CardGuard™

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ME345: Project Final Report

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Introduction

Americans are increasingly relying on cards to make purchases, which is expressed in the data collected by the 2019 Federal Reserve Payments Study.[1] According to the study, card payments in 2018 reached a total of 131.2 billion, which was up 29.7 billion from 2015. Additionally, check payments decreased by 3.6 billion to a total of 14. 5 billion. ATM cash withdrawals also experienced a slight decline of 0.1 billion to a total of 5.1 billion. This data from America likely reflects a global trend in which people are increasingly using credit/debit cards to make purchases. A safe and simple way of carrying cards has incredible utility within the consumer market. Traditional wallets are one method by which people can keep all their cards, money, checks, etc in one place. These can be bulky, however, and the overall size is unnecessary. As the data suggests, a large number of people only necessarily need to carry cards on them to make purchases. Therefore, our slim, card-holder is the perfect tool for holding the essential cards (credit card, debit card, ID, etc.) when going out.

Similar products have been made to address this issue, but none designed with the simplicity and ease of use in our design. The ROCO minimalist wallet uses an aluminum frame with a flexible silicone band to hold the cards in place.[2] This product does provide a compact storage for cards, but there are drawbacks with the design. The silicone band applies pressure to the end faces and holds them together with any cards inside. This causes the cards to be easily scratched when inserting or removing them, which can potentially damage the cards.[3] Additionally, the design does not allow for the easiest possible access to the cards being stored. Another similar product that exists on the market is the carbon fiber credit card holder by Yinuode.[4] This design operates much like the ROCO wallet, except the silicone band is integrated into the two end plates. While this is a better design than the first, the same issues arise nonetheless.

Similar to the products currently on the market, our design should utilize a slim, minimalistic shape that successfully contains several cards. It should also be able to accommodate a different number of cards so that the user is not restricted by a minimum they must have. Our design should also address the issues of the previously made products. It should not scratch the cards, especially when inserting / removing them from the holder. It should also improve upon the accessibility of the cards, so that the design is easy to use and repeatable.

To address the goal of providing a compact means to carry cards, we aim to provide a new design that fixes the issues of what has already been done. We also plan to use pressure between two end plates to hold the cards together. This pressure will not come from an elastomer, however, but from a tight fit with frictional forces. The user will manually push the two faces together and they will stay in place from the friction between the pins and holes. This design will successfully hold the cards together, and it fixes the problems with the other products on the market. The cards are easier to access by pulling apart the two end plates, and this method prevents scratching. Another benefit of our design is that it does not wrap around the entire perimeter of the cards. This makes the holder smaller, and it exposes some of the cards so that the user can easily identify the one that they need.

By implementing an automated assembly line such as the ADML to manufacture our product, we can absolutely speed up all the processes involved in the manufacturing process. Using automated assembly lines allow for “higher production rates and increased productivity, more efficient use of materials, better product quality, improved safety, shorter workweeks for labour, and reduced factory lead times[5].” Despite the fact that humans who have worked on their manufacturing processes to perfection, automated manufacturing still has the upperhand as the machines can perform the manufacturing processes with much less variability, which leads to greater consistency and control of product quality. On top of that, greater control of the processes is much more efficient with materials, which saves a lot more material and money. Furthermore, implementing an automated assembly line towards manufacturing our product drastically reduces our labor time, which frees up more of our time to work on other aspects of the process/product.

The creation and introduction of our product to society will positively impact and alter society’s use of wallets. Today’s wallets on the market are generally either money clips or traditional leather wallets. However, our product is the most simple and possibly the slimmest wallet on the market. It eliminates any extra, unnecessary layers of a traditional wallet, but reinforces the weak aspects of a money clip. It provides a perfect balance between a traditional wallet and a money clip, giving consumers the ability to safely house their credit cards and money with a stable, firm grip that doesn’t add any extra thickness or width.

Project Plan

1. Introduction

The project plan focuses on the design itself and the intended manufacturing method and techniques. This section will show the actual design and describe all the key features that relate to the overall function of the product. The decisions made within the design will be explained in relation to how they enhance the overall performance and how they intend to be manufactured with the CNC in the ADML. The production process of the cardholder as it relates to the ADML will also be discussed with our intended manufacturing strategy. This includes the overall schematic and how each aspect should be utilized.

2. Design of the Product and Its Part

The CAD Models for CardGuard are shown in Figures 1-3. Figure 1 shows the assembled product in use, and Figures 2 and 3 show the two halves.

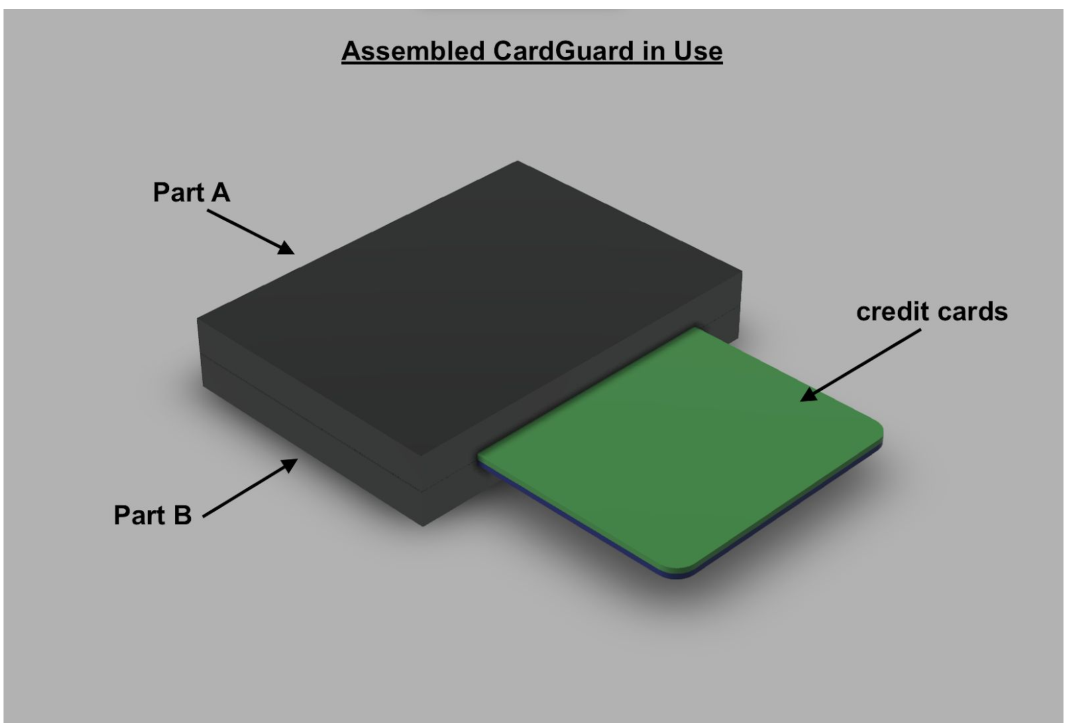

Figure 1: Assembly of CardGuard

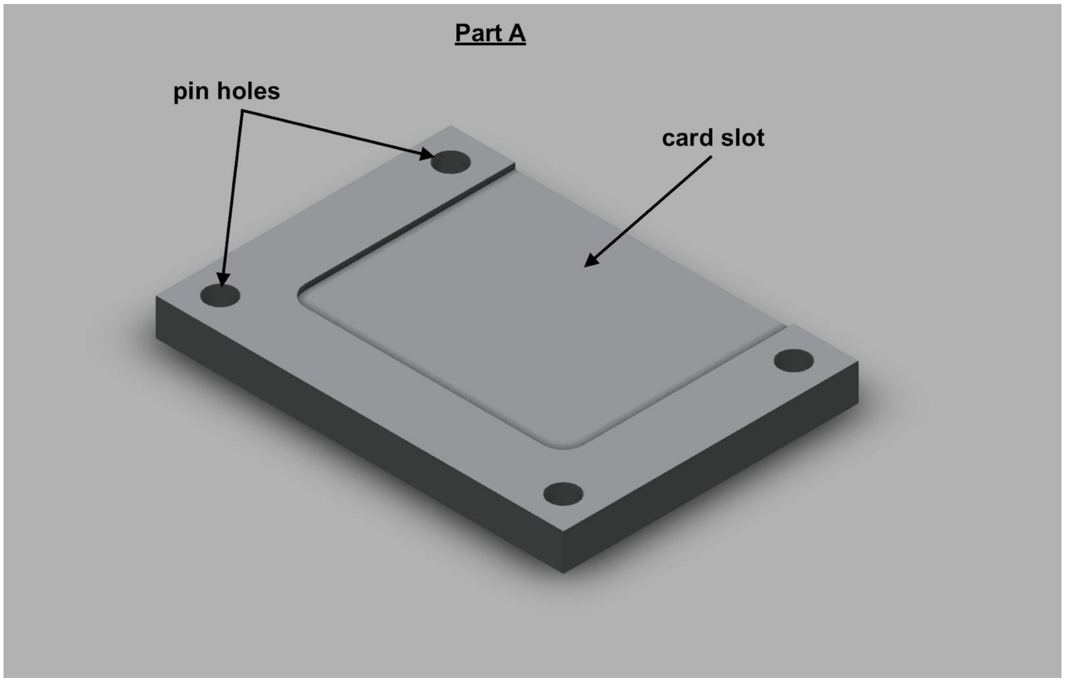

Figure 2: Part A of CardGuard

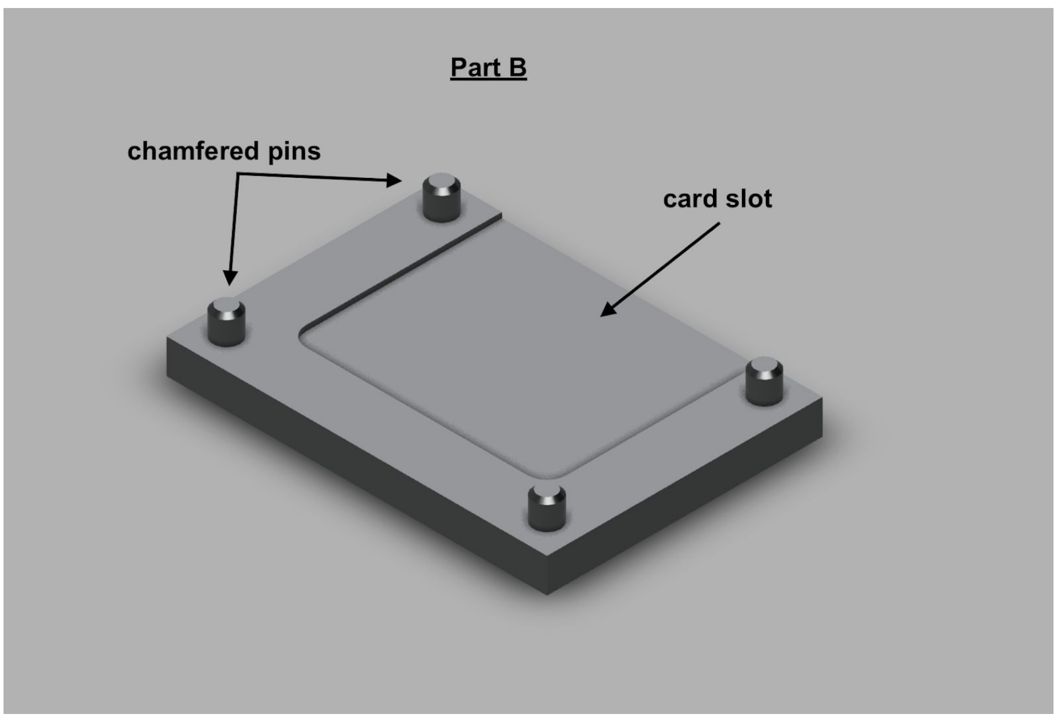

Figure 3: Part B of CardGuard

Part A of the CardGuard contains four pin holes, each with a diameter of 5mm. It also contains a 1mm deep card slot, and the slot is marginally larger than the dimensions of a standard credit card to allow easy insertion and removal (Figure 2).

Part B of the CardGuard contains four chamfered pins, also with diameters of 5mm. These pins are chamfered to allow easier insertion and removal, and they are intended to fit very snuggly in their respective pin holes (Figure 3).

The overall assembly (Figure 1) shows how the two parts will fit together to create a sleek and aesthetically pleasing product. The two slots create a gap for the cards, which can be adjusted by adjusting how tight the two faces are pressed together.

The CardGuard assembles together using four press-fit chamfered pins and respective pin holes. When the two halves are pushed together, the pressure between Parts A and B should be enough to hold the cards together. The slot between the two faces allows the cards to be lined up properly and allows the cards to be half exposed upon assembly. This creates a slimmer product, and easier access to any desired card.

The assembly has overall dimensions of 2” x 3” x 0.5”. It is designed to be milled from two of the 2” x 3” x 0.5” stock pieces. This stock part was selected because it most closely fits the dimensions of a credit card, and has enough extra space to comfortably include four pins/holes. Each of the two parts is designed to be milled from a single orientation, allowing them to be milled in only one process. Also, both parts can be laid flat on the vise in the same manner as the hole-plate from the second homework assignment. This makes the parts easily compatible with the current mill setup in the ADML. Additionally, all the geometry and features shown in Figures 2 and 3 can be easily created on the milling machine.

The dimensions of both the pins and holes need to be tested to determine the best combination for creating a press fit that can easily be opened and closed. Currently, the CAD model has the diameters of both features exactly the same, which may result in too tight of a fit. Based on the Cordganizer process, which utilizes the same assembly scheme, the hole diameter should be 0.002” larger. The pin diameters should therefore be 0.197” and the hole diameters should be 0.199”. It will require some trial and error to get the proper press fit, but is ultimately one of the most important elements of our design. The chamfered edge on the pins was created to better accommodate the assembly of the two halves. The robot would not be able to line up the pins and holes perfectly upon assembly, so the chamfer is necessary to allow room for error. Additionally, the chamfer will help the user when opening and closing the product.

3. Development of Manufacturing Strategy and Processes

The production of CardGuard will be on the computer-controlled assembly line based in Automated Design and Manufacturing Lab (ADML) at Boston University's Engineering Product Innovation Center (EPIC). The layout of the ADML is shown in Figure 4. The automated manufacturing of the product will utilize two CNC mills, three robotic arms, a camera, and a conveyor. For the overview of the manufacturing processes, two components of the product will be manufactured from stock material using two separate milling machines. The parts will be loaded and unloaded at each station by robots, and they will be transferred among stations on the conveyor belt. In the final process, all of the components will be assembled at the assembly area.

The machines' names and numbers are referred to Figure 4, and all of the manufacturing processes are shown in a process flow diagram in Figure 5. In the production, Part A and Part B will be produced at Station 4 and Station 3 respectively. The assembly of both parts will be at Station 1.

Manufacturing of Part A, Robot 4.1 (Edie) will pick up a stock of selected size and place it onto Work Area 4.4. Edie will push on both sides of the stock to align the horizontal location with a bench, and then Edie will pick up the stock again. This strategy will allow the robotic arm to grasp a stock in the same orientation every time. Then Edie will place the stock in Mill 4.3 (Paprika). Edie's arm will apply a force onto the stock to hold it still until Paprika's jaw fixes the stock firmly. Paprika will mill the stock becoming the Part A according to the mounted design G-code. After finishing the milling operation, Edie will load the manufacted part onto a pallet on the conveyor belt. Part A will be transferred from Station 4 to Station 1 via the conveyor. Robot 1.1 (Rosie) will unload the pallet and place part A at Bench Vice 1.9 in Assembly Area 1.4.

Similar to the processes and techniques of Part A production, at Station 3, Robot 3.1 (Mary) will place a selected stock into Mill 3.3 (Cayenne). Cayenne will manufacture the stock turning it into Part B. Mary will load Part B onto a pallet on the conveyor. Part B will be transferred from Station 3 to Station 1 by the conveyor belt.

In the process of assembling, after the arrival of Part B pallet at Station 1, Rosie will unload the pallet by picking up Part B and placing it at a bench. Rosie will slightly push Part B to align it with the bench horizontally, and then Part B will be grabbed in a precise orientation. Rosie will assemble Part B into Part A tightly by pressing them together firmly. Finally, the assembled product will be moved by Rosie to a designed empty space in Assembly Area 1.4.

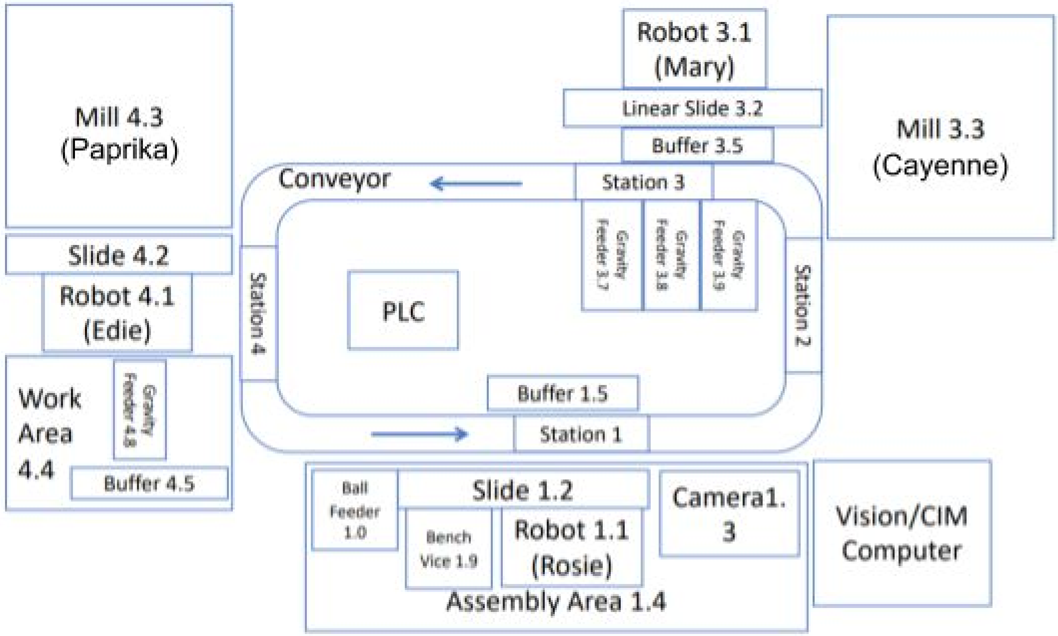

Figure 4: Schematic of Automated Design and Manufacturing Lab (ADML)

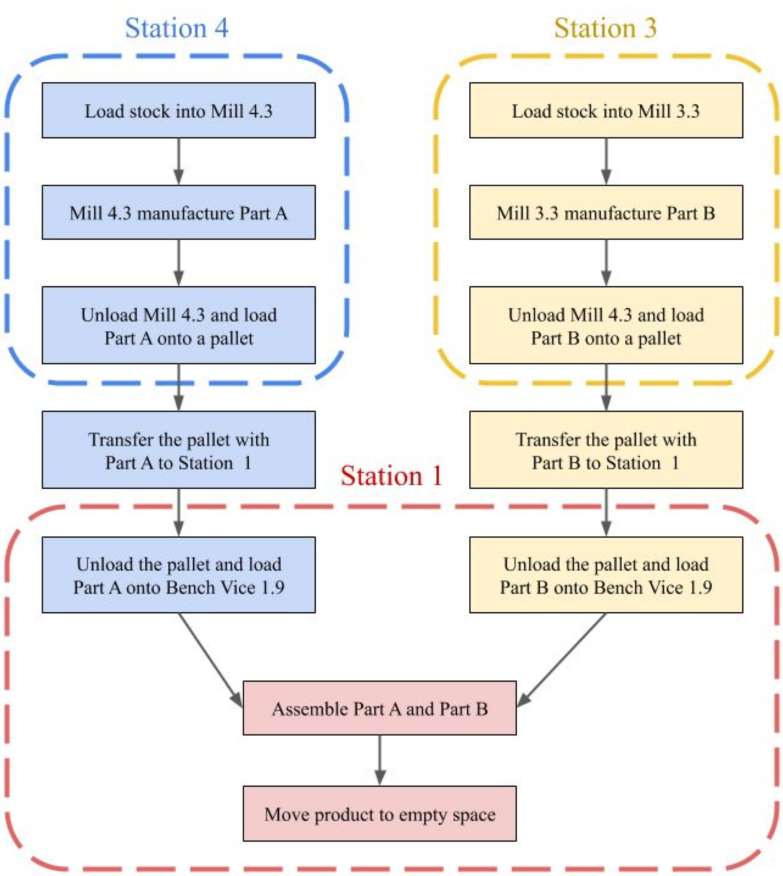

Figure 5: Process Flow Diagram of CardGuard

As shown in Figure 6, for the milling of Part A, a 1/4" end mill should be used in a roughing operation to shape the surface and card pocket. The roughing operation is used to cut the general shape in a quick manner. Then, the machine should switch to a 1/8" end mill, which should be used for the contour operation and pin holes. The contour operation better traces the edges of the part to create the final geometry with a nice surface finish and accurate dimensions. The 1/8" end mill should also be used to cut the pin-holes performing both the roughing process and contour on these features.

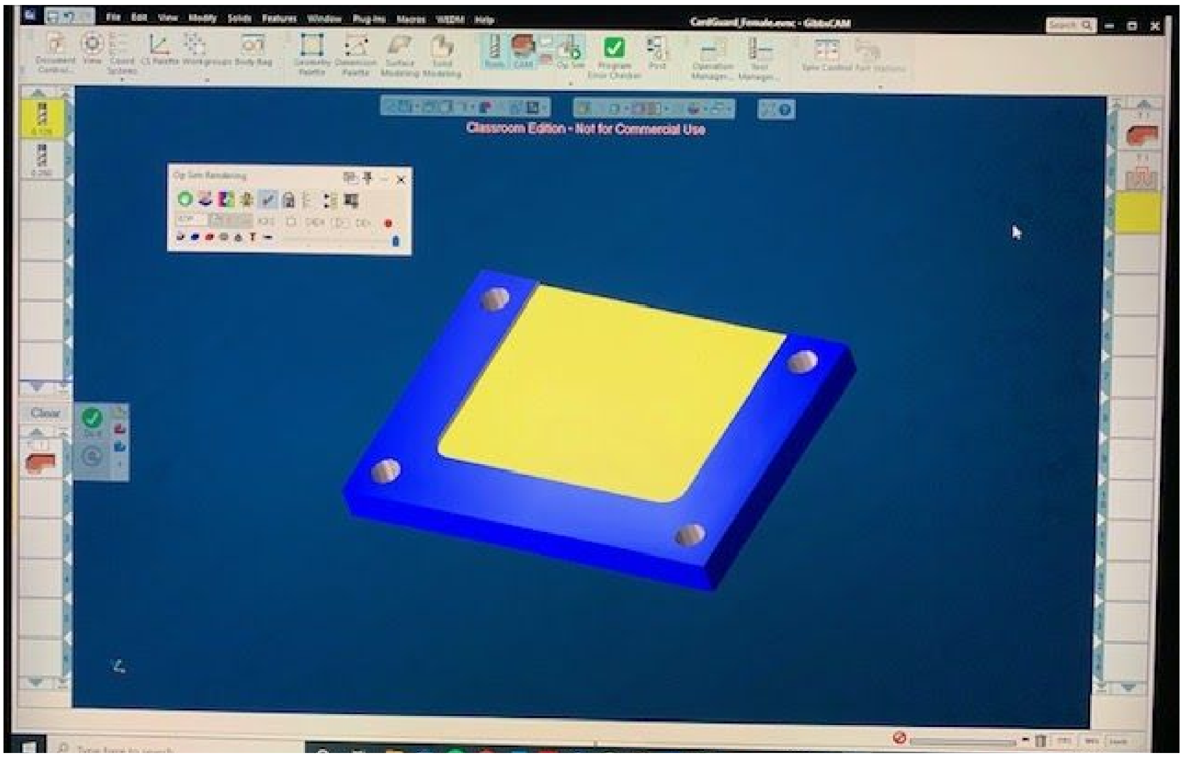

Figure 6: CAM Milling of Part A

A similar milling procedure should be done for Part B (Figure 7). A 1/4" end mill will be used for the roughing pass along the surface. This pass should keep material for the pins and create the general pocket shape as well. Then, a ⅛” end mill will be used for the finishing operation on the surface, pocket, and around the pins and a ¼” 90° spot drill will be used to create the chamfers on the pins.

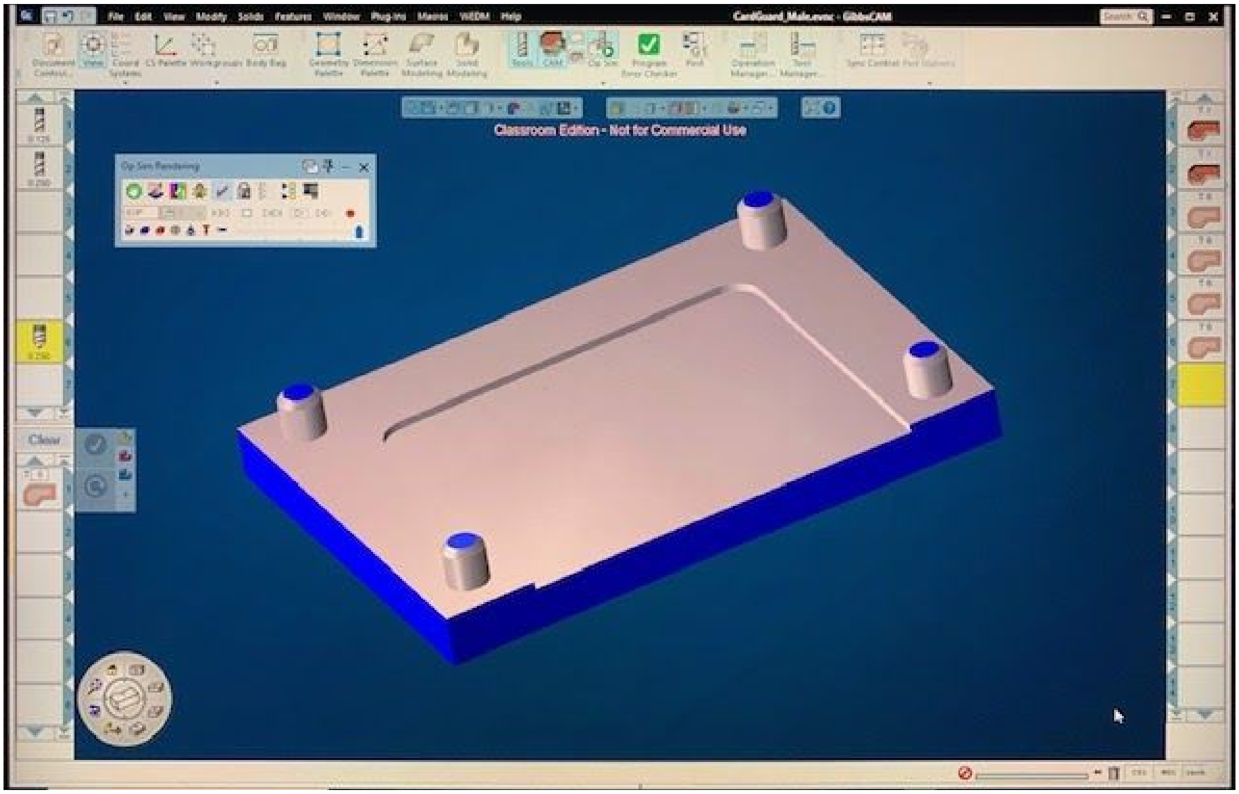

Figure 7: CAM Milling of Part B

4. Computer Integrated Manufacturing (CIM) Control

Tables A1 and A2 (in the Appendix) show the CIM spreadsheet for both parts. The four columns are the 'Task type', 'step', 'time', and 'manufacturing step'. The task type corresponds to what general category of tasks is being performed. For example, it can be a task for a robot, the conveyor, or the CNC. The step is the specific action being performed. The time corresponds to how long it takes to complete the task. The manufacturing step is a way of organizing the tasks by general process groups to see how it relates to the overall development of the part. See Figure 5 for some of the general manufacturing steps presented in a flowchart.

The spreadsheet is largely based off of the Cordganizer CIM spreadsheet as the steps are nearly identical throughout the process. This is because the two halves for both products involve relatively similar geometry including the use of pins and holes to assemble the parts together. The two main differences are the naming of the programs and the time for milling the two halves.

The program names have been changed to account for slight changes that need to be made in our robot paths and milling program. For example, our part consists of the same stock material for the two halves. Therefore, the robot must go to the same gravity feeder for both components unlike in the Cordganizer process. This is a minor change that will also affect robot paths down the line for that change in material.

The only source of time difference between this process and the Cordganizer process is the milling operation. All the other steps should be identical or nearly identical to the Cordganizer, so there is no reason to suspect a difference in time for those steps. This includes assembly as the assembly of the 'Male Half' and 'Female Half' utilizes the same mechanism as the 'Body' and 'Lid' of the Cordganizer. Therefore, the time for assembly was also kept the same. For milling, however, the time to manufacture each half will be different. The times shown for this step are estimates based off of the Cordganizer manufacturing duration. A better approximation cannot be obtained as we have no access to GibbsCAM. It was estimated that the female half will take 200 seconds to machine, while the male half will take 260 seconds. Therefore, the female half, which is a quicker milling operation, will be sent to station 3 to be milled. It is assumed to be quicker because pins do not need to be created by milling down the face. The pin-holes require much less material removal to create. There is much less intricate geometry then the Cordganizer body, which is why the milling time is closer to the Cordganizer lid.

5. Scheduling

The routing diagram of CardGuard production is shown in Figure 8. Description of an abbreviation of each step can be found in Table A3 of Appendix. The diagram indicates required time in one cycle. It demonstrates time of each process in producing Part A and Part B as well as time to assemble together.

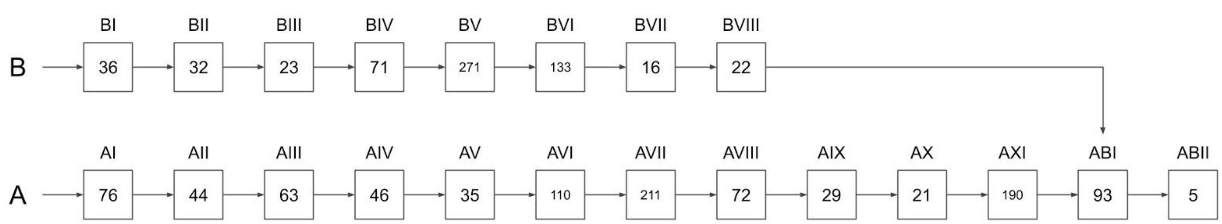

Figure 8: Routing Diagram CardGuard (Units in Seconds)

The process at each individual station is continuous in an unbreakable chain. Therefore, multiple steps can be grouped into a single parent process. Those processes are: Process A is referred to production of Part A, Process B is referred to production of Part B, and Process AB is referred to assembly of Part A and Part B. For Process A, the total process time is added up to 875 seconds or 14.58 minutes. To simplify the analysis, time in Process B can be rounded to 15 minutes. Similarly, Process A takes 17 minutes and Process AB is accounted for 2 minutes.

The throughput (TH) of the production process depends on the rate of output product which is upon the bottleneck rate. Process A is the bottleneck of an entire production. Due to Process A, the production is able to release new material every 17 minutes. Therefore, the throughput can be defined as:

$$TH = \frac{1\ part}{17\ min} \times \frac{60\ min}{1\ h} = 3.5\ {}^{parts}\!/_{hour}$$

The work-in-process (WIP) calculated at steady-state is 2 parts. The scheduling analysis of WIP can be found in Table A4 in Appendix. According to Little's Law, the cycle time (CT) can be calculated as:

$$CT = \frac{WIP}{TH} = \frac{2\ parts}{3.5\ {}^{parts}\!/_{hour}} \times \frac{60\ min}{1\ h} = 34\ minutes$$

Process A has the largest process time (17 min) among processes. It is the bottleneck which controls the rate of material releasing as shown in Table A4 in Appendix. New material can only be released after a completion of Process A.
The entire production process's throughput is optimized by steps organization. Every step in each process is arranged in manner to maximize the throughput. To significantly increase the throughput, the production should consider changing the type of the milling tools or adding new conveyor paths which are linked between each station directly.

6. Implementing Lean Principles

We designed our part with lean manufacturing principles in mind, employing their focus on reducing waste, whether that's waste of materials, time, costs and/or labor. Our thought process from the beginning was to design a part that would be simple enough to manufacture, but also serve its purpose well. We ultimately decided on splitting CardGuard into two halves and designed the parts to fit into each other to form one complete part, as shown above in Figures 2 and 3. In Figure 2, Part A shows one part with four simple holes towards the edges and a simple, shallow, chamfered extrusion, all of which are relatively easy machining processes. In Figure 3, Part B shows the other part with 4 short pins towards the edges and the same simple, shallow, chamfered extrusion, all of which are to match its respective corresponding components. The overall design of this part was all conceptualized around efficient, straight-forward manufacturing, which encompasses lean manufacturing's principle of elimination of waste.

As we had to take into consideration the manufacturing processes whilst designing the part, we tried to optimize our manufacturing processes and design it so that it optimizes and minimizes manufacturing time and labor. As shown above in Figure 7, we can manufacture both Parts A and B simultaneously, by loading, manufacturing, unloading and transferring both stocks from Stations 3 and 4 to Station 1, where both parts are to be assembled and completed together. By manufacturing both parts together, we ultimately maintain the manufacturing and assembling time to a minimum, which implements lead method's core principles of reducing waste and unnecessary time and labor.

7. Cost Estimation

In order to estimate the cost per part and cost per hour for the manufacturing process of CardGuard, the guidelines explained in class were applied to our CIM. Operating costs included: robot ($1.00/hr), CNC ($20.00/hr), and conveyor ($1.00/hr). Material costs include the stocks of HDPE ($0.42/in^3).

The total cost per part is $5.74, and the total cost per hour is $4.62. All of the cost information is shown in Table 1.

Table 1: Cost Estimation

	Time Per Operation by Machines (s)		
	Robot	CNC	Conveyor
Male	17	6	1
	12	260	1
	22	6	1
	64		30
	38		2
	71		1
	20		22
			1
			1
			15
			1
			1
			1
Female	10	13	14
	10	200	1
	22	6	1
	25		1
	20		31
	22		1
	74		1
	51		34
	19		1
	19		1
	93		1
			1
			28
			1
			1
			1
TOTAL	609	491	197

Machine	Cost/Hour	Cost/ Second
Robot	$1	$0.00
CNC	$20	$0.01
Conveyer	$1	$0.00

Machine	Cost/Part	Cost/Hour
Robot	$0.17	$0.27
CNC	$3	$4.27
Conveyor	$0.05	$0.09

	Cost/Part	Cost/Hour
TOTAL	$5.74	$4.62

Material	Cost/in^3
HDPE	$0.42

Material	Volume (in^3)
HDPE	$6.00

Material	Total Cost
HDPE	$2.52

8. Limitations and Future Work

As we cannot physically manufacture our part due to COVID-19, at the moment, our part theoretically seems functional. However, if we were to look beyond the scope of the COVID-19 limitations, we could predict a few limitations and areas for improvement.

1. As mentioned in the **Design of the Product and its Part** section, the tolerances of the pins on **Part A** could be manufactured slightly off, which would prevent a nice press fit into **Part B**, as this part would require trial-and-error to obtain the proper press fit. This would either cause the pins to either catch midway into **Part B**, or not entirely align with its corresponding pin holes in **Part A**. As a result, this would pose a major error in the part, as we can no longer easily assemble the two components or they won't align at all. To improve upon this or ensure trial-and-error is not necessary, we would need to be certain our calculations and tolerances are extremely accurate and that the CNC can machine our parts to our expected tolerances.
2. The CIM software is a bit difficult and unstable to operate. From our experience with previous labs, we know that this can pose many issues in our machining process, potentially incorrectly rearranging the planned processes described in our **Scheduling** section. Thus, for future work, the CIM software could use improvements to boost stability and adherence.
3. As evident in our **Scheduling** section, there is no other foreseeable method in **Lean manufacturing** to improve on our manufacturing process. However, as **Part A** is our bottleneck, taking approximately 17 minutes to manufacture, we could potentially start **Part A** first, and delay the start of **Part B** until both parts require an equal amount of time to complete. By doing this, we could potentially eliminate our only bottleneck, thus, improving and altering our manufacturing process.

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Appendix

Table A1: The CIM spreadsheet for the Male Half

CIM Breakdown, CardGuard Male Half (Part B)			
Task Type	**Step**	**Time (Seconds)**	**Manufacturing Step**
Resource	Resource (Seize) - Raw Inventory B	0	Initialize CardG Male Half
Resource	Resource (Seize) - AssemblyStepB	0	
Resource	Resource (Seize) - 1.11 Conveyor Stop	0	Rosie picks empty pallet, scans it, loads it onto an AGV
Resource	Resource (Seize) - 1.1 - Robot & Linear Slide	0	
Robot Path	STN1_adminCardG-RawBToCamera	17	
Conveyor Task	Bring Empty Vehicle to Station (PLC ID 1)	0	
Conveyor Task	Lock Vehicle At Station (PLC ID 1)	1	
Vision Inspection	Vision Inspection (1.12 Bar Code Camera)	4	
Conveyor Task	Transfer Pallet ID To Vehicle (PLC ID 1)	1	
Robot Path	STN1_adminCardG-CameraToConveyor	12	
Conveyor Task	Unlock Vehicle At Station (PLC ID 1)	1	
Resource	Resource (Release) - 1.1 - Robot & Linear Slide	0	
Resource	Resource (Release) - 1.11 Conveyor Stop	0	
Resource	Resource (Seize) - 4.9 - Conveyor Stop	0	AGV travels to station 4
Conveyor Task	Send Vehicle to Station (PLC ID 4)	30	
Resource	Resource (Release) - 1.11 Conveyor Stop	0	
Conveyor Task	Lock Vehicle At Station (PLC ID 4)	2	
Resource	Resource (Seize) - 4.1 - Robot & Linear Slide	0	Edie unloads the AGV into her inventory
Robot Path	STN4_adminCardG-ConveyorToInvB	22	
Conveyor Task	Unlock Vehicle At Station (PLC ID 4)	1	
Resource	Resource (Release) - 4.9 - Conveyor Stop	0	
Resource	Resource (Release) - 4.1 - Robot & Linear Slide	0	
Resource	Resource (Seize) - 4.3 - Mill	0	Edie loads stock material into the milling machine
Resource	Resource (Seize) - 4.1 - Robot & Linear Slide	0	
CNC	Load Mill	6	
Robot Path	STN4_adminCardG-GFYToMill	64	
Wait Time	Wait for 1 sec	1	
Resource	Resource (Release) - 4.1 - Robot & Linear Slide	0	
CNC	Machine Male Half	260	The male half is machined
Wait Time	Wait for 5 sec	5	
CNC	Load Mill	6	
Resource	Resource (Seize) - 4.1 - Robot & Linear Slide	0	Edie loads the male half into the pallet and then on an AGV
Robot Path	STN4_adminCardG-MaleHToInvB	38	
Resource	Resource (Release) - 4.1 - Robot & Linear Slide	0	
Resource	Resource (Release) - 4.3 - Mill	0	
Resource	Resource (Seize) - 4.1 - Robot & Linear Slide	0	
Resource	Resource (Seize) - 4.9 - Conveyor Stop	0	
Conveyor Task	Send Vehicle to Station (PLC ID 4)	22	
Conveyor Task	Lock Vehicle At Station (PLC ID 4)	1	
Robot Path	STN4_adminCardG-InvBToConveyor	71	
Resource	Resource (Release) - 4.1 - Robot & Linear Slide	0	
Conveyor Task	Unlock Vehicle At Station (PLC ID 4)	1	
Resource	Resource (Release) - 4.9 - Conveyor Stop	0	
Conveyor Task	Send Vehicle to Station (PLC ID 1)	15	AGV travels to Station 1
Resource	Resource (Seize) - 1.11 Conveyor Stop	0	
Conveyor Task	Lock Vehicle At Station (PLC ID 1)	1	
Resource	Resource (Seize) - 1.1 - Robot & Linear Slide	0	
Resource	Resource (Seize) - 1.11 Conveyor Stop	0	
Robot Path	STN1_adminCardG-ConveyorToRaw2	20	Rosie unloads the male half from the AGV
Resource	Resource (Release) - 1.1 - Robot & Linear Slide	0	
Conveyor Task	Remove Pallet ID From Vehicle (PLC ID 1)	1	
Conveyor Task	Unlock Vehicle At Station (PLC ID 1)	1	
Resource	Resource (Release) - 1.11 Conveyor Stop	0	
Resource	Resource (Release) - AssemblyStepB	0	
Resource	Resource (Seize) - AssemblyStepA	0	Wait until female half arrives for assembly
Resource	Resource (Release) - AssemblyStepA	0	Rosie Assembles the parts and places it with Finished Goods (see the female half breakdown for more detail)
Wait Time	Wait for 5 sec	5	
Resource	Resource (Release) - Raw Inventory B	0	
Rinse and Repeat			

Table A2: The CIM spreadsheet for the Female Half

CIM Breakdown, CardGuard Female Half (Part A)			
Task Type	**Step**	**Time (Seconds)**	**Manufacturing Step**
Resource	Resource (Seize) - Raw Inventory A	0	Initialize CardG Female Half
Resource	Resource (Seize) - AssemblyStepA	0	
Resource	Resource (Seize) - 1.11 Conveyor Stop	35	Rosie picks empty pallet, scans it, loads it onto an AGV
Resource	Resource (Seize) - 1.1 - Robot & Linear Slide	0	
Robot Path	STN1_adminCardG-RawBToCamera	10	
Conveyor Task	Bring Empty Vehicle to Station (PLC ID 1)	14	
Conveyor Task	Lock Vehicle At Station (PLC ID 1)	1	
Vision Inspection	Vision Inspection (112 Bar Code Camera)	4	
Conveyor Task	Transfer Pallet ID To Vehicle (PLC ID 1)	1	
Robot Path	STNI_adminCardG-CameraToConveyor	10	
Conveyor Task	Unlock Vehicle At Station (PLC ID 1)	1	
Resource	Resource (Release) - 1.1 - Robot & Linear Slide	0	
Resource	Resource (Release) - 1.11 Conveyor Stop	0	
Resource	Resource (Seize) - 4.9 - Conveyor Stop	12	AGV travels to station 4
Conveyor Task	Send Vehicle to Station (PLC ID 4)	31	
Conveyor Task	Lock Vehicle At Station (PLC ID 4)	1	
Resource	Resource (Seize) - 4.1 - Robot & Linear Slide	41	Edie unloads the AGV into her inventory
Robot Path	STN4_adminCardG-ConveyorToInvB	22	
Robot Path	STN4_adminCardG-GFWToInvB	25	Edie loads stock material pallet and places it back onto an AGV
Robot Path	STN4_adminCardG-STN4-InvBToConveyor	20	
Resource	Resource (Release) - 4.1 - Robot & Linear Slide	0	
Conveyor Task	Unlock Vehicle At Station (PLC ID 4)	1	
Resource	Resource (Release) - 4.9 - Conveyor Stop	0	
Conveyor Task	Send Vehicle to Station (PLC ID 3)	34	AGV travels to Station 3
Conveyor Task	Lock Vehicle At Station (PLC ID 3)	1	
Resource	Resource (Seize) - 3.1 - Robot & Linear Slide	0	
Resource	Resource (seize) - 3.11 Conveyor Stop	0	
Robot Path	STN3_adminCardGConveyorToInvB	22	Mary unloads the AGV and loads the stock material into the milling machine
Conveyor Task	Unlock Vehicle at Station (PLC ID 3)	1	
Resource	Resource (Release) - 3.11 Conveyor Stop	0	
Resource	Resource (Seize) - 3.3 - Mill	0	
CNC	Mill Load	13	
Robot Path	STN3_adminCardG-InvBToMill	74	
Resource	Resource (Release) - 3.1 - Robot & Linear Slide	0	
CNC	Machine Female Half	200	The female half is machined
Wait Time	Wait for 5 sec	5	
CNC	Mill Load	6	
Resource	Resource (Seize) - 3.1 - Robot & Linear Slide	0	
Robot Path	STN3_adminCardG-LidToInvB	51	Mary loads the female half into the pallet and then onto an AGV
Resource	Resource (Release) - 3.3 - Mill	0	
Conveyor Task	Send Vehicle to Station (PLC ID 3)	0	
Conveyor Task	Lock Vehicle At Station (PLC ID 3)	1	
Resource	(Seize) - 3.11 Conveyor Stop	0	
Robot Path	STN3_adminCardGInvBToConveyor	19	
Resource	(Release) - 3.1 - Robot & Linear Slide	0	
Resource	(Release) - 3.11 Conveyor Stop	0	
Conveyor Task	Unlock Vehicle At Station (PLC ID 3)	1	
Conveyor Task	Send Vehicle to Station (PLC ID 1)	28	AGV travels to Station 1
Conveyor Task	Lock Vehicle At Station (PLC ID 1)	1	
Resource	(Seize) - 1.1 - Robot & Linear Slide	0	Rosie unloads the female half from the AGV
Resource	(Seize) - 1.11 Conveyor Stop	0	
Robot Path	STN1_adminCardG-ConveyorToRaw	19	
Resource	(Release) - 1.1 - Robot & Linear Slide	0	
Conveyor Task	Remove Pallet ID From Vehicle (PLC ID 1)	1	
Conveyor Task	Unlock Vehicle At Station (PLC ID 1)	1	
Resource	(Release) - 1.11 Conveyor Stop	0	
Resource	(Seize) - AssemblyStepB	190	Wait until male half arrives for assembly
Resource	(Release) - AssemblyStepA	0	
Robot Path	STN1_adminCardG-AssembleAToB	93	Rosie Assembles the parts and places it with Finished Goods
Resource	(Release) - AssemblyStepB	0	
Resource	(Release) - Raw Inventory A	0	
Rinse and Repeat			

Table A3: Descriptions of Steps' Abbreviation

Process A		**Process B**		**Process AB**	
AI	Load pallet on AGV	BI	Load pallet on AGV	ABI	Assemble parts
AII	Move to S4	BII	Move to S4	ABII	Wait time
AIII	Unload AGV	BIII	Unload AGV		
AIV	Load stock on AGV	BIV	Load stock to mill		
AV	Move to S3	BV	Milling		
AVI	Load stock to mill	BVI	Load Part B on AGV		
AVII	Milling	BVII	Move to S1		
AVIII	Load Part A on AGV	BVIII	Unload Part B		
AIX	Move to S1				
AX	Unload Part A				
AXI	Wait for Part B				

Table A4: Process Schedule

Time (min)	**Process A**	**Process B**	**Process AB**	**WIP (parts)**
0	A1	B1		2
1	A1	B1		2
2	A1	B1		2
3	A1	B1		2
4	A1	B1		2
5	A1	B1		2
6	A1	B1		2
7	A1	B1		2
8	A1	B1		2
9	A1	B1		2
10	A1	B1		2
11	A1	B1		2
12	A1	B1		2
13	A1	B1		2
14	A1	B1		2
15	A1	B1		2
16	A1			1
17	A1			1

18	A2	B2	AB1	3
19	A2	B2	AB2	3
20	A2	B2		2
21	A2	B2		2
22	A2	B2		2
23	A2	B2		2
24	A2	B2		2
25	A2	B2		2
26	A2	B2		2
27	A2	B2		2
28	A2	B2		2
29	A2	B2		2
30	A2	B2		2
31	A2	B2		2
32	A2	B2		2
33	A2			1
34	A2			1
35	A3	B3	AB2	3
36	A3	B3	AB2	3
37	A3	B3		2
38	A3	B3		2
39	A3	B3		2
40	A3	B3		2
41	A3	B3		2
42	A3	B3		2
43	A3	B3		2
44	A3	B3		2
45	A3	B3		2
46	A3	B3		2
47	A3	B3		2
48	A3	B3		2
49	A3	B3		2
50	A3			1
51	A3			1

52	A4	B4	AB3	3
53	A4	B4	AB3	3