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Integrated Digital Manufacturing: CAD/CAM and Generative Design in Advanced Process Planning

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Abstract

The use of computers in the field of design, manufacturing, and process planning is increasing day by day. Computer-aided Design (CAD), Computer-aided Manufacturing (CAM), and Computer-aided Process Planning (CAPP) are gaining huge importance across the world. This paper scope encompasses the Design for Manufacturability (DFM) process through the use of computer-aided design and manufacturing (CAD/CAM), as well as generative design. IENG 405 Group 3 worked within Autodesk Fusion 360 to create a simple, easy to manufacture, and functional CAD design (named DeskNote) which was then used in the analysis of overall manufacturability. To do this, the team created two toolpaths for an aluminum part - one for a 3-axis milling machine and one for a 5-axis milling machine within Fusion 360's Manufacture Workspace. The 5-axis design for manufacturing approach was similar to that of the 3-axis, but only contained one centralized setup, a facing operation, and a decreased cutting speed for toolpaths 1-6 by 100 sfpm. The team's purpose in reducing cutting speed for the 5-axis process was to investigate the result - longevity in tool life. Setup and tool data are used ultimately to display the cost per unit of manufacturing DeskNote on a 3-axis milling machine versus a 5-axis milling machine. The results obtained from the process plans were ultimately compared. Those results then rivaled against the produced outcomes of the generative design (from the Fusion 360 Generative Design Workspace), which used Aluminum 6061 and Stainless Steel AISI 304 materials. The team concluded that the 5-axis machining process with a 100 sfpm reduction in toolpaths 1-6 produced an over 48% reduction in cost per DeskNote.

Keywords
Design for Manufacturing, product design, Digital Manufacturing, CAD/CAM Application, Process Planning

1. Introduction
Design for manufacturability (DFM) is the process of designing a product or a component that is used to make the final production product process easier at the lowest cost. It uses a computer system that helps simulate different iterations of the design by using different materials and the different iteration of the production process that would benefit the manufacturer, consumer, and the designer.DFM occurs before the process of tooling and assembly production, it occurs in the product development process which prevents any complications during the production stage. Therefore, it would also help to optimize the design to make it efficient and simple and have a simplicit process. It reduces the number of the parts that would be used in the production process, minimizes the amount of manufacturing, to reduce the production time and the setting up time. CAD/CAM is a Computer-Aided Design and Manufacturing is a software program that is used in manufacturing to design and manufacture a final product. It assists DFM by designing a product with CAD and then it uses CAM to plan a process for production. The process that the CAM uses is called numerical control (NC). It directly controls the milling machines. The purpose of CAM is to produce a quicker production process.

1.2 Research Objectives

The objective of this project is to evaluate and compare manufacturing process plans using Autodesk Fusion 360, with a focus on cost-effective and efficient production through Design for Manufacturing (DFM). This will be achieved by:

1. Utilizing the Generative Design module in Fusion 360 to explore multiple design alternatives and analyze their cost implications.
2. Creating process plans for both 3-axis and 5-axis CNC machines, capturing key operational and economic parameters.
3. Analyzing critical machining characteristics such as tool paths, cutting parameters, time, cost, and tool usage.
4. Comparing results from Generative Design with traditional process planning to determine the most financially viable and manufacturing-efficient approach.
5. Supporting industry-relevant decision-making by providing a quantitative, objective framework for selecting optimal manufacturing strategies)

2. Literature Review

Design for manufacturability (DFM) is the process of designing a product or a component that is used to make the final production product process easier at the lowest cost. It uses a computer system that helps simulate different iterations of the design by using different materials and the different iteration of the production process that would benefit the manufacturer, consumer, and the designer. Design for Manufacturing (DFM) is a pivotal methodology in modern engineering, emphasizing the integration of manufacturing considerations into the early stages of product design. By aligning design specifications with manufacturing capabilities, DFM aims to minimize production complexities, reduce costs, and enhance product quality (Boothroyd and Dewhurts 2011), (aPriori 2021). The advent of advanced Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) tools has further facilitated the implementation of DFM principles, enabling designers to assess manufacturability and cost implications concurrently during the design process (Gao et al. 2022).

Autodesk Fusion 360 exhibits the integration of CAD, CAM, and Computer-Aided Engineering (CAE) in a single platform, providing capabilities to support DFM techniques. Its Generative Design (GD) module enables engineers to enter design objectives and restrictions, and it generates a plethora of optimum design alternatives. These solutions frequently show unique geometries and structures that would not have been created using typical design methodologies (Savage 2019), (IntrinSIM 2019). GD in Fusion 360 is especially useful for applications that need lightweight structures and part consolidation, resulting in material and cost savings (Shrestha 2021), (Hou 2021).
In manufacturing, especially when comparing 3-axis and 5-axis CNC machining, process planning is crucial for determining the most cost-effective and efficient production methods. While 3-axis machines are simpler and more cost-effective, they may be limited in handling complex geometries. Conversely, 5-axis machines offer greater flexibility and precision but come with higher operational costs and programming complexity (Altintas 2014), (Soori and Ahmed 2032).

Evaluating these alternatives necessitates a thorough analysis of machining parameters such as tool paths, cutting speeds, feed rates, machining time, and overall production costs (Zhang and Wang 2023).Recent advancements in CAM simulation tools within Fusion 360 enable accurate estimation of machining parameters, tool wear, cycle times, and total manufacturing costs. These tools support engineers in comparing process plans with high precision and objectivity, facilitating informed decision-making (Engineering LibreTexts 2020). Cost estimation models embedded in GD and CAM workflows assist in evaluating factors like tool life, tool change frequency, operator costs, and other operational parameters critical for manufacturing strategy selection (Burke 2024)

Integrating GD with process planning provides a solid foundation for comparing traditional and AI-driven design methodologies. Studies have offered frameworks for evaluating generative and traditional design processes using digital platforms such as Fusion 360. These frameworks use quantitative criteria to evaluate the time, cost, and feasibility of specific manufacturing approaches, bridging the gap between innovative AI-driven designs and practical manufacturing restrictions (Smell 2020). Industry case studies show that combining DFM and Process Planning can dramatically reduce design iterations and tooling changes, hence increasing total production efficiency (Als-Shebeeb 2018), (Al-Shebeeb 2016).

3. Part Design, Description, and Functionality

The part designed by the team has potential to serve as a multifunctional item, but it was determined by the team that the most effective use is a desktop sticky note and writing utensil holder. This part, named DeskNote, could hold pens, pencils, or even markers (with a diameter less than 0.40 in or 0.50 in) and a small set of sticky notes inside the inner shape (Figure 1). A top view of this part shows the two size differences of diameters to enhance user experience and usability of this part (see Figure 2). An additional feature of this part is the drilled side holes, which can be seen in Figure 1**.** These drilled side holes allow for further part applications and user creativity, or could simply serve a decorative purpose. If desired by the user, a solid bottom (such as sheet metal or plastic) could be placed onto the part and the side holes could allow for easier transport, while the utensils stay in place. The options are endless for this part, and the team's goal is to keep the purpose open-ended to ensure space for ultimate creativity.

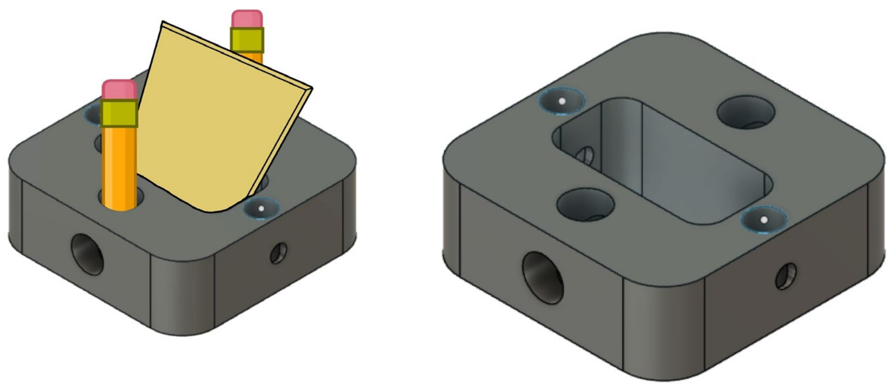


Figure 1. Isometric View of the DeskNote with and without a functional application

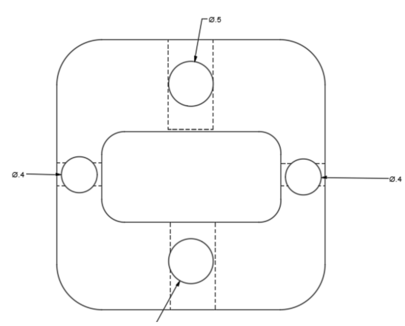


Figure 2. Drawing view (top of part) showing the hole diameters

4. Methodology

As stated in the part description above, the part designed by the team has potential to serve as a multifunctional item, but it was determined by the team that the most effective use is a desktop sticky note and writing utensil holder. The part is curved in nature and contains a large oval shaped hole in the middle with four holes on its top surface. There are also holes on the side that can be used for a multitude of purposes. The holes on the top of the surface are two different sizes: 0.4" and 0.5" in diameter. The main gap in the part has a width of 1" and length of 2". The holes on the side are different sizes as well with the smaller size being 0.25" in diameter and the larger being 0.5" in diameter. The length and width of the DeskNote is 3" and it has a height of 1". When creating the part, DeskNote was first drawn in the Design section of AutoFusion with holes and filets at the corners. The sketch was then extruded to its listed dimensions where the team cut out additional holes to make the part more functional.

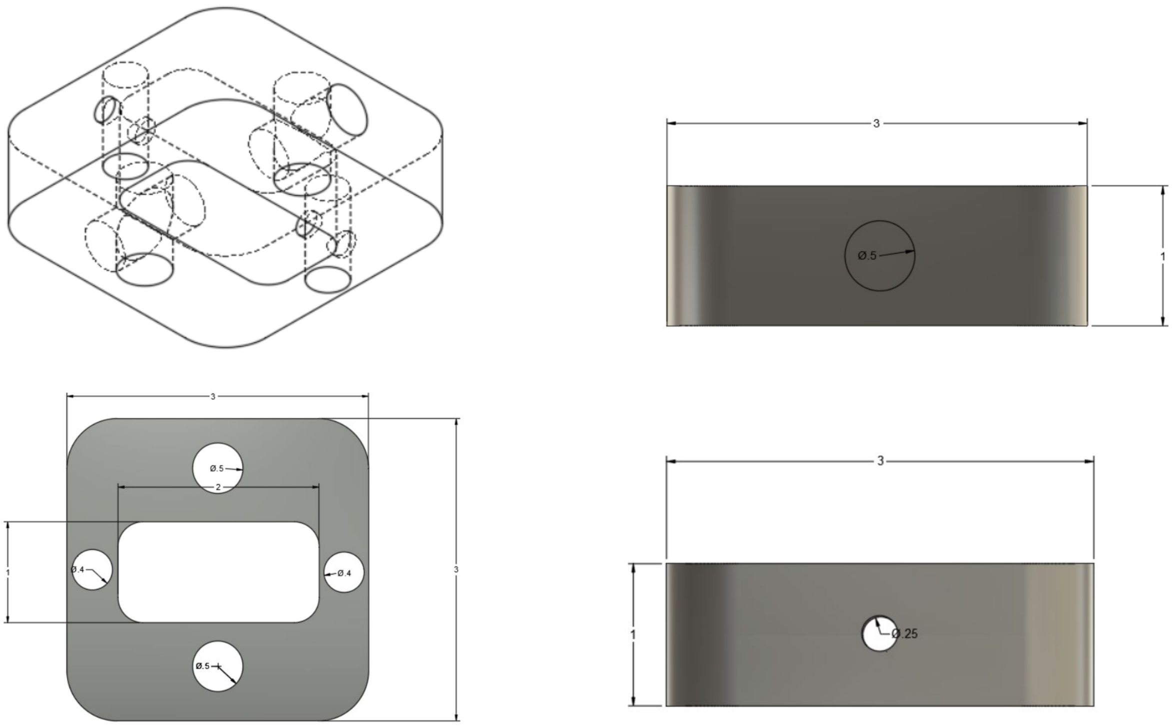


Figure 3. CAD Design in AutoDesk Fusion 360

4.1 3-Axis Milling

The team started off the DFM CAD/CAM process by designing the part and creating a toolpath setup specific to a 3-axis milling machine. Stock dimensions that were determined by the team are 3.08 in (Width, X) x 3.08 in (Depth, Y) x 1.04 in (Height, Z). Part dimensions are 3.00 in x 3.00 in x 1.00 in, which can be seen in Figure 3. As a result, the volume of the part is 5.961 in^3. Since the volume of the stock material is 9.87 in^3, the milling process results in a subtraction of 3.91 in^3 of stock material. The main part of this stock material subtraction results from the inner rectangle, which does not allow for much more optimization of stock material usage, since a rectangular shape is utilized as the stock material.

For the 3-axis milling machine setup, the number of setups established within Fusion360 was 5. The first step consisted of Parallel Finishing passes followed by Adaptive Clearing (Figures 5 and 6). Parallel Finishing removed any initial stock material, and Adaptive Clearing followed by milling out the 4 holes and middle rectangular shape. The tool assigned to both of these operations was a #1 - Ø1/4" ball end mill. This ensures a smooth machining process as a tool change is avoided at this point.

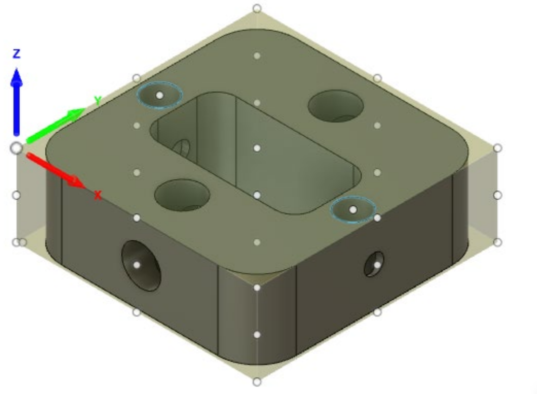


Figure 4. 3-Axis Setup

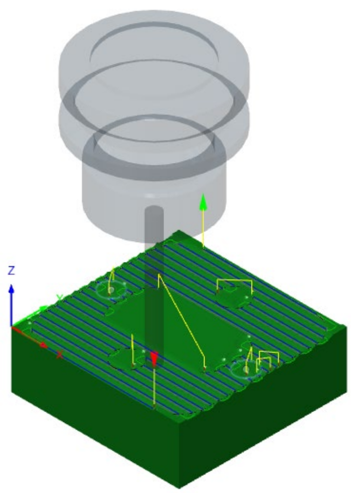


Figure 5. Parallel: ¼” Ball End Mill

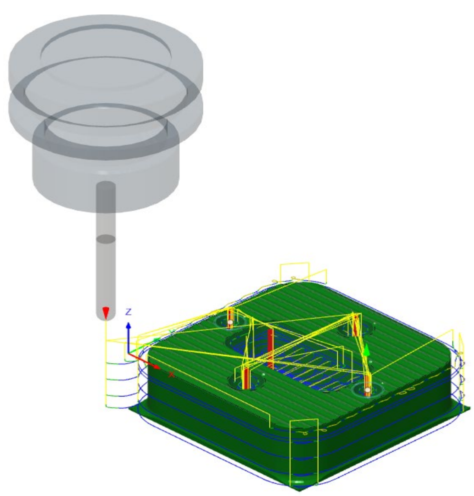


Figure 6. Adaptive Clearing ¼” Ball End Mill

The second and third setups consisted of a Drilling process to create the smaller side holes. Specifically, the operations were Small 1 and Small 2 [Rapid Out], respectively. Both of these setups also were assigned the same tools, #3 - Ø0.2” 118° drill. The part was flipped for each of these (first on the left side and next on the right side) and the tool performed the drill by moving down vertically in the Z direction. See Figure 7 for a visual of these Drilling operations.

Figure 7. Drill: 0.2" 118° (drill)

The fourth and fifth (final) setups also consisted of an additional Drilling process to create the larger side holes. Both of these operations consisted of Big 1 and Big 2 [Rapid out], respectively. The tool assigned to these operations was a #4 - Ø1/2” 118° drill. First, the part was flipped on its front and then its back for another vertical drill performed on the Z axis. See Figures 8 for a visual of both of these operations.

Figure 8. Drill: ½ " 118° (drill)

4.2 5-Axis Milling

After the 3-Axis Milling’s respective setup and tool paths were completed, the team decided to use a 5-Axis Milling approach by generating one set up that contained a multitude of tool paths that performed various operations. The team utilized a relative sized stock box that was 3.08” in width (x), 3.08” in depth (y), and 1.04” in height (z). The team used one set up with seven different operations. The total volume of the stock material was 9.87 in^3 and the final part's volume is 5.96 in^3. This results in a total material removal of 3.91 in^3. The first operation that was performed was the parallel process which is a common finishing procedure. This operation eliminated the initial layer of the stock material.

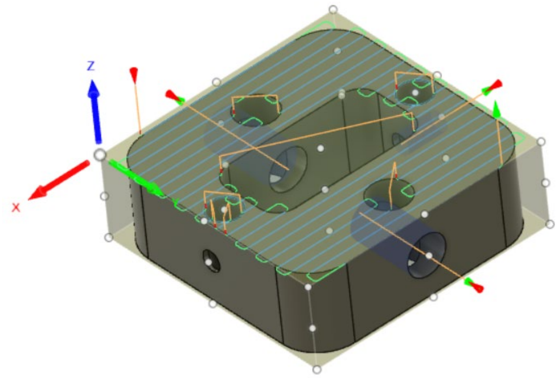


Figure 9. 5-Axis Set-Up

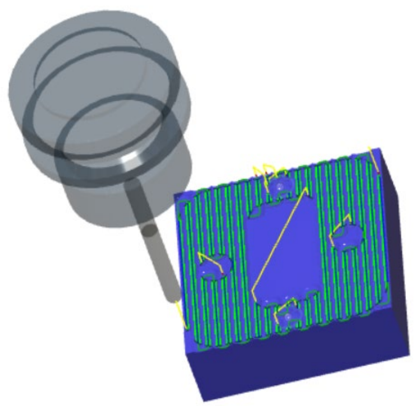


Figure 10. Parallel: ¼" Ball End Mill

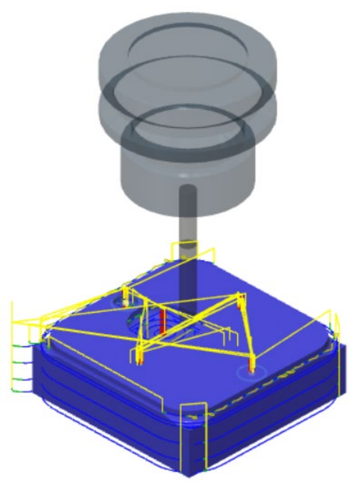


Figure 11. Adaptive Clearing: ¼" Ball End Mill

Following the parallel procedure, the team used an adaptive clearing tool path to remove the material around the part's most prominent features. Once this was completed, the team used drilling to remove the material within the remaining four holes. The figures listed below show the tool paths for each of these procedures. The drilling's coordinate system's orientation was manipulated so that the z-axis faced the opposite direction the drilling tool initially faced to effectively penetrate the part. The drilling penetrated the part 0.975 inches which was the width of the sides of DeskNote.

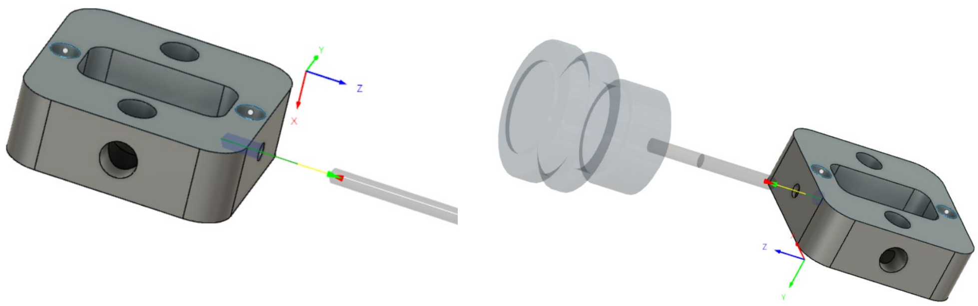


Figure 12. Drilling: 0.2" 118° Drill

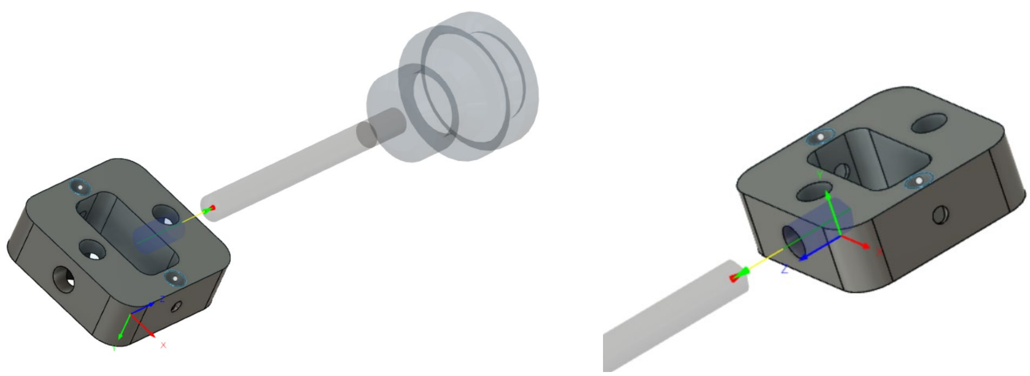


Figure 13. Drilling: 0.5" 118° Drill

After drilling was completed, the team finally created a tool pathing for the Face Mill. The purpose of the Facing was to eliminate the grooves that the parallelling made in the first operation. The orientation of the coordinate system for the facing mimicked that of the parallel and the adaptive clearing. The facing operation was found to have removed 0.379 in^3 of material.

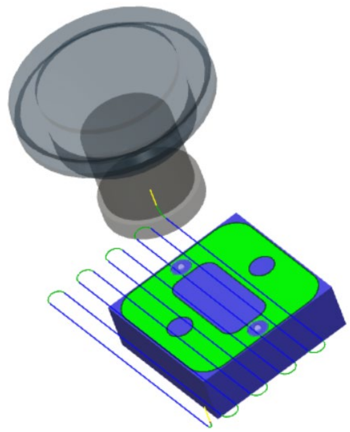


Figure 14. Facing: 2” Face Mill

4.3 Generative Design

After creating the product the next step was to create the Generative Design in order to get the possibilities when producing the DeskNote. With the Generative Design setup the first step is to set the Preserve Geometry which sets what part of the DeskNote is the essential piece of the product. The Preserve Geometry is denoted by the green piece. After the Preserve Geometry then immediately have to set the Obstacle Geometry this will set the holders in for the DeskNote. The Obstacle Geometry is there to maintain essential gaps. The Obstacle Geometry is denoted by the pieces.

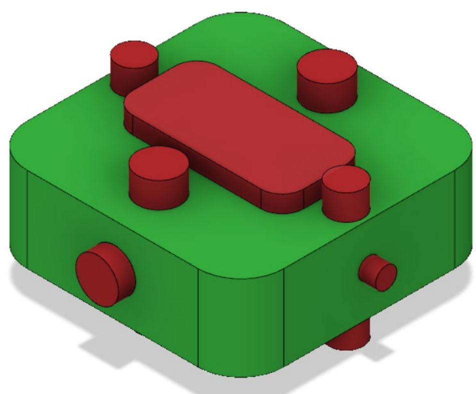


Figure 15. Figure 15 Preserve and Obstacle Geometry

The team’s next step was to set the Structural Constraints. These Structural Constraints were fixed constraints, the fixed constraints selected were the outer circles where pencils or pens will be held because they will need to be structurally sound in order to hold multiple pencils or pens. Also, the Structural Loads needed to be set which sets the amount of force these certain locations will have to be able to undergo. With the DeskNote it will not have to be under a great amount of force, but in order to take precautions, the team had to set the forces at 20N. The DeskNote could fall off your desk and hit the ground so that is why this precaution was taken. The Structural Constraints are denoted by locks and Structural Loads are denoted by blue arrows.

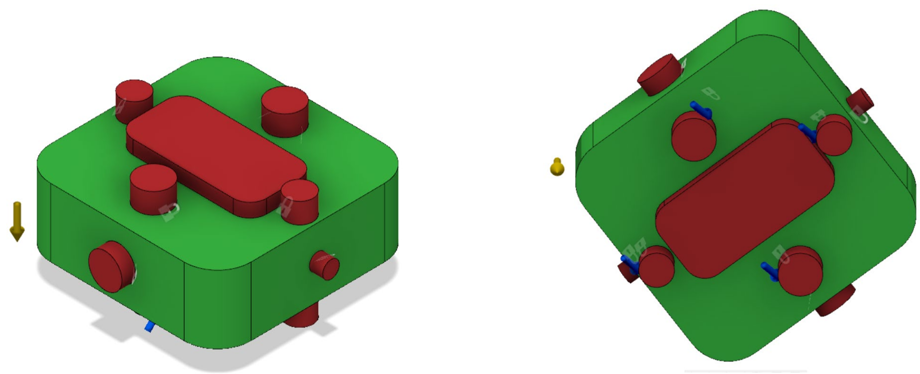


Figure 16. Structural Constraints (left) & Structural Loads (right)

With all of these set the team could then focus on the manufacturing part of the study. With this section, the team set how many pieces will be manufactured and what kind of manufacturing process will be used. The team focused the study around manufacturing 1000 products with 3-axis and 5-axis milling. The safety factor was set to 2.00 to minimize mass because the team did not want DeskNote to be extraordinarily heavy.

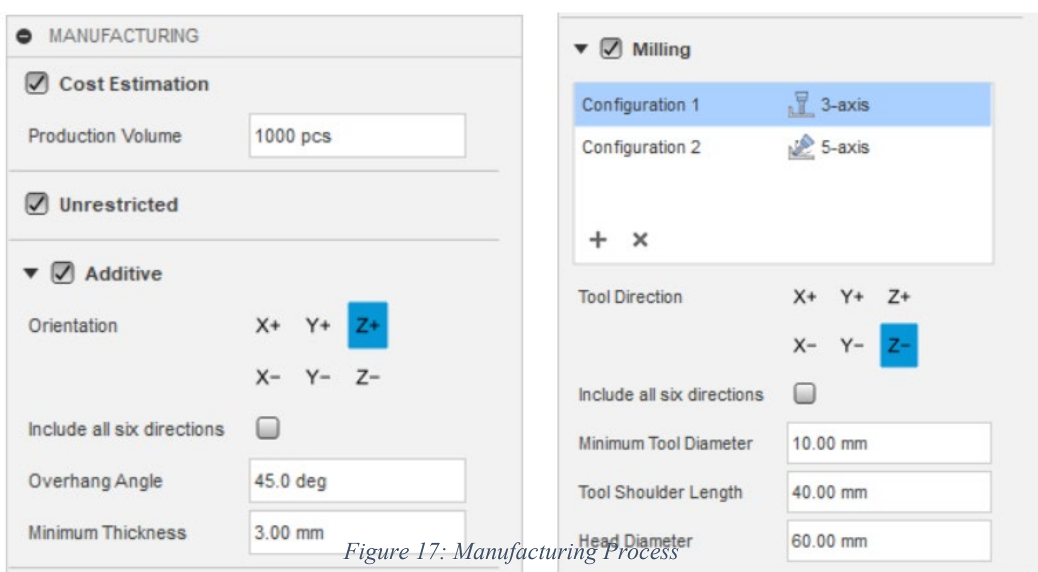


Figure 17. Manufacturing Process

Once setting this, the materials the team wanted to study were decided upon. It was decided to use Aluminum 6061 and Stainless Steel AISI 304. These are durable materials that allow the DeskNote to be strong and sleek.

5. Results/Discussion

3-Axis

To effectively obtain all of the correct tool paths, the team created 5 setups for the 3-axis milling operation. From the tool and machining data, IENG 405 lecture slides, IENG 302 textbook, and information found online, the team was able to create a comprehensive process plan for the 3-axis milling process.

This process plan (see Table 2 below) was built on a variety of assumptions based on the team's research. The first was that the part material was aluminum. The second assumption was that C, the Machining Constant in the

Taylor's Tool Life Equation, was equal to 420. This was based on both the IENG 405 Lecture 4 and homework assignment 2. The third assumption was that n, the cutting tool index from Taylor's Tool Life Equation, was equal to 0.3. This was determined as the team's research uncovered that a general range for high speed steel (HSS) tools was 0.1 to 0.5. The team decided to find the average of this range and use it in the calculations. A list of the various process indices along with sources of information/equations that were used in the process plan calculations can be found in Table 1 below.As a result of the 3-axis milling process plan analysis, it was determined that the total machining cost was $81.63, and the total tool cost was $79.11. This resulted in a total cost for one milling process of $160.74.

Table 1. Process Indices Source of Information and Equations Used for 3-Axis and 5-Axis Process Plans

Process Index	**Source of Information**	**Equation Used (If Applicable)**
Depth of Cut	Autodesk Fusion 360	N/A
Cutting Speed	Autodesk Fusion 360	N/A
Feed Rate	Autodesk Fusion 360	N/A
M. Setup Time Ts	Cutting Tool Parameter Selection Table (Lecture 4)	N/A
Op. Cost	Calculation/Cutting Tool Parameter Selection Table (Lecture 4)	N/A
Tool Chng. Time	Cutting Tool Parameter Selection Table (Lecture 4)	N/A
Han. Time	Cutting Tool Parameter Selection Table (Lecture 4)	N/A
Tool Life (HSS 2 Flute)	Calculation	$VT^n = C$
Tool Chng. Time/Pc (min/np)	Calculation	$\frac{T_t}{n_p} = \frac{T_t}{\frac{T}{T_m}}$
Total M. Cost	Calculation	$T_m * C_o$
Total Tool Cost	Calculation	$\frac{T_m}{T_l} * 8$
Total Cost for One Process	Calculation	$T_{mc} + T_{tc}$

Table 2. 3-Axis Milling Process Plan

Process Index		M. Process Name	Depth of Cut	Cutting Speed	Feed Rate	M. Time	M. Setup Time Ts	Op. Cost	Tool Chng. Time	Han. Time	Tool Life (HSS 2 Flute)	Tool Chng. Time/Pc	Total M. Cost	Total Tool Cost	Total Cost for One Process
Setup 1			(in)	(sfpm)	(in/min)	(min)	(min)	($/min)	(min)	(min)		(min/np)			
1	[T1] Parallel1	Milling	0.08	314.15	60	1.13	10	$1.08	0.5	2	2.632	0.2146	$14.72	$3.43	$18.15
2	[T2] Adaptive1	Milling	0.3	314.15	60	18.37	0	$1.08	0.5	2	2.632	3.4894	$22.54	$55.83	$78.37
Setup 2															
1	[T3] Small 1 [Rapid out]	Drilling	0.492	261.79	40	0.27	15	$1.08	0.5	2	4.834	0.0279	$19.19	$0.45	$19.64
Setup 3															
1	[T3] Small 2 [Rapid out]	Drilling	0.492	261.79	40	0.27	0	$1.08	0.5	2	4.834	0.0279	$2.99	$0.45	$3.44
Setup 4															
1	[T4] Big 1 [Rapid out]	Drilling	1.025	654.49	40	0.27	15	$1.08	0.5	2	0.228	0.5923	$19.19	$9.48	$28.67
Setup 5															
1	[T4] Big 2 [Rapid out]	Drilling	1.025	654.49	40	0.27	0	$1.08	0.5	2	0.228	0.5923	$2.99	$9.48	$12.47
Total							**40**						**$81.63**	**$79.11**	**$160.74**

<u>5-Axis</u>

After the 3-Axis milling setups and their respective tool paths were completed, the team created a 5-Axis milling set up with seven toolpaths. One of the main differences between the 3-Axis and 5-Axis design for manufacturing approaches was that only one set up was used for the 5-axis machine whereas 5 setups were used for the 3-Axis approach. In addition to adding the facing operation in the 5-Axis DFM, the team also detracted 100 sfpm from the cutting speed of the tool paths 1-6 as listed below in the process plan. The intent of this was to investigate the relationship of Taylor's Equation, $VT^n = C$, and more specifically analyze the effect of lowering V (cutting speed) on the overall tool life. By deducting 100 sfpm from the cutting speed, the tool life increased 4x to 5x depending on the process. Furthermore, after making the appropriate adjustments in AutoFusion 360, it was found that there was no effect on the machine time from reducing the cutting speed. However, it is important to note that the feed rate was not adjusted when performing this analysis.

Another aspect of switching to the 5-Axis milling is that the machine set up time decreased from 40 minutes to 10 minutes which is equivalent to a 75% savings in set up time. By consolidating all of the set ups into one, the team was able to save time and consequently money in set up time alone. Even though an operation (facing) was added, there was an overall reduction in total machine cost of $28.06 which is a 34.37% reduction in this specific process index. There was also a savings of $50.31 in total tool cost which is equivalent to a 63.60% reduction in this process index. In total, there was a savings of $78.37 which is a 48.76% reduction in total cost by using a 5-Axis milling machine and reducing the parallel, adaptive, and drilling processes' cutting speed by 100 sfpm. All of the sources for the data found by the team can be referenced in Table 1 above and the data itself can be referenced in Table 3 below.

Table 3. 5-Axis Milling Process Plan

Process Index		M. Process Name	Depth of Cut	Cutting Speed	Feed Rate	M. Time	M. Setup Time Ts	Op. Cost	Tool Chng. Time	Han. Time	Tool Life (HSS 2 Flute)	Tool Chng. Time/Pc (min/np)	Total M. Cost	Total Tool Cost	Total Cost for One Process
Setup 1			(in)	(sfpm)	(in/min)	(min)	(min)	($/min)	(min)	(min)		(min/np)			
1	[T1] Parallel1	Milling	0.08	214.16	60	1.13	10	$1.08	0.5	2	9.442	0.0598	$14.72	$0.96	$15.68
2	[T2] Adaptive1	Milling	0.3	214.16	60	18.37	0	$1.08	0.5	2	9.442	0.9728	$22.54	$15.57	$38.10
3	[T3] Small 1 [Rapid out]	Drilling	0.492	161.80	40	0.27	0	$1.08	0.5	2	24.039	0.0056	$2.99	$0.09	$3.08
4	[T3] Small 2 [Rapid out]	Drilling	0.492	161.80	40	0.27	0	$1.08	0.5	2	24.039	0.0056	$2.99	$0.09	$3.08
5	[T4] Big 1 [Rapid out]	Drilling	1.025	554.50	40	0.27	0	$1.08	0.5	2	0.396	0.3408	$2.99	$5.45	$8.44
6	[T4] Big 2 [Rapid out]	Drilling	1.025	554.50	40	0.27	0	$1.08	0.5	2	0.396	0.3408	$2.99	$5.45	$8.44
7	Face	Facing	0.0027	209.44	40	1.52	0	$1.08	0.5	2	10.169	0.0747	$4.34	$1.20	$5.54
Total							**10**						**$53.57**	**$28.80**	**$82.37**

3-Axis Generative Design Result

The results for the 3-axis milling with Stainless Steel as the material consisted of a range cost of $26-$76, with a median of $44, and a mass of 0.812 kg. The results with Aluminum as the material consisted of a range cost of $8-$26, with a median of $14, and a mass of 0.274 kg.

With these results, the team has some immediate issues: not all of the side holes have been created for either material. The inner holes of the design were also not created with this design. Structurally, it is quite similar to the design the team created, as it has the rounded edges and the rounded rectangular center.

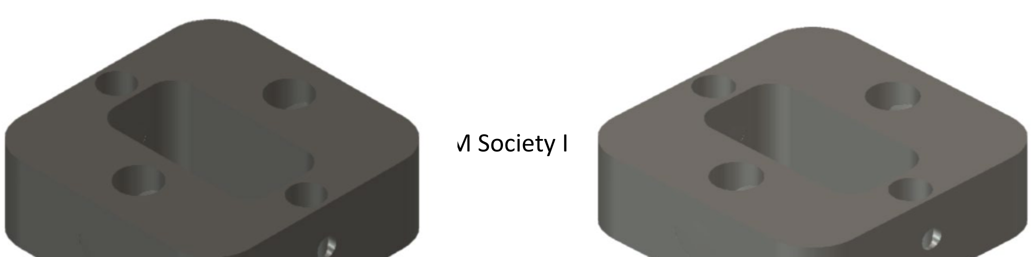
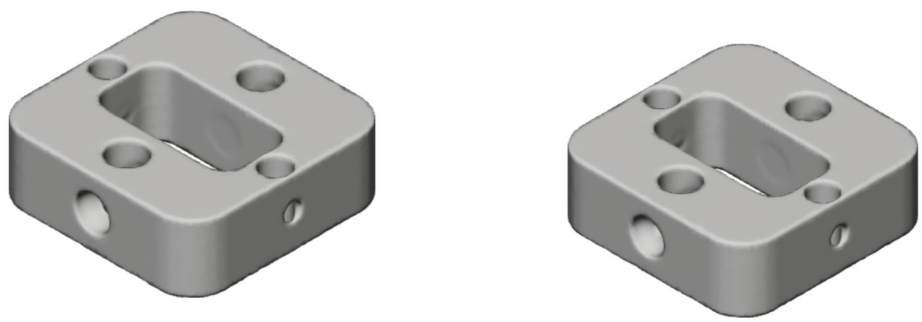


Figure 18. 3-axis Generation Stainless Steel (left) & 3-axis Generation Aluminum (right)

5-axis Generative Design Result

The results for the 5-axis milling with Stainless Steel as the material consisted of a range cost of $31-$90, with a median of $60, and a mass 0.795 kg. The results for Aluminum as the material consisted of a range cost of $10-$30, with a median of $19, and a mass of 0.269 kg.



*F*igure 19. 5-axis Generation Stainless Steel (lrft) & 5-axis Generation Aluminum (right)

In these generations, the team only noticed a slight variance from the design. The smaller inner holes were not created which is only a slight issue because the holes are on the side and they may not have any true functionality. The team also saw a difference from the 3-axis process since this process actually drilled all of the outer side holes. Structurally, they both have the rounded edges and rounded rectangular center.

6. Conclusion and Limitations

For the 3-Axis machining, the total machining cost was calculated to be $81.63, the total tool cost was found to be $79.11, and the resulting total cost was $160.74. There were a total of five setups which accounted for 40 minutes of set up time. For the 5-Axis machining, the total machining cost was calculated to be $53.57, the total tool cost was found to be $28.80, and the total cost for one process was $82.37. There was only one set up for the 5-Axis machining process which had a set up time of 10 minutes.

It can be seen that the 5-Axis machining process with a 100 sfpm reduction in toolpaths 1-6 produced an over 48% reduction in cost. The 5-Axis machining also offers more ability and greater accuracy than 3-Axis which maxis this machining method even more appealing.

The process planning part of the analysis was not the only aspect of the DFM that pointed to using the 5-Axis machining. The Generative Design process did as well. When generating other designs within AutoFusion 360, it was found that 3-Axis machining produced designs that eliminated the holes on the sides which in turn limits the functionality of DeskNote. When analyzing the generated designs for the 5-Axis machining, it was found that the generated designs did not have any limitations in functionality. All in all it can be seen that 5-Axis machining is the better approach in both cost and in functionality as seen in the analysis above.

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