, Stock, AISI 301	0.16	0
Rear Beam	1	Plastic Molding	10.000	61	ABS	0.84	9,712.28
Acrylic Plate	1	Plastic Molding	10.000	16	ABS, Transparent	0.56	12,069.70
Clip	1	Plastic Molding	10.000	15	PET, Injection	0.26	7,472.35
Cylinder	1	Plastic Molding	10.000	11	PET, Injection	0.22	8,573.41
Delay Assembly	1	Plastic Molding	10.000	37	ABS	0.57	9,514.84
Double Peg	1	Plastic Molding	10.000	63	PET, Injection	0.81	7,496.97
Left Shell	1	Plastic Molding	10.000	62	ABS, Fittings	1.64	26,086.01

Main Axel	1	Bar & Tub Fab.	10.000	28	Stainless Steel, Stock, 440B	0.58	341.71
Parcel	2	Plastic Molding	10.000	33	Acetal, Copolymer	0.47	7,446.05
Plunger Arm	1	Plastic Molding	10.000	216	Acetal, Copolymer	2.85	10,505.59
Top Shell	1	Plastic Molding	10.000	38	ABS, Fittings	1.03	26,866.66
Trigger	1	Plastic Molding	10.000	57	Nylon, type 6	0.76	10,573.08
Wheel	1	Plastic Molding	10.000	159	Nylon, type 66	5.98	11,893.37
Ratchet Gear	1	Plastic Molding	10.000	98	Acetal, Copolymer	1.35	9,739.35
Small Sprocket	2	Plastic Molding	10.000	25	Acetal, Copolymer	0.37	7,483.00

Table 6, manufacturing cost analysis

In the previously shown table it can be observed the different kind of manufacturing processes used for building the parts of the product as well as the material used for each of the parts. As it is presented, injection molding using several types of plastics and polymers is the most popular manufacturing process for the device. However, for those parts that required being more rigid and resistant, metal Bar-Tub and Sheet fabrication process was used with steel. This case was used mainly for manufacturing axes. All these material used where selected with a quality-price ratio in mind, in order to produce the most effective device spending the less amount of money possible. Parts that required being robust, like the housing, were decided to be made out of ABS that is a light plastic with a really high impact resistance. Moreover, nylon was also used for high resistance pieces, as it could be the wheel, nevertheless, this material is not as light weighted as the previous one. Besides, PET was another low quality plastic used for those pieces that will not be require such a good quality grade for its performance.

The labor time required for building up a single device result to be 1054 second, which is 17 minutes and 33.6 seconds.

Regarding the cost of manufacture of each device, adding up every piece cost, it would give a result of 21.19€. If the product is sold for 26.38€ each, leveling the price and exceeding the quality of the device in comparison with the already existing products, it would give a profit of 5.19€ per product sold. Taking into account the fact that 10,000 door openers are expected to be sold per year, the company would produce an annual profit of 51884.07€. If the Total Capital Investment needed for the manufacture of the whole product is 214,696.26€, the outlay would be completely covered after 4 years, 1 month and 21 days of door openers production and sales. This means that the company could start to be profitable on the second month of the fifth year of performance.

8. Management Plan

Finally, in the coming Gantt chart it can be observed the evolution of the project from the ideation of the product to the creation of the final prototype. A Gantt chart is one of the most attractive and advantageous methods used as a way of explaining the development of a project and the activities performed. Each action is represented by a bar with certain length, which represents the duration of the process; and position, which represents the initial and final date of the case. On the other hand, the color of the bar also indicates the state of the process. If the bar is colored in green, it means that the action has already been completed. Yellow colored means that the activity is in process of being completed. While red color means that the action have not even been started. Therefore, it has not been fulfilled yet. It can be observed that the larger length of time was spent in the research, analysis and optimization of the second prototype in order to create the final one. This previously named part was crucial for the device since it was a great leap forward for the project.

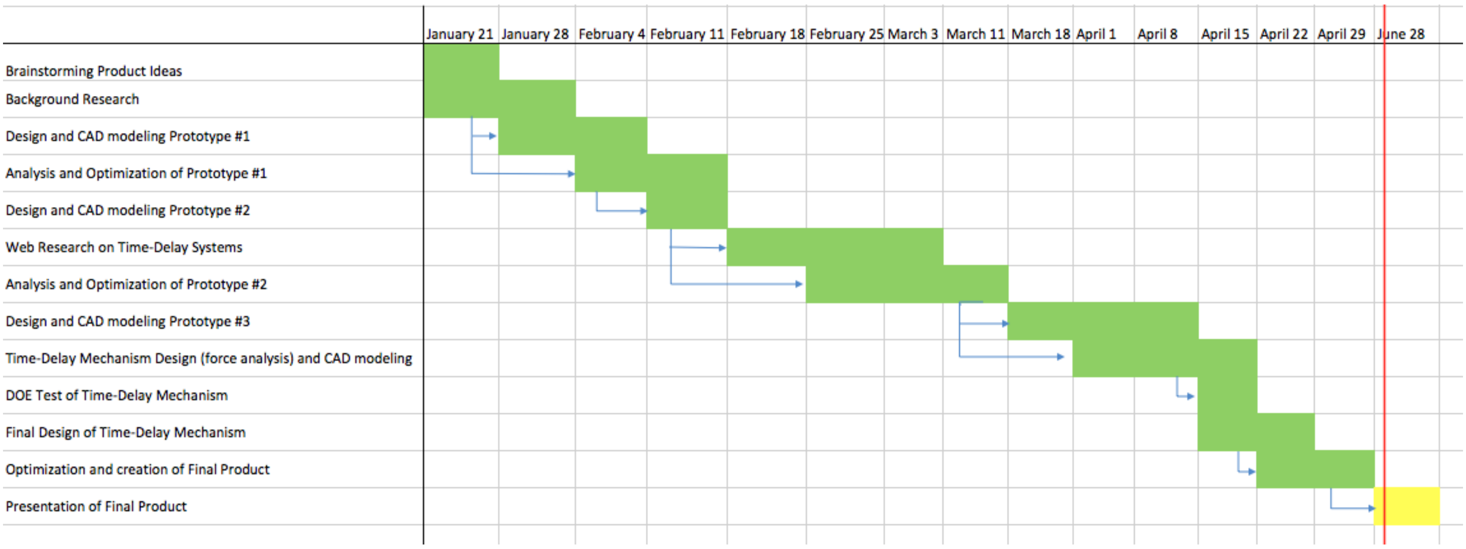

Figure 62, Gantt chart