

AALBORG UNIVERSITY COPENHAGEN

Integration of Computer Aided Process Planning to Rapid Prototyping and Manufacturing for the use of 4 axis Computer Numeric Controlled milling machines

Master Thesis

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Abstract

The investigation of this thesis derives from the Maker Culture and the issues that both the users and the staff are exposed to – the use and the integration of the machines requiring high tech skill level and experience to operate. The particular problem of 4 Axis CnC Mill machines integration is tackled by the research in the domains of Rapid Prototyping, Rapid Manufacturing and Computer Aided Process Planning. The research has led to design and implementation of the Add-On tailored for Fusion 360 software, which analyses the 3D model of the object to be machined and helps the user to choose appropriate parameters related to setting up the rotary machining operations.

The functionality of the solution was tested via online experiment where the performance of small sample of 8 subjects, mostly experienced CnC users, was compared to the performance of the Add-On. Experiment results showed promise as the overall performance of the Add-On surpassed the test subjects. The results also indicate possibility of simplifying the solution while focusing on the sequencing of machining orientations already defined by the user to optimise total machining time.

Despite positive results, functionality experiment should be tested further with wider sample and additional 3D models for more conclusive results. Additionally, not all implemented features were part of the functionality experiment, thus further User Experience testing is required to evaluate the usability of the Add-On.

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1. Introduction

“Making is fundamental to what it means to be human.

We must make, create, and express ourselves to feel

whole. There is something unique about making

physical things. Things we make are like little pieces

of us and seem to embody portions of our soul.”

- Mark Hatch, “Makers Movement Manifesto” [1].

People of all times and cultures have fabricated physical objects. Amongst many complex reasons to do so, the basic will to survive offers itself as the simplest. Nevertheless, the objects that have been created throughout history bears testimony to an innate drive to create beyond the means of survival. The artistic way of self-expression and the sheer curious inventiveness of the human mind, has led to creative and innovative creations increasingly advanced.

The technological advancement has progressively given way to new fabrication techniques to accommodate human desire to create, thus pushing the technical advancement even further ahead. These subsequently changes human societies in an ongoing process. The close to omniscient digital technology, that today has been implemented into nearly every aspects of life, has also given way to new fabrication technologies. Until recently these high end fabrication technologies were due to their high cost mainly available to large institutions or industry manufacturers, and therefore not accessible to the general public.

A maker movement, a technology oriented part of a broader do-it-yourself (DIY) culture and community, emerged in the 1990's. When Neil Gershenfeld, professor and director at MIT Centre for Bits and Atoms, initiated the first Fab Lab (Fabrication Laboratory) at MIT in 2001, it was the beginning of a growing global network of Fab Labs. Personal fabrication was made accessible via prototyping tools such as 3D printers, laser cutters and CnC¹ machines.

Gershenfelds vision to make the Fab Lab an inventive and innovative space, where the student/user should be able to fabricate almost anything, using the latest digital fabrication technology, has since grown to be “a knowledge sharing network of over 1,000 Fab Labs in 97 countries and 24 time zones. Because all Fab Labs share common tools and processes, the program is building a global network, a distributed laboratory for research and invention” [2]. The realization of Gershenfelds vision, and the growth of Fab Labs outside university domain, was also made possible by the “rapidly dropping costs of digital manufacturing tools, the availability of powerful free software, the rise of open hardware, social networking and the growth of community spaces where makers can gather” [3].

¹ CnC – Computer Numeric Control, used for automation of machine tools and control via computers

Alongside and in extension of the early DIY movement and the increasing number of Fab Labs, an array of spaces where individuals or groups can transform their ideas into physical form has emerged.

The makerspaces are individually as different as their users, who could be the enthusiastic hobbyist, or the experienced engineer, and so the term makerspace is very inclusive. However, a shared mind-set can often be found as the foundation of these spaces, valuing creativity in the learning progress, the sharing of knowledge and invention, thus a learning/teaching synergy with emphasis on the space to be open and available to those who wish to engage.

In addition to the single individual gaining knowledge and skills in the makerspace, the makers DIY or do-it-with-others (DIWO) approach to fabricating, is being argued to have other positive effects on society. A creative maker, with access to high end technology, and the pool of knowledge the maker community provides, might prove a positive influence in a world, where economic, ecological and social challenges are reoccurring, and constantly demands new and innovative solutions.

The accessibility to the technologies can also be seen as democratizing, as the means of fabrication are no longer a privilege of the few. Via economic and ecological perspective, the maker movement can also be seen as part of a more sustainable solution to production. The Fab Labs in developing countries have proved useful by providing sustainable solutions, to very specific and hands-on problems, by subsequently improving the community's welfare and livelihood [4].

The processes and approaches exercised in the makerspaces, has resonated with teachers in both formal in informal educational programs, and supports the idea that education "grounded in "making" has the capacity to transform the way we think about pedagogy and learning " [5].

Aiming to educate people of all ages and using the technology already available in many educational institutions, the maker movement is being offered as a "vehicle that will allow schools to be part of the necessary return to constructivist education. It is a movement that will allow students to be creative, innovative, independent, and technologically literate; not an "alternative" way to learn, but what modern learning should really look like" [6].

Besides the users – teachers and students, the equipment available is what binds the maker culture as a whole. With the help of tools the makers create and experiment, however tools are also what stand between the concept and its realisation. Basic tools, such as hack saws or hand drills do not require much prior knowledge to operate compared to band saws or 3D printers. Nevertheless, the latter two can be taught and learned much easier than the heavy tools such as CnC mills or lathes.

Task	Tech Level	Tool
Constructing a 3D object	Low	Hand model and cast
	Medium	3D Printer
	High	CNC Mill
Making a hole in metal plate	Low	Hand drill w/ hole saw
	Medium	Plasma cutter
	High	CNC Mill

Figure 1. Different tools for the same task [7]

The knowledge sharing and tool accessibility differs across makerspaces and is defined by local rules. An example of well organised laboratory facilities - University makerspace on campus of Georgia Institute of Technology. Being well funded it has state of the art fabrication equipment, and is ran mostly by the undergraduate student volunteers. Despite the users of the lab being the students of engineering, the CnC mills and lathes are still handled by a university staff machine shop professional [8]. This proves problematic to makerspaces and Fab Labs with a less technically skilled user base in regards to complex machinery integration – its availability to public, maintenance and the optimal use.

While integration of heavy machinery for makerspaces pose multiple problems, this thesis will approach the integration through the process optimisation and automated assistance for the users of mentioned spaces as target group.

1.1. Background

In this chapter, necessary concepts and vocabulary of CnC machining is explained. Concepts presented here are needed to understand the research and the implementation that follows. Additionally, concepts of rapid fabrications and Computer Aided Process Planning are elaborated upon due to its importance to the Maker Movement and to the research of optimisation processes.

1.1.1. CnC milling

CnC machining is a subtractive fabrication process involving control of machine tools using computers. A variety of machines can be controlled this way such as lathes and grinders, however this thesis will focus on mills and routers. In manufacturing, CnC machining is advantageous due to its precision and ability to produce complex shapes out of hard materials such as titanium alloys.

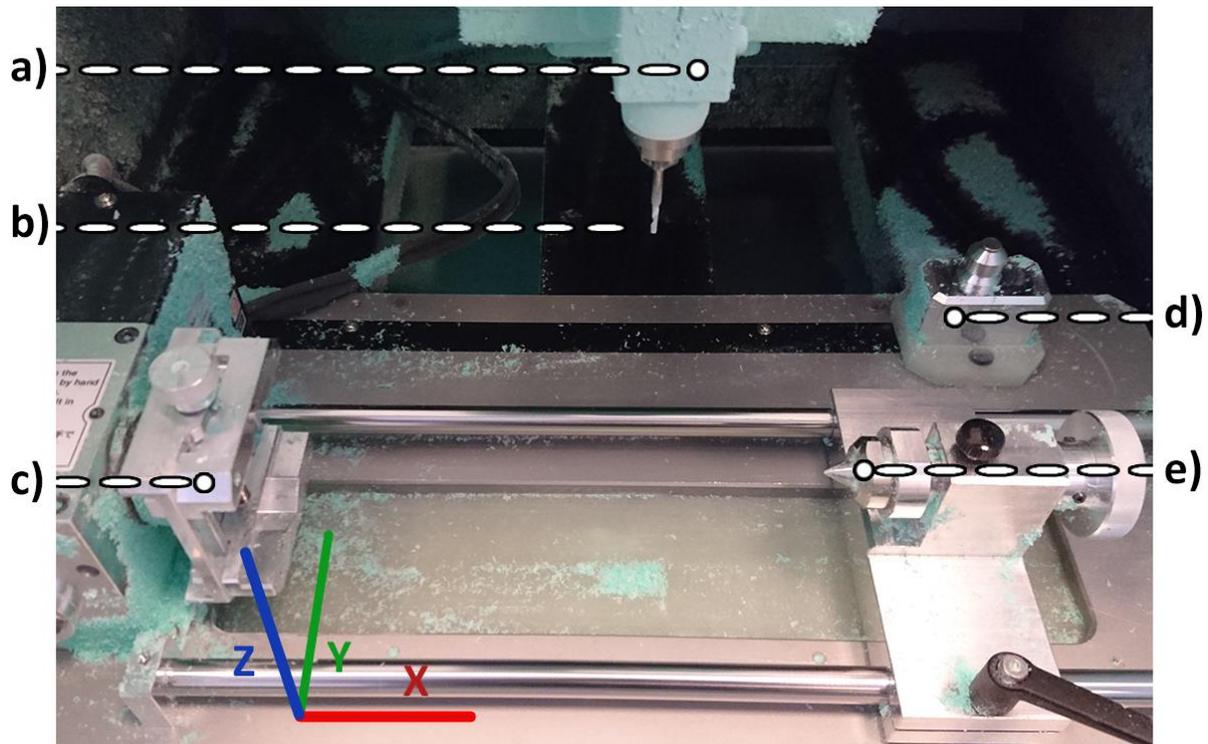


Figure 2. Image of Roland MDX- 40A with Rotary unit: a) Spindle Head b) Cutter c) Clamps on rotary motor – Rotary Axis d) Tool measuring sensor e) Tailstock to secure the backside of the stock

Basic CnC milling preparation and execution:

- The desired object is modelled using Computer Aided Design (CAD) software.
- The machine contains a spindle head (a), which holds the cutter (milling bit) (b) and motors able to move the spindle in number of directions. The spindle contains a motor to spin the cutting tool with varying power. A piece of material a.k.a. stock (metal, wood, plastic, etc.) is secured inside the machine and the appropriate cutting tool is secured inside the spindle.
- The toolpaths – directions of “how” the machining will be performed using the particular cutter is generated inside the Computer Aided Manufacturing (CAM) software. The toolpaths are then converted to code, which particular CnC machine can read and is sent for the execution. As code is being executed, the activated spindle is moved by motors cutting the stock and removing material in layers in order to obtain desired shape.

Typically, to machine the object from the start to the finish, the toolpaths generated are categorised as Roughing operations and Finishing operations. The roughing operations are done using the bigger and more resilient milling bits in order to remove the most bulky part of the stock in shortest time. Through finishing operation the remaining stock is removed in a much slower manner to cut the intricate features of the geometry and to finish the surface detail.

Between roughing and finishing operations tool has to be changed. Depending on the CnC machine, tool change can be either performed manually by the machine operator or automatically if necessary attachment is present.

CnC machines vary in complexity depending on the number of active axis a workpiece and/or the spindle can be manipulated simultaneously. This thesis will focus on CnC machines with indexer

(rotary) axis. Rotary axis is used to orient the stock piece of material so that the cutter would be able to access all sides of the stock along the axis of rotation. While using Rotary Axis, machining can be “continuous 4 axis wrapping” or “indexed (3+1)”. In continuous milling, the y axis is locked on the centre of the rotary axis - thus the cutter is always perpendicular to it. Cutting is then performed by simultaneously moving the bit to the sides along the x axis, up and down along the z axis and rotating stock around the A (rotary) axis. In “3+1” machining, the rotary axis is only used to position the stock and then perform standard 3 axis vertical milling. In other words, “3+1” is not continuous because during the actions of the rotary axis, there can be no machining of the stock.

Intricacies of CnC machining come from multiple preparation steps and a great number of parameters involved in every step. Additionally, any mistake in calibration, positioning or speed values is likely to damage costly materials, break cutting tools or worst case break the CnC machine.

1.1.2. Rapid Prototyping and Rapid Manufacturing

Rapid Prototyping (RP) is a family of fabrication methods used to make engineering prototypes in the shortest possible time, based on a Computer Aided Design (CAD) model of the item. RP technologies were first used for fabricating prototypes, however some of these technologies were able to produce items of near net shape² quality, thus creating a new group of manufacturing technologies – Rapid Manufacturing (RM) [9][10]. Rise of both RP and RM can be accredited to the technological development and integration of CAD and Computer aided manufacturing (CAM) applications. Main difference between RM and RP is the perspective of a produced item, whether it is a nearly finished product or if it serves as a prototype. Despite the differences of the final outcome, both RP and RM pipelines focus on producing items in the most optimised manner.

“Unlike other RP systems that use CNC machining for only a part of the process, CNC-RP is a fully subtractive process that uses a 3-axis vertical milling machine with a 4th axis indexer”[12].

Analogically, same can be said about CNC-RM.

In additive manufacturing rapid prototyping (AM-RP) technologies, such as Selective Laser Sintering (SLS) or Fused Deposition Modelling (FDM), the time consumption in overall production is spend mostly in execution rather than planning. Whereas CNC-RP/RM is the opposite – the planning stage is the more time consuming stage.

² “Near net shape” is manufacturing technique, which implies that the produced item is very close to being final and require little to none surface finish.

1.1.3. Computer Aided Process Planning

Computer Aided Process Planning (CAPP) – refers to the use of “computer technology to aid in the process of planning of a part or a product, in manufacturing. CAPP is the link between CAD and CAM in that it provides for the planning of the process to be used in producing a designed part” [13].

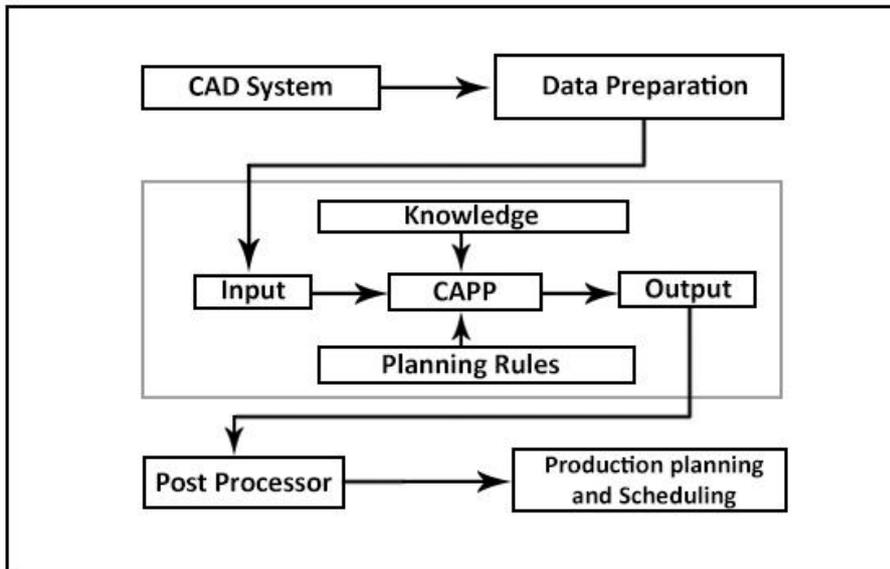


Figure 3. Model of Computer Aided Process Planning [13]

CAPP is concerned with full automation of manual processes related to CAM and its standardization. Some aspects of CAPP are researched in the later chapters in connection to automated solution integration for the problem at hand.

1.2. Problem Statement

Advances in fabrication technologies and its growing availability, creates an environment where users without engineering background are able to learn, create and build. However the learning curve of some machinery is steeper than others. A first goal of self-taught and novice machinists is to focus on the part³ at hand and fabricate it without causing damage to the CnC machine and the tools used.

The learning curve is steep and looking for solutions online is not straight forward – a variety of machines and software available complicates the search of a tailored solution to the problem. As the user learns, the collision factor decreases, and the planning and the machining time optimisation becomes the focus.

This thesis targets user of rapid CNC prototyping and manufacturing – attendants of makerspaces, such as low volume manufacturers, students, beginners and hobbyists in attempt to reduce the time spent during the planning stage of the development.

The research question:

³ Part – the object which is to be fabricated

How the planning stage of CnC Rapid Manufacturing/Rapid Prototyping could be reduced (optimized) via a software solution for the target user?

2. Related Work

The following chapter is the investigation of manual planning of CNC-Rapid Prototyping/Rapid Manufacturing optimisation progression, and key features of CAPP which could significantly assist in the planning stage, without seizing all of the manual control. The further research will revolve around these components of CNC-RP/RM planning:

- Selecting machining orientations
- Selecting tool sizes and shapes

2.1.1. Machining orientation

First milestone in standalone CNC-RP/RM for complex parts was the use of indexer (rotary) axis. The same parts could be produced using only 3-axis vertical milling, however the indexer saves tremendous amounts of time by eliminating the need of flipping the stock and accurate re-positioning, the machine calibration and the securing of the stock via clams and vices.

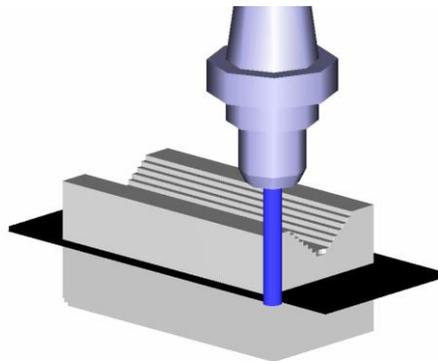


Figure 4. “Thin Web” [16]

During first roughing operation, while trying to remove maximum amount of material from the stock, the logical assumption is to start with the two angles, 180 degrees apart. However, after the second being angled cut, a thin layer of material will remain between the opposite angled cuts called “thin web”. If the material at hand is metal, while machining thin web, the tool is likely to break due to the thin layer of material wrapping around the tool. While machining hard plastic (like sika block), as the thin web breaks, it can reduce the smoothness of the finish and produce extra post machining manual work or damage the surface all together. “The current heuristic method to avoid creating a thin web is to machine from 0°, 135° and 225° which is used to safely remove the bulk of the stock material”. [14]

On the other hand, the study by Osman Zahid et. al. [15] proposed slightly different approach concerning machining orientations. Instead of performing roughing and finishing operations one side at the time separately, authors proposed 4 angles (0°,90°,180°,270°) at which firstly all roughing is

done and then all finishing. The cutting depth of the roughing operation was reduced, thus taking longer to run, however it was found that it resulted in a reduction of the total machining time. Additionally, due to this kind of approach the tool change occurred only once.

If comparing only the angle degrees and amounts of machined sides – three angles are more optimal and would be executed and planned faster, requiring less toolpaths to generate and still would avoid the thin web problem. On the other hand, milling (without knowing the shape of the part) at four angles, equally spaced by 90° – operation is more likely to leave less excess material still attached to the part. Thus leaving less material to remove for the finishing operation.

If left to CAPP, Visibility Algorithm (VISI) would be used to determine a minimum set of machining orientations, covering all features of the part. VISI uses a CAD model of the part and analyses cross sectional slices in order to return the orientations required. Renner [16] proposed improvement to VISI in order to additionally avoid the thin web problem by generating a minimum set of orientations first via VISI, then pass one of the generated orientations as initial angle for VISI to return more equally spaced remaining orientations.

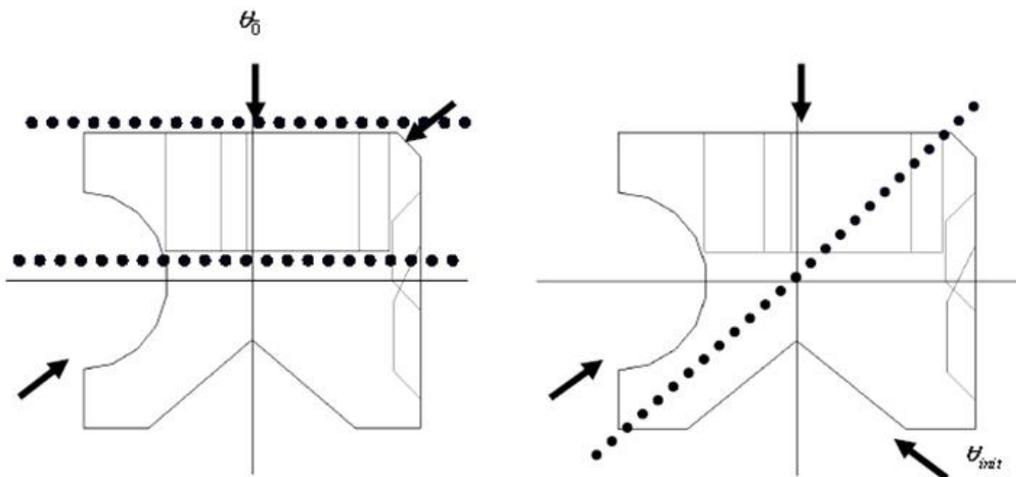


Figure 5. Minimum set of orientations (left) and Set of VISI results given an initial angle (right) [16]

2.1.2. Tool size and shape

In order to reduce milling time, the suggestion to use a single operation (one milling bit) arose: “Initially, due to the objective of simplifying the process planning, only a single cutting tool with the smallest possible diameter is used in CNC machining for rapid processes” [14].

Despite reducing the planning stage, the use of a single cutting tool caused inefficiency of machining time and the excess material left on the finished part. In order to balance this, the use of different tool sizes to handle roughing and finishing operations was introduced [17][18].

The study [19] investigated how CnC milling in Rapid Manufacturing could be pushed further (regarding usability and time consumption) by introducing variation of milling bits to the process. Authors suggest using both flat end mill and ball nose end mill in order to retain similar aspects of CnC-RM as mentioned before, thus adding an extra planning step. Their simulations show, that

despite using more time in planning, the whole machining time is reduced with a lower amount of material remaining on the finished part.

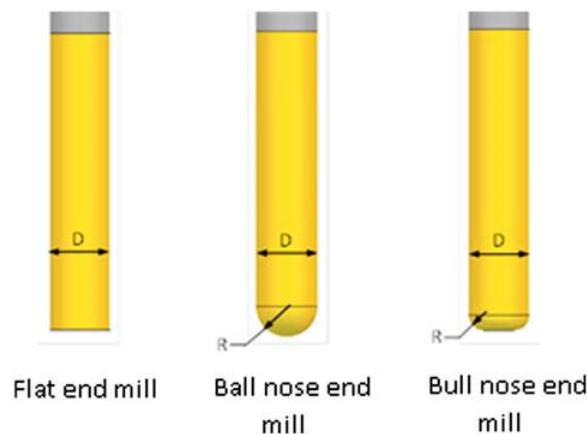
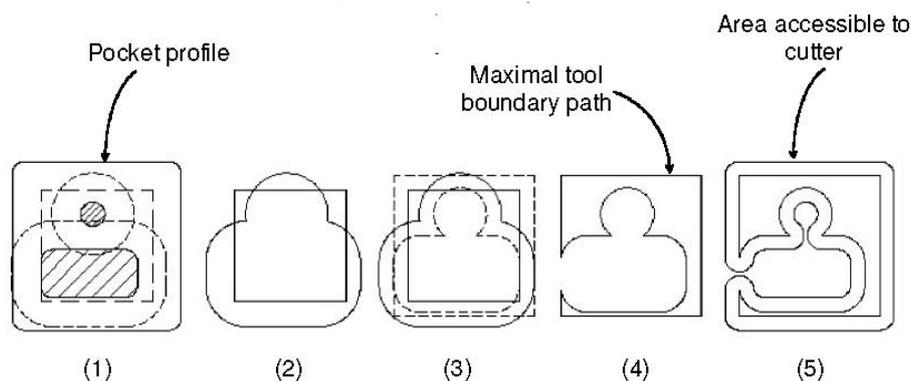


Figure 6. Common shapes of end mill tool [20].

As studies show better results while using optimally two different size and shape tools for roughing and finishing, the challenge becomes choosing appropriate tools for the job. In CAPP, Tool Access Volume (TAV) method was developed to determine tool choices and sequencing [21].



TAV procedure—(1) Offset profiles (broken lines) of the islands and pocket by tool diameter. (2) Intersecting island profiles are united. (3) Offset united islands and pocket profile by tool radius. (4) Unite offset united profiles with sheet plane—the result is the exact boundary path accessible by the tool. (5) Offsetting this tool path by its radius and sweeping it by the feature's range generates the TAV.

Figure 7. Tool Access Volume (TAV) method [20]

Other related research investigates the reduction of machining time by manipulating the cutting parameters [22][23][24], such as the cutting speed, the feed rate and the depth of cut. As Agarwal N. research states: “based on multiple regression models, a previous study indicates that the depth of cut was the most influential parameter in determining the level of surface roughness achieved” [25].

2.1.3. Summary

The role of both manual and automated planning is a significant factor determining the time it takes to CNC mill any part at hand. Fully automated CAPP systems are not being used and standardised due to manual tasks still being a necessity in most industries of low volume CNC manufacturing. However, as technology and applications are pushing these kinds of fabrications towards more

optimised manner, some elements of automated CAPP could possibly improve the overall machining times.

In most commonly used software for CAM solutions (Fusion 360, DeskProto, Vcarve, cut2D) it is up to the user to choose number of parameters manually in order to machine the part. Parameters such as tools to be used (amount, shapes, sizes) their cutting parameters (RMP⁴, feed rate, cutting depth), machine orientation angles and others – is mostly decided based on the users own experience. It is the core of a planning stage and the research presented show how the slightest adjustments can improve the overall fabrication time significantly.

2.2. Software solution

The following is an investigation into software used by the target group so that a platform for the solution could be decided. Firstly, software had to be available for student for free, longer term than 30 days or available at relatively low cost. Also, software should accommodate both CAD and CAM so that the solution would not be limited by it. Preferably with CAM features are present by default without using it as 3rd party add-on.

Blender with Blender Cam, Rhinoceros 3D and Fusion 360 were selected for extended comparison. Blender is a free form modelling suite, suited for the artists more than the engineers. The CAM tools are provided separately – Blender CAM is an open source solution for artistic CAM to generate G-code⁵. Blender Cam is still work in progress and developers recommend the user evaluating tool paths created by it before running the generated code.

Rhinoceros features tools more suitable for professional design, including the architectural and mechanical designs. Rhino also supports third-party add-ons and API to code scripts and automate features via Visual Basic. The CAM features can be purchased as RhinoCAM plugin. Despite not being free, Rhino is available with student discounts.

Fusion 360 has both CAD and CAM present from the get-go and offers parametric solid modelling suited for engineering applications as well as freeform modelling for artists. Software also features API⁶ for running and creating scripts supporting Python, JavaScript and C++.

As similarities and differences of packages were compared, Autodesk Fusion 360 was chosen as a platform to develop a potential solution to the problem. The software has an active online community who could be approached for target group testing in regard to the solution.

⁴ RPM – Rotations per Minute

⁵ G-code – name of most common CnC programming language

⁶ API – Application Programming Interface

3. Simulation TESTs

3.1.1. Introduction

The following is an investigation of Fusion 360 CAM environment, adjustable parameters of the planning stage and its influence to the machining performance. In Fusion 360, every parameter of both general “setup” and individual toolpaths directly affect the machining operation performance.

A “setup” defines a number of general properties for a set of machining operations and serves as a holder of the toolpaths associated with the particular setup. The major parameters to be set inside Setup are the geometry of the object to be machined (“The Part”), the object representing the stock, the specification of the local coordinate system and the bodies representing fixtures and clamps.

A toolpath (TP) is an operation of a setup, executed with a single tool. While setting a toolpath manually, user is requested to set up the general parameters:

- Properties related to the cutter (milling bit)
- Geometries of objects to be machined and object representing the stock
- Heights, Passes and Linkage

Another important property to set up before generating a toolpath is the selection of Rest Machining (RM) type. Rest Machining is used to define the type of toolpaths interaction with the stock and the toolpaths executed beforehand, inside same setup. For example: Rest Machining with type “Previous Operation” attempts to remove the overlapping factor between separate toolpaths, taking into account how much and which part of stock first toolpath removed so that the following toolpath would machine only the remaining stock.

Fusion 360 possess the functionality of virtually simulating generated toolpaths. These simulations provide data such as total machining time, distance the cutter has travelled, excess material remaining, etc. The following experiments were designed to extract data from simulations, in order to find correlations between adjustable parameters and the performance of machining while combining multiple toolpaths in an ordered sequence approaching the stock from different angles.

3.1.2. Base of the Simulation Set-up

The focus of the investigation concerns the orientation dependant toolpaths, the excess material remaining and how it affects the machining time. In order to find the most influential parameters, the simulations of the setups and the toolpaths was executed inside Fusion 360 to retrieve the data regarding to the respected milling.

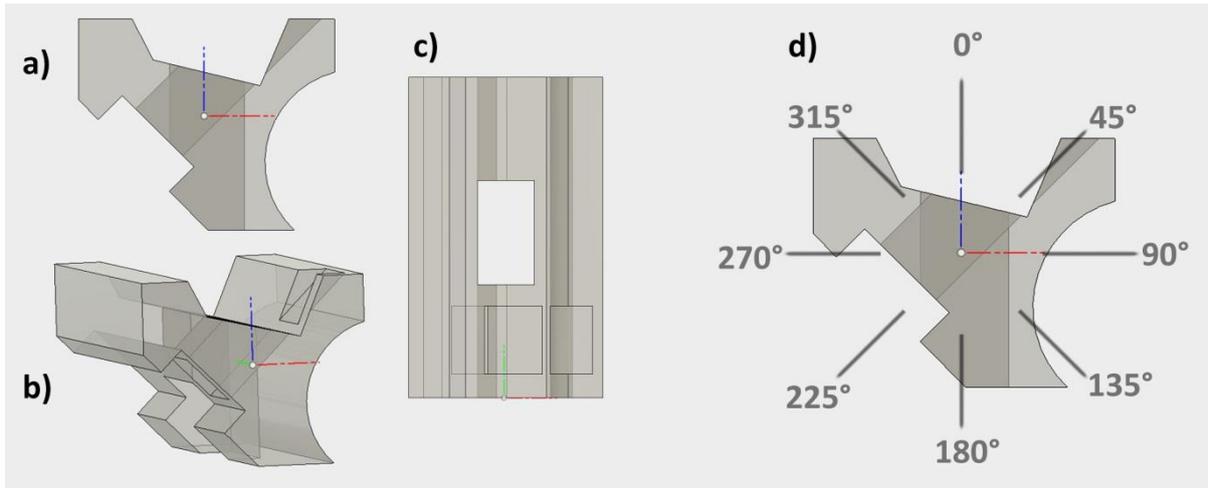


Figure 8. Object to be machined (the part) geometry views: a) Front b) Perspective c) Top d) Front with angles corresponding to created toolpath direction

Obtain base values of toolpath simulations:

- Model an asymmetrical part with features on multiple sides.
- Create setup with 8 toolpaths, each approaching the part from different orientations angled 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315° in relation to rotary axis. All toolpaths are created with exactly same parameters, with only variant – the orientation.
- Every toolpath is then simulated separately and all data is extracted and recorded.

Table 1: Data representing “Performance Table” extracted from simulating the toolpaths. The last column is used as coefficient and is composed by division of time the tool was being positioned and the actual machining time of the path.

Angles	Total time (s)	Machining (s)	Positioning (s)	Volume Removed (cm ³)	Machining Distance (m)	P(t)/M(t)*100]
0°	3156	2157	999	113.872	52.2777	68.3460076
45°	4851	3385	1466	179.372	80.5614	69.77942692
90°	2415	1546	869	87.015	40.0204	64.01656315
135°	3559	2369	1190	120.822	58.9827	66.56364147
180°	3805	2783	1022	183.165	63.1567	73.14060447
225°	4209	2748	1461	172.694	69.81	65.28866714
270°	3079	2160	919	117.157	51.0427	70.15264696
315°	3651	2347	1304	115.763	60.5913	64.28375787

The following test is made to see if the data extracted this way is correlated to how these TPs could be prioritised and sequenced in aid of optimisation. The excess material is not influenced by the sequence order of machining orientations, however it is influenced by the number of TPs from the different angles. The following should indicate if there is correlation between machining angles used, machining time and excess material remaining.

3.1.3. Angle selection [3-4 angles]

How, using data from Performance table, 3-4 toolpaths could be selected to machine the object in the most optimal manner?

Given the conditions, logic of how the appropriate angles could be chosen was implemented. The logic derives from the methodologies of authors [14][15] regarding the number of orientations and the spacing in between, while also taking into account the variable related to angle performance, from Table 1.

Logic of finding most suited angles:

1. Find first, by comparing Positioning (t)/ Machining (t) of all available angles, call it **a1**
2. Find second best (a2), between $a1+90^\circ < a2 < a1-90^\circ$
3. If $a2 \neq a1+180^\circ$, find best suited angle between $a2+30^\circ < a3 < a1-30^\circ$
4. if $a2 = a1+180^\circ$, find best $a1 < a3 < a2$ and $a2 < a4 < a1$

Following the approach, three angles were selected, by the order of efficiency $a1 = 180^\circ$, $a2 = 270^\circ$, $a3 = 45^\circ$. Three toolpaths with identical parameters were generated, with the only difference being Z orientation angle, equal to corresponding $a1$, $a2$ and $a3$ value.

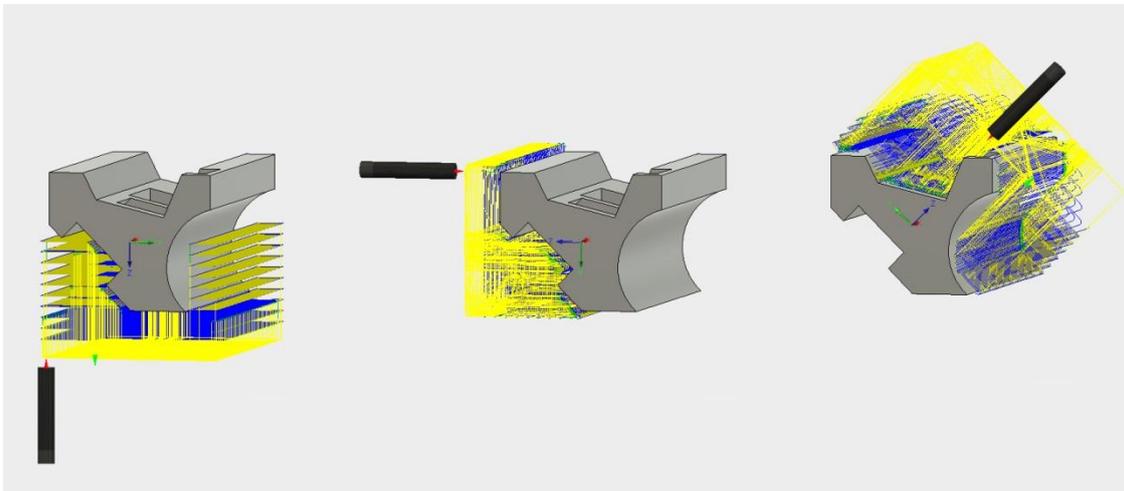


Figure 9: Three tool paths, oriented at 180°, 270° and 45°. The Part to be machined is grey, blue lines indicate movement of the milling bit while machining and yellow show movement while positioning the tool.

3.1.4. Angle order sequencing and RM-PO

How the order of different angles together with “Previous Operation” type of Rest Machining, influence total machining time?

6 setups with all possible sequences of previously chosen angles (180°, 270°, 45°) and their respective toolpaths were created and duplicated. The first group of setups all had all toolpaths with Rest Machining turned off, while the second had it set to Previous Operation. All setups were simulated and data recorded.

Table 2. Results of how sequence order affects the machining time.

Data from setup group with Rest Machining – Previous Operation

Setup name	Angle sequence	Machining Time with RM (h.m.s)	Machining Time without RM (h.m.s)	Machining distance (m)	Volume left (%)
1v3.1	180°, 270°, 45°	3.12.25	3.15.06	194.761	29.4
1v3.2	180°, 45°, 270°	3.13.10	3.15.06	192.827	29.4
1v3.3	270°, 180°, 45°	3.13.06	3.15.06	192.753	29.4
1v3.4	270°, 45°, 180°	3.14.42	3.15.06	194.349	29.4
1v3.5	45°, 270°, 180°	3.14.44	3.15.06	194.397	29.4
1v3.6	45°, 180°, 270°	3.14.45	3.15.06	194.414	29.4

The group of setups with Rest Machining off for all of the toolpaths show that the order of the angles does not affect the machining time. This is because toolpaths do not interact – generation of one does not influence the remaining ones in the same setup.

The group of setups with Rest Machining – Previous Operation takes less time to execute than the ones without RM, however time difference is insignificant [**0.18% - 1.38 %**]. The sequence order of toolpaths with RM-PO does influence machining time, however insignificantly as well - up to **1.2%**. Findings show that the RM-PO parameter doesn't work well between neighbouring TPs if they are separated by more than 45°.

In order to compare the angle selection logic, two additional setups representing angle selection recommendations by Osman Zahid et. al. were created and simulated. Two setups were 1v4.1 with angles [0°, 90°, 180°, 270°] and 1v4.2 with angles [45°, 135°, 225°, 315°].

If comparing results of 1v3.1 with 1v4.1[0°, 90°, 180°, 270°], first one is executed **7%** faster. 1v3.1 is also faster than 1v4.2[45°, 135°, 225°, 315°] by **10.64%**. Despite being slower, both 1v4 simulations remove additional **3%** of excess material, due to having wider reach with four orientations instead of three.

3.1.5. Sequencing of 8 angles for minimal Excess material remaining

As found out in previous simulations, in order to use RM-PO to full potential, the angles of the setup have to be no further than 45° apart. The 1v5 simulations were created and analysed to see how the increase of machining angles contribute to the excess material removed and how big of the increase in the machining time it creates.

Setups containing 8 TPs were compared, all TPs are angled 45° degrees apart [0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°]. All of the following setups remove **75.1%** of the initial stock volume.

Table 3: Simulation of setups with eight paths, in different angle order

	1v5.1	1v5.2	1v5.3	1v5.4	1v5.5	1v5.6	1v5.7	1v5.8	1v5.9
a1	0°	180°	90°	90°	90°	90°	90°	90°	90°
a2	45°	225°	0°	270°	270°	135°	0°	270°	180°
a3	90°	270°	315°	0°	0°	180°	135°	135°	135°

a4	135°	315°	270°	180°	135°	225°	315°	315°	225°
a5	180°	0°	135°	135°	315°	270°	180°	0°	270°
a6	225°	45°	225°	315°	180°	315°	225°	180°	315°
a7	270°	90°	45°	225°	225°	0°	270°	225°	0°
a8	315°	135°	180°	45°	45°	45°	45°	45°	45°

Machining time

In seconds	17366	17959	17147	19265	18612	17551	17244	18750	18144
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Firstly, setups 1v5.1 and 1v5.2 were compared, both having same clockwise 45 degree incremental sequence for angles, with different starting point **a1** as 0° and 180° respectively. Evaluation shows that 1v5.1 is **3.3%** more optimal in regards to the total machining time and proves the importance of the sequence order of the machining orientations.

Additional setups with varying orientation sequences were prepared. The sequences were chosen in regards to initial Table 1 data and with “neighbouring” toolpaths in mind (toolpaths not further than 45° apart). Out of the sequences chosen, the fastest ones seem to be the ones which order is sequenced by volume removed. Angles which removed the least - being the first in the sequence and the angles which removed the most being the last. If sequenced inversely, TPs that remove the least become inefficient by attempting to clear remaining excess material by mostly positioning and aligning the milling bit in comparison to actual machining time. Setup 1v5.3 was fastest and its sequence was chosen by rules:

- Volume removed – removed the least volume first
- First neighbour can be 90° apart if it is a second by the volume removed least
- Remaining neighbours 45° apart from any of the first two, prioritising angles which remove least volume

3.1.6. Rest Machining - From File [RM-FF]

As efficiency of RM-PO is limited if toolpaths are further than 45° apart, Rest Machining – From File was tested as an alternative.

During a simulation of toolpaths, it is possible to save the remaining stock as STL⁷ file, which then can be set as a stock for the next operation, thus theoretically fixing the issue of RM-PO. Despite being possible, this kind of approach requires additional computational power. Firstly, the STL file needs to be imported, which tends to rescale and reposition the body⁸, complicating its precise alignment with the previous stock position. Also, the mesh needs to be converted to BREP⁹ model and the result is hard to manipulate – selecting, moving or scaling of this newly created object creates stuttering effect inside the software. Practically the approach works, however it’s far from optimal.

⁷ STL – Stereolithography file used by CAD software and solid modelling to represent 3D objects. Due to standardization STL files are possible to import to most 3D modelling software.

⁸ “body” is the term of calling the model of the object inside the Fusion 360 software

⁹ BREP – Boundary Representation – is way to represent models in solid modelling and CAD software. BREP bodies possess information about models topology and geometry.

3.1.7. Rest Machining – Setup Stock [RM-SS]

The toolpaths created with Rest Machining – Setup Stock tend to have more optimal way of machining top layers of the stock by taking into account the curvature of the stock surface more accurately. However toolpaths with RM-SS are not affected or influenced by other TPs machining same stock, thus not taking into account what has been machined previously.

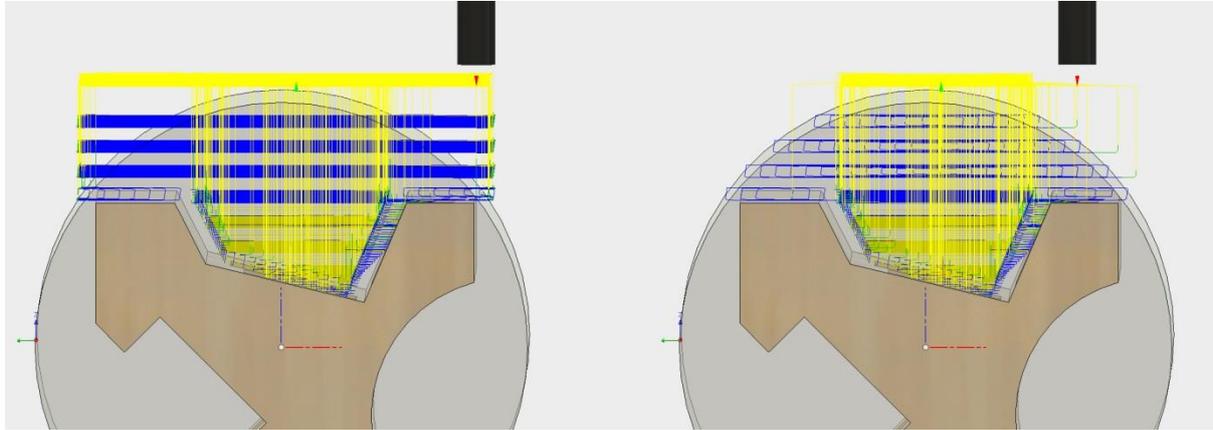


Figure 10. Two toolpaths generated from the same angle with identical parameters except for the type of Rest Machining. RM-off/RM-PO on the left and RM-SS on the right.

RM-SS can be harvested best if used in setups where the orientation angles are too far apart for RM-PO to have a significant effect. Also, RM-SS can be efficiently used for roughing operations only, unless both roughing and finishing are executed with same size cutting tool.

3.1.8. RM-SS integration/comparison to previous tests

The following is the integration of RM-SS to best performing setups so far, in order to analyse its best use either as stand alone or in combination with RM-PO. If converted all three TPs of 1v3.1 to RM-SS, the machining time is reduced by **16.2%**. Also, if the same is done to 1v4.1 where all TPs are 90° apart, the machining time is reduced by **25.53%**. In both cases the results are significant because RM-PO failed to intersect TPs present and all TPs were more than 45° apart.

While integrating RM-SS with 1v5.3 setup, only the first two TPs (angled at 90° and 0°) were converted from RM-PO to RM-SS due to not being close enough neighbours for RM-PO to be effective. Newly created setup performs **7.89%** faster than original.

An additional setup using same eight angles was created, where the first four TPs angled at 0°, 90°, 180° and 270° were RM-SS and the remaining had RM-PO turned on. The result was faster than original 1v4.3 by **5.32%** however still slower than 1v4.3 with the first two TPs converted to RM-SS by **2.71%**.

3.1.9. Simulation summary and Findings

Parameters which influence creation of toolpaths inside Fusion 360 were explored, focusing on the parameters affecting the planning of multiple orientations machining. A generic part was modelled inside Fusion 360, representing a number of features on multiple sides of its surface.

Eight equally spaced angles were chosen to serve as the base of machining directions for the part. The toolpaths representing these angles were created and simulated. The data retrieved served as the base criteria for testing the machining setups varying in toolpaths and its amounts, toolpath

parameters, angles and the sequence in which they were executed. The simulation results were compared in regards to the duration of the machining required, overlapping toolpaths as well as excess material remaining on the part.

The influence of the Rest Machining parameters were investigated in depth: From Previous Operation (RM-PO), From File (RM-FF) and From Setup Stock (RM-SS). RM-SS show best results while used in setups with fewer toolpaths, where TPs do not overlap or overlap minimally. Out of setups with eight TPs, best results were achieved by combination of RM-SS and RM-PO.

Both RM-SS and RM-PO have advantages and disadvantages and should be picked according to the situation. The key variables to keep in mind while choosing are: the number of total machining angles for the operation, the angle overlapping factor and volumes of both the stock and the part.

Additionally, the simulation for the part shows that to remove most excess material off the stock, three to four TPs are most optimal in duration. Increasing amount of angles reduces the overall excess material slightly, however it increases the total machining time significantly. Thus, number of machining angles should be decided based on the priorities of the user, whether it is the shorter machining time or the volume of the material remaining.

Testing the sequence order of chosen angles indicate that toolpaths, which remove least material should be executed first, while the ones removing least – last. This way the generated toolpaths produce less “positioning” movement and reduce the total machining time.

Lastly, the analysis of the toolpath performance and the geometry of the part accessible at the angle of that particular toolpath indicate correlation between the parts’ surfaces and total machining time. Surfaces perpendicular to the cutter are machined fastest and the steeper the angle the more time the toolpath spends positioning the cutter. Curved surfaces are the slowest to machine as it requires constant cutter repositioning. Thus, in order to prioritize the machining speed over the excess material remaining, the orientation of the toolpaths should be as perpendicular to flat surfaces as possible while attempting to avoid direct curved surface machining.

4. Requirements

The literature investigated and the simulations performed led towards a creation of pointers, of how a digital solution inside Fusion 360 could be implemented, assisting the user with the selection of machining orientations while using the 4 axis CnC machines. Despite the simulations chapter showing promise, the results could be more precise if the procedure were to be automated. This would allow the performing of multiple simulations on parts varying in shape as well as a higher number of angles to be analysed.

4.1. User Input

As stated previously, the digital solution has to cover the needs of the target group - various users fabricating in a number of materials and operating different CnC machines. Thus, the user should be able to set priorities to the parameters important at the time. This could be achieved via Command Box Interface, programmable via Fusion 360 API. Input methods supported range from selectable objects in the scene, drop down menu items, sliders, direct numeric input, etc.

Proposed command box inputs:

Select the body to be machined – use mouse to select an object user wants to machine.

Select the stock – use mouse to select an object representing the workpiece/stock.

Resolution – value connected to the accuracy of the outcome for the price of code execution time. In example, resolution value would be connected to the number of angles the geometry is analysed.

Tool Size – represents milling bit diameter to be used for the operation. It directly influences which parts of geometry falls under “unreachable” by the selected tool.

Surface finish: Fine vs Rough – slider which value determines the number of machining angles suggested to the user after analysis.

Machining Time vs Excess Material Remaining – slider with mentioned values at different ends. Value chosen by the user would become coefficient, scaling values to be prioritized while analysing data of machining angles and its performance.

4.2. Add-on Execution and Logic

A digital solution which would try to predict the most suitable machining angles, given the part and stock objects could be programmed in two ways. The core of the first solution would be creating machining simulations in a CAM environment, the amount of which would be set by the user via the “resolution” parameter. The data extracted from each simulation then could be compared in order to find angles at which parameters such as excess material over machining time would excel over the other angles simulated. Logic could be set how to sequence the most optimal angles in a manner so that the thin web problem would be avoided, similar to procedure described in 1.1.3.

Alternatively, a solution could be based on analysing the geometry of the part via a modelling environment. This way would require more coding in order to extract data such as excess material remaining per particular angle, however it would be executed faster than the solution mentioned previously. Solving the “material removed” at a certain angle via the use of geometry and object body operations could possibly solve the problem of Rest Machining – Previous Operation. In order to predict the machining time at a certain angle without the use of CAM Simulations data, the faces of the object (accessible by the cutting tool from that angle) could be analysed. Angles where the machining tool is exposed to a bigger area of curved surfaces will most likely create a toolpath with more tool positioning movement than at angles where curved surface area is smaller.

5. Implementation

5.1. API Limitations

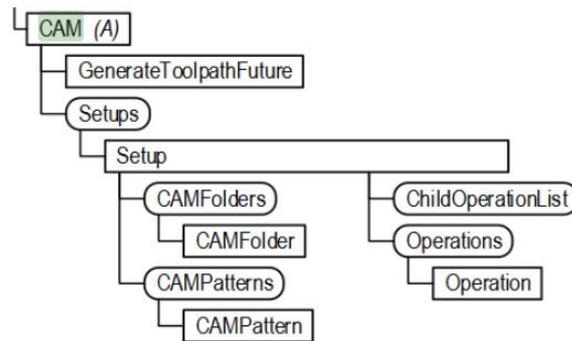


Figure 11. Fusion 360 API Object Model - CAM branch

As previously stated, Fusion 360 was chosen as platform for the solution development for a number of reasons (2.2. Software solutions). One of them was the presence of API and the access to both the modelling and CAM environments of the software. However, shortly after starting the implementation phase, it was clear that the entities listed in Figure 11 regarding CAM accessibility and manipulation were too basic to carry out the goals of the implementation. The presented list shows the entities such as Setups and Toolpaths, however in reality API only allows the developers to “regenerate” (refresh) the already created instances rather than making creation itself and manipulation of the involved parameters possible.

5.2. Code Overview and structure

The solution was implemented as an Add-On inside Fusion 360, using Python programming language. As the CAM API was unavailable, implementation was restricted to modelling environment. Workaround was developed to extract data usually obtained by running machining simulations. The following figure represents the core elements of the programmed solution.

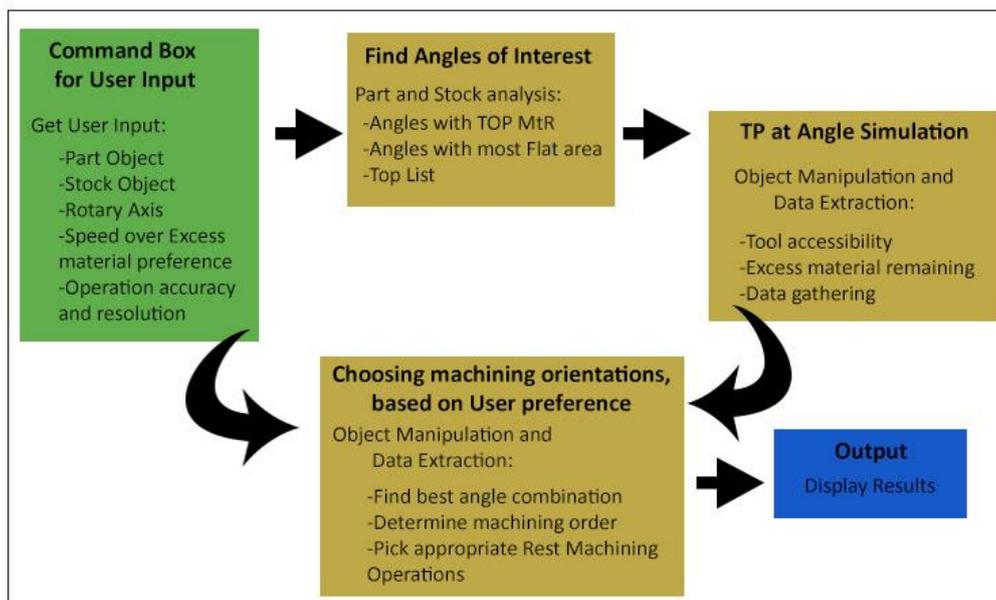


Figure 12. Code structure for Add-On implementation

The Add-On requires user input to determine the 3D space, the orientation, the objects representing the Part and Stock as well as the machining preference. The angles of interest are determined via:

- a) Volume of possible material removed at certain angle
- b) Area of flat faces, at certain machining angle

Angles of Interest are passed on as a list to Angle Simulation function, where every angle is analysed, by creating geometry representing Material Removed, Excess Material Remaining and extracting data corresponding with newly created bodies. Lastly, given the user stated preference and newly created bodies, the add-on attempts to find the best combination of angles for the task at hand, to determine optimal machining order and to assign suited Rest Machining type of property.

5.3. User Input

Running the add-on pops the command box for users input. User is requested to choose objects from the currently active Fusion 360 design window, which body represents the Part to be machined, the Stock (workpiece) and Rotary Axis. Other parameters user inputs here determine the resolution at which models are analysed. Consequently, demand for higher precision results with longer code execution.

5.4. Angles of Interest

It is of importance to identify at which possible machining angles the Part has most “flat” face areas. As previous investigation shows, toolpaths created at angles where geometry of the part is perpendicular to the tool tend to be more optimal timewise as opposed to geometries with curved or steeper angled surfaces.

The Part is rotated by 1° at the time and all of its faces then are analysed. Every planar face has a vector pointing outwards face geometry. A loop going through all of the body faces is initialised, comparing every face vector to a normal vector with positive Z direction of the 3D scene (0,0,1). If satisfying the threshold of angular steepness, the area of those faces is summed up. A matrix, representing the angle of rotation and the area of flat faces at that angle is stored.

```
499     for i in range(0, RotDegrees):
500
501         mainBody = root.bRepBodies.itemByName('Part (1)')
502         upDir = adsk.core.Vector3D.create(0,0,1)
503         flatUp = 0
504         CurrentFlatArea = 0
505
506         for face in mainBody.faces:
507             if face.geometry.objectType == adsk.core.Plane.classType():
508                 faceEval = face.evaluator
509                 (retVal, normal) = faceEval.getNormalAtPoint(face.pointOnFace)
510
511                 if normal.angleTo(upDir) < 0.01: #threshold evaluation
512                     CurrentFlatArea = CurrentFlatArea + face.area
513
514         AngleToFlat[i][0] = i*RotAngle
515         AngleToFlat[i][1] = CurrentFlatArea
```

Figure 13. Code for evaluating the direction of the surface planes (faces) of the Part.

The second section of the list containing the Angles of Interest is gathered by identifying angles, at which most of the Stock needs to be removed, in order to reach the Part. This method is not capable of identifying which part of the stock is not accessible by the tool, however it is fast to perform and yields important angles, especially if the Part has more curved than flat surfaces area.

The model named Material to Remove (**MtR**) is created by performing combine cut¹⁰, where the target body is the Stock and the tool body is the Part. Using same resolution of 1° at the time, the absolute origin plane of the Part at that angle is determined. Then, MtR is reduced to represent the stock present per angle – with its angular value and volume data stored as a list.

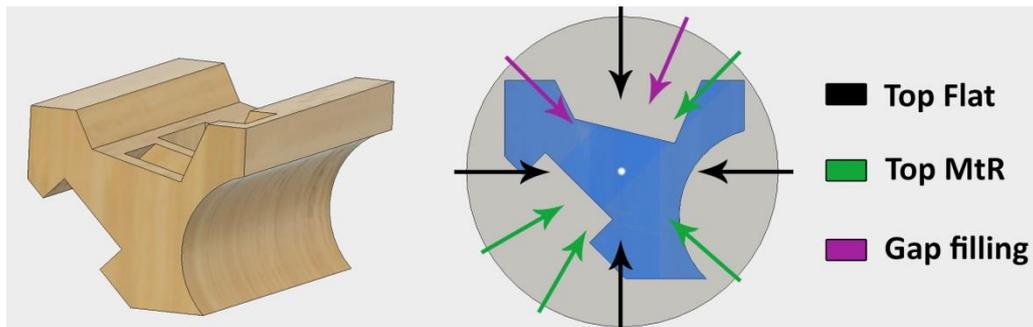


Figure 14. The Part on the left and the corresponding “Angles of Interest” on the right

Lastly, the angles with highest values of “flatness” and biggest volume of MtR per angle are combined into one. The combination process filters angular values so that duplicates and close neighbours are removed. After the certain amount of angles is stored, the remaining values are created by identifying the biggest gaps between angles which are already present. It is done so in order to have more consistent circularity of angles for further evaluations.

5.5. Toolpath at Angle Simulation

The purpose of the Angle Simulation section is to imitate the toolpath simulation from the CAM environment and extract necessary data related to it. The input of the function is the Angles of Interest list and every angle is analysed individually, one at the time.

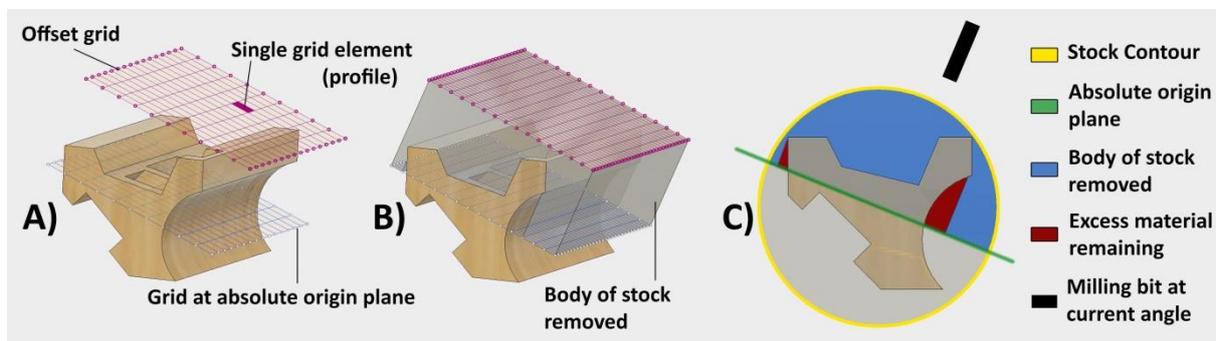


Figure 15. Steps performed in order to simulate toolpath at certain orientation

¹⁰ Combine Cut and Combine Join – represents modification of models via use of geometry, where overlapping bodies are either subtracted or merged. This function in Fusion 360 requires a Target Body – receiving model and a Tool Body or Bodies as manipulator.

Once the angle is received, the grid at the absolute origin is drawn and rotated to be perpendicular to the angle at hand. Then, the grid is offset by the height of the stock, a) of Figure 15. In order to simulate the tool access regarding the part geometry, every profile of the grid is then extruded towards the Part, until it either hits the absolute origin plane or the Part itself, b) of Figure 15. All extrusions are combined into one solid body representing geometry of the stock, which tool is able to remove at that angle. Newly created model is then named – “Body of Stock removed”.

The newly created body then is “combine-cut” with the bodies of the part and the stock, resulting with geometry of “Excess Material Remaining” if machined at that particular angle, c) of Figure 15. The data such as volume and shape of both “Body of Stock removed” and “Excess Material Remaining” is later used to compare whether one angle should be chosen over the other.

5.6. Analysis of Surface Change

Additional data is gathered in relation to angle performance and face related calculations possibly aiding to estimate the neighbouring angle performance.

Using the geometry produced by the Angle Simulation, the data regarding surface change is extracted, with the goal to identify the shape and volume of part-per-angle and excess material. Models of the Part at angle and the excess material at angle are rotated to align with positive z direction of the 3D scene b) of Figure 15.

Code similar to the one presented in Figure 13 is then executed to analyse the area, the direction and the approximate angular value for all of the faces of the Part object. Faces pointing upwards are grouped by steepness - $[0^\circ]$, $[1^\circ-15^\circ]$, $[15^\circ-45^\circ]$ and $[45^\circ-70^\circ]$ by the surface area. The area of curved faces cannot be extracted directly and the direction it is facing is unknown. However, the curved area can be calculated by deducting the area of all the Part with all planar areas facing positive and negative z, x and y directions. All of the data is stored to a multidimensional matrix with indicator “BM” – Before Merge.

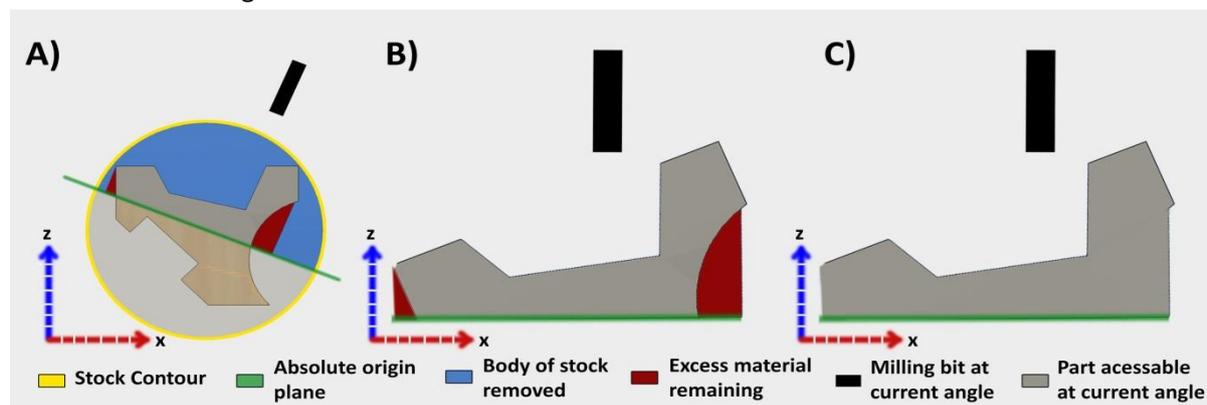


Figure 16. Transformation of bodies in order to perform Surface Change analysis. A) State after TP at angle simulation. B) Part at angle and excess material rotated. C) Part and Excess material combine-joined.

Furthermore, bodies of both the Part and Excess Material are combine-joined, c) of Figure 16. Function to analyse all faces is executed once again and added to previously mentioned matrix with indicator “AM” – After Merge.

A variety of calculations can be performed to extract information regarding the surface of the Part body by comparing BM and AM parts of matrix. For instance, now it is possible to identify which way

the curved surface is pointing. Before Merge data of the part in Figure 16 -b) would return area of faces pointing respectively to x negative and to x positive direction which is close to being equal. The area of the curved surface on right side of the part is labelled as unaccounted-for non-planar surface with unknown direction. Its area is bigger than sum of both planar faces pointing to x- and x+. If compared to the data gained analysing After Merge body of c) in Figure 16: unaccounted-for surface area is 0, while planar face of x+ area is increased by at least 60%.

Direction at which there was an Increase of planar surface after merge, while unaccounted-for surface decreased – indicates direction of curved surface. Also, if unaccounted-for surface area has not changed After Merge, or changed slightly – the curved surface is likely to be accessed by the milling bit at that orientation.

Nevertheless, getting this data is performance costly and requires higher number of “angles of interest” to be most efficient.

5.7. Machining orientation, Sequence and type of Rest Machining

A function “pickAngles” is responsible for determining the final set of angles. As input, it takes bodies, lists and parameters, produced by both the Angles of Interest and the Command Box code sections.

At its core, the final set of angles is selected by using the geometries of the “bodies of stock removed” and deducing the Stock body with it. The combination that yields the body with the least volume (versus machining time expected) is outputted as final set of angles recommended by the Add-On.

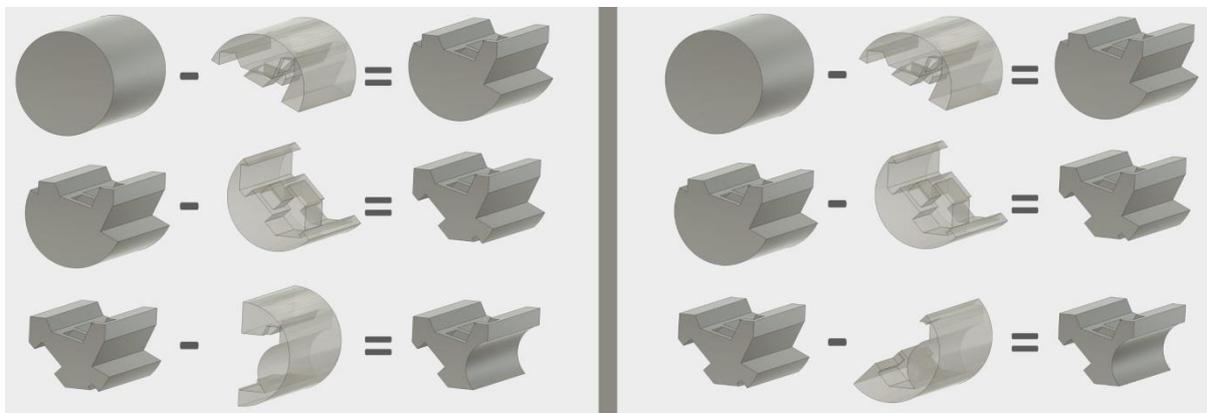


Figure 17. Visual example of comparing two sets of angle combinations

Figure 17 contains the example of the function comparing two sets of angle combinations, [25°, 225°, 90°] on the left and [25°, 225°, 135°] on the right. The resulting geometries can be compared by volume and evaluated.

The set of rules derived from simulations (3.1.9.) are guiding the code for the optimal execution time. For example, if the function is requested to output 2 or 3 final angles while using 10 Angles of Interest, the code can “brute force” through all possible combinations in less than 2 minutes¹¹ which

¹¹ All tests performed on laptop with following specifications: Intel(R) Core(TM) i7 – 3610QM CPU @ 2.30 GHz, 16.0GB RAM, 64-bit Operating System, Windows 7.

is perfectly acceptable. However, if using the same approach and requested to brute force 4 angles combination, code execution takes around 20 minutes, and over an hour if the final angle set is made out of 5 angles.

In case of needing to output the final angle set containing 4-5 orientations, the inputs of function are evaluated to pre-pick the best 2-3 angles, excelling over others in either best reach, suitable geometry or possible volume removed. Remaining angles are brute forced to find the best combination and the code is executed in less than 5 minutes.

Regarding sequencing chosen angles in order and picking appropriate Rest Machining type – logic extracted from section (3.1.9.) was implemented. Sequence is set by comparing the final set of angles corresponding “Body of Stock removed” model volume, and arranging the list to have removed least – first and removed most – last.

Properties influencing RM type chosen:

- Number of Machining Orientations recommended by the Add-On and the overlapping factor. The setups, with least overlapping toolpath would more likely receive recommendation for From Setup Stock RM type, while most overlapping ones would prioritise Previous Operation.
- The volume difference of the stock and the part. Threshold was set, so that setups where the stock was significantly bigger than the part, would favour PO over SS.

6. Experiment

6.1. Experiment Design

In order to evaluate the performance of the add-on, the experiment was designed to compare how the Add-On and the users with varying experience of 4 axis CnC machining would machine particular objects.

The experiment was designed in a manner so it could be carried out online, aiming to gather higher number of participants. The goal was to ask subjects, given the geometry of the object to be machined, the stock and the number of the orientations available, what angles, its order and type of rest machining they would choose in order to remove most excess material in shortest possible time.

Two objects representing the parts to be machined were modelled. Object 1 was designed to have more easily distinguished features on four sides. Object 2 was modelled to be symmetric, with features standing out on five sides, forcing the subject to evaluate geometry differently. In order to differentiate both parts even further, the stock of the Object 1 was modelled bigger, while the stock of the Object 2 was made smaller.

Volumes:

Object 1 (Part I) = $1.831E+05 \text{ mm}^3$, Stock 1 = $6.536E+05 \text{ mm}^3$

Object 2 (Part II) = $2.598E+05 \text{ mm}^3$, Stock 2 = $5.046E+05 \text{ mm}^3$

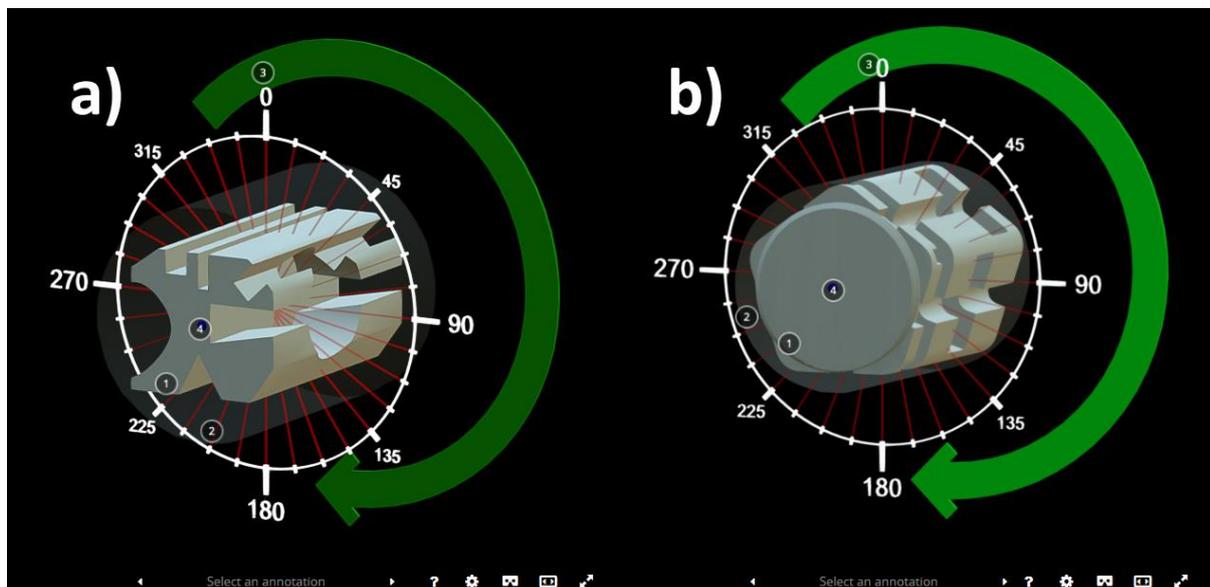


Figure 18. the Model 1 (Part I) on the left and the Model 2 (Part II) on the right, uploaded to sketchfab.com

In addition, the subjects were given the option to manipulate the objects in 3D space. The objects were uploaded to Sketchfab¹², where the users could use mice or touchpads to perform basic camera manipulations – rotation, pan and zoom. For the convenience of the test subjects, an arrow indicating the direction of the rotary axis movement was included in the 3D scene. Additionally, dials

¹² Sketchfab.com – web page where 3D content can be uploaded, stored and shared for interactive viewing.

with projections of angular values towards the object to be machined were presented to aid picking precise orientations.

6.2. Questionnaire

6.2.1. CAM and CnC experience

Test subjects are first asked about their experience related to Computer Aided Manufacturing and Fusion 360.

What is your occupation and relation to CAM?

Which Fusion 360 License are you using?

Your experience with any CAM software and CnC machining (years/months)

Your experience with Fusion 360 CAM (years/months)

6.2.2. Model 1 and Model 2

The next section starts with a link to the external browser window to view the Part 1 in 3D and the detailed instructions follow of what is asked of the subject. Additionally, instructions were accompanied by images to clarify the objectives which could have been misunderstood.

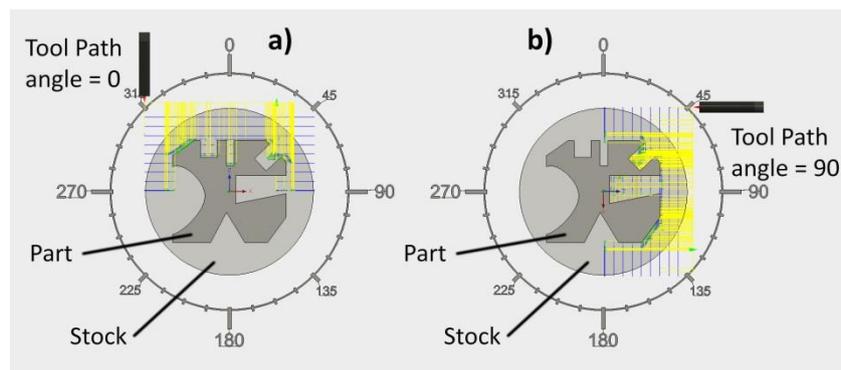


Figure 19. Example of angle choice for the first object

6.2.3. Instructions

Imagine that you need to set up a roughing operation on Model 1, using CnC machine with 4 Axis. Movement of rotation Axis is represented by green arrow in 3D view.

The goal is to set up operations so that most stock material is removed during shortest time.

You need to pick the angles at which object will be machined, the order and type of Rest Machining.

The chosen angles work as tool orientation – the direction of the milling bit which will approach the stock. For all chosen angles, machining operations created are Adaptive Clearing, Top Height = Stock Top and Bottom Height = Origin(absolute).

The focus of the study is the machining orientation, thus please ignore the parameters not mentioned above, such as Tool type and size, stock material, etc. Imagine that the tool used is small enough to reach most gaps available at certain angles.

If you had to choose 2 machining angles:

Angle No. 1 [0-360]
[]
Angle No. 1 Rest Machining Type:
SS [] PO [] Not sure []
Angle No. 2 [0-360]
[]
Angle No. 2 Rest Machining Type:
SS [] PO [] Not sure []

If you had to choose 3 machining angles:

Angle No. 1 [0-360]
[]
Angle No. 1 Rest Machining Type:
SS [] PO [] Not sure []
Angle No. 2 [0-360]
[]
Angle No. 2 Rest Machining Type:
SS [] PO [] Not sure []
Angle No. 3 [0-360]
[]
Angle No. 3 Rest Machining Type:
SS [] PO [] Not sure []

If you had to choose 4 machining angles:

Angle No. 1 [0-360]
[]
Angle No. 1 Rest Machining Type:
SS [] PO [] Not sure []
Angle No. 2 [0-360]
[]
Angle No. 2 Rest Machining Type:
SS [] PO [] Not sure []
Angle No. 3 [0-360]
[]
Angle No. 3 Rest Machining Type:
SS [] PO [] Not sure []
Angle No. 4 [0-360]
[]
Angle No. 4 Rest Machining Type:
SS [] PO [] Not sure []

If you had to choose 5 machining angles:

Angle No. 1 [0-360]
[]
Angle No. 1 Rest Machining Type:
SS [] PO [] Not sure []
Angle No. 2 [0-360]
[]
Angle No. 2 Rest Machining Type:
SS [] PO [] Not sure []
Angle No. 3 [0-360]
[]
Angle No. 3 Rest Machining Type:
SS [] PO [] Not sure []
Angle No. 4 [0-360]
[]
Angle No. 4 Rest Machining Type:
SS [] PO [] Not sure []
Angle No. 5 [0-360]
[]
Angle No. 5 Rest Machining Type:
SS [] PO [] Not sure []

Figure 20. Questions about machining angles - every numeric angle value is followed by users specified type of Rest Machining, where SS – Setup Stock, PO – Previous Operation.

After filling the questions related to the Model 1, same questions are repeated regarding machining of the Model 2. Images in instructions are replaced to represent second geometry and the new link for the interactive 3D scene containing Model 2 is provided.

7. Results

In this chapter methodology of the data extraction from both User and Add-on inputs will be presented. The data is then compared and analysed individually and in groups.

7.1.1. Test Participants

In total there were 8 participants who qualified to answer the questionnaire, which was posted on the official Fusion 360 forum, under computer aided manufacturing sub-forum. As experiment required input from CnC users with any experience with 4 axis machining, questionnaires filled by people with no experience in particular machining were discarded. Despite small amount of test participants, most of them have over 5 years of CnC and CAM experience, with the most experienced one being 18 years. Experience with particular Fusion 360 software varies between 4 months and 4 years, averaging with at 25 months of experience per subject.

In order to extract data of how the answers of the subjects would stand as the directions for CnC machining, information from questionnaires containing selected orientations and types of rest machining had to be recreated inside Fusion 360 CAM environment as setups and toolpaths. The information submitted by the subjects summed up to 64 setups containing 224 toolpaths.

Every setup was generated and virtually simulated as machining operation to extract performance related data – total machining times, machining distance, volume of material removed, etc.

7.1.2. Add-On

The Add-On was designed to intake adjustable parameter “resolution” as an input by the user. This parameter controls the precision of the estimations for the cost of the execution time. As stated earlier, the focus of Add-On implementation spanned around the accuracy over the code execution time. Nevertheless, limited resolution was chosen in order execute code in less than 30 minutes and to prevent the system to use up all of the virtual memory and possibly crash.

The Add-on was executed using both Model 1 and Model 2 geometries and returned corresponding machining angle suggestions, sequences and rest machining types. The information gained was converted to 8 setups containing 24 toolpaths and simulated.

7.2. Findings

Using the data from the test participants and the Add-On, the simulations were made, results of which were compared individually per “angle challenge” and in summation per subject. Out of all the data gathered, the rate of material removal per minute (**MR/min** - mm³/minute) was chosen as most representative for the evaluation. The higher the number, the less time the cutter spent being repositioned (instead of machining) and fewer toolpath overlaps occurred during the machining operation. The MR/min Rate also indicates how costly for total machining time the removal of the extra stock is. I.e.: to question “pick 2 orientations to remove the most material from Model 2 fastest” subject 1(S1) chose 0° SS and 180° SS, where Subject 4 (S4) chose 90° PO and 270° PO. Simulated operations show, that S4 would remove **0.2%** more of material than operation of S1, however it would take **17.48%** more time to execute. Hence, if compared MR/min, where S1 – 0.822

and S4 – 0.681 it is clear that S1 is more optimal per minute of its execution time.

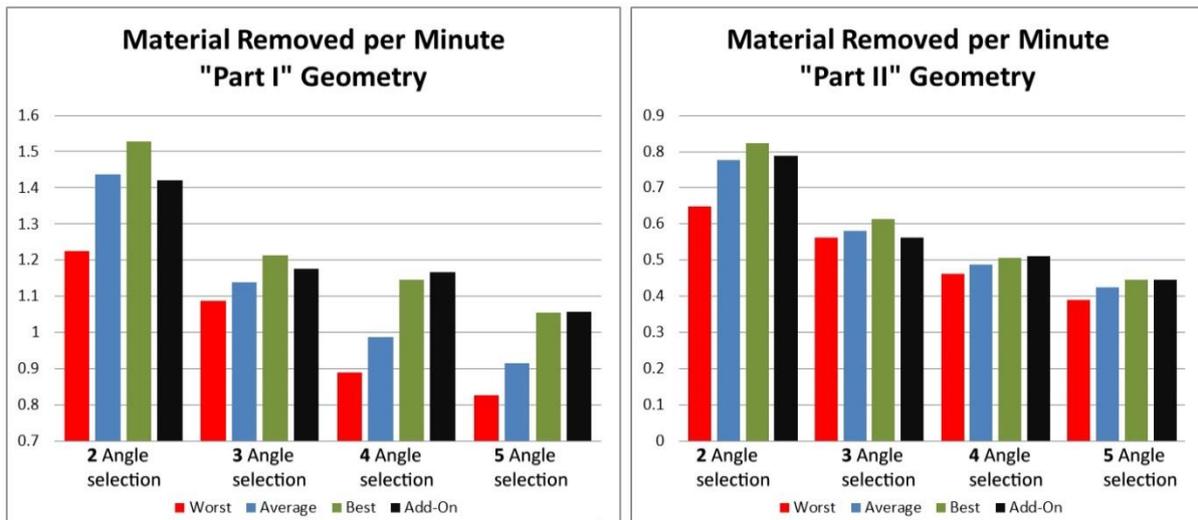


Figure 21. Material Removed per Minute comparison of both Part I and Part II geometries.

Figure 21 show how the test subject machining operations (best, worst and average) compare to the Add-On suggested machining operations for the same number of orientations involved. Note that graph scale for Part II geometry is different. It is so as differences between simulated operations were more subtle.

Out of 8 operation challenges, 6 times Add-On scores above average over the test participant input, 3 times of those recommendations surpassed the best user suggested ([Part I, 4 angles],[Part I, 5 angles], [Part II, 4 angles]) and once broke even with the users best (Part II, 5 angles).

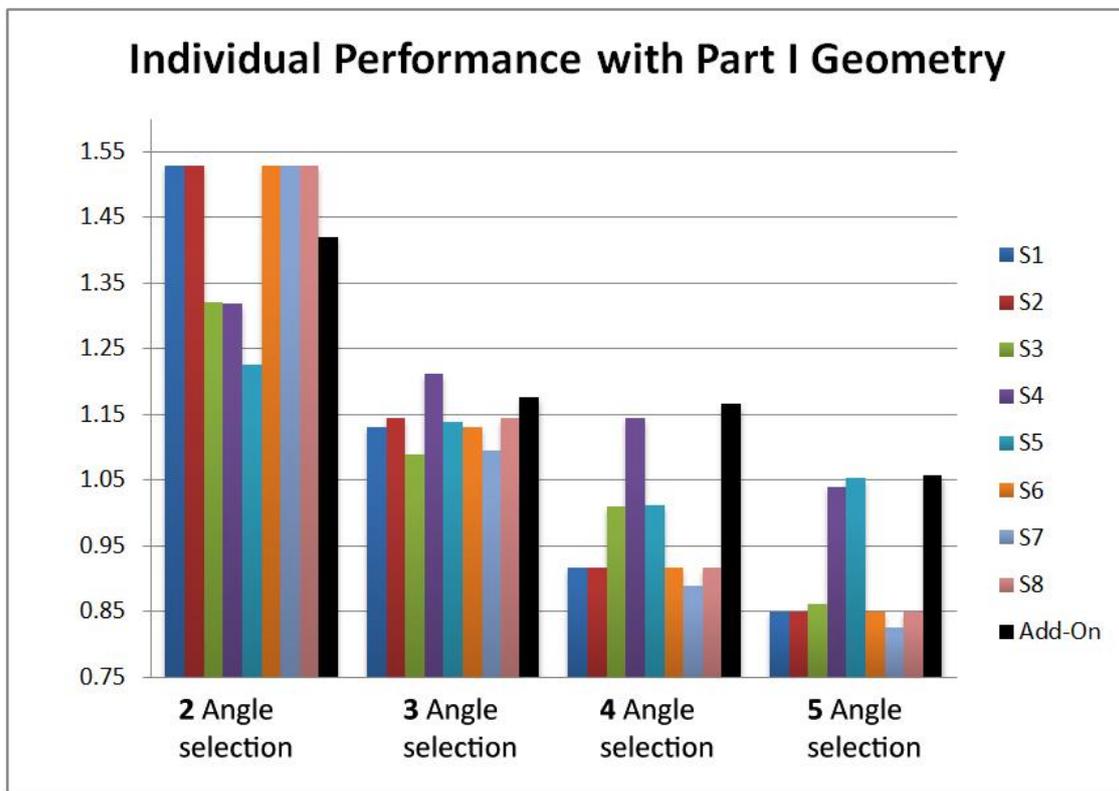


Figure 22 Individual Performance with Part I Geometry

From Figure 22 it can be seen that most of the operations chosen by test participants regards 4 and 5 angle selections for Part I geometry performed poorly compared to the Add-On.

During 4 angle selection, all of the subjects (except S5) and the Add-On chose same (0°, 90°, 180°, 270°) angles as the appropriate ones for the operation, which in all cases resulted in 457.867 mm³ material removed. In this phase, the order of angles and type of rest machining made a difference between fastest 6h 32m 36s by Add-On to slowest 8h 19m 35s by S1, S2 and S6. The most optimal choice belonging to Add-On was 180° PO, 0° PO, 270° PO and 90° PO, where the slower choice (slower by 1h 46m 59s) was 90° SS, 270° SS, 0° PO and 180° PO.

Similarly, selecting 5 angles for the Part I geometry compared between Add-On and the test subjects' performance – same angles chosen, however sequencing of angles and type of Rest Machining resulted in 2 hours longer machining time between the fastest and the slowest operations.

In order to evaluate consistency of each of the subjects' answers and the Add-On suggestions, averages of total Material Removed per Minute were calculated.

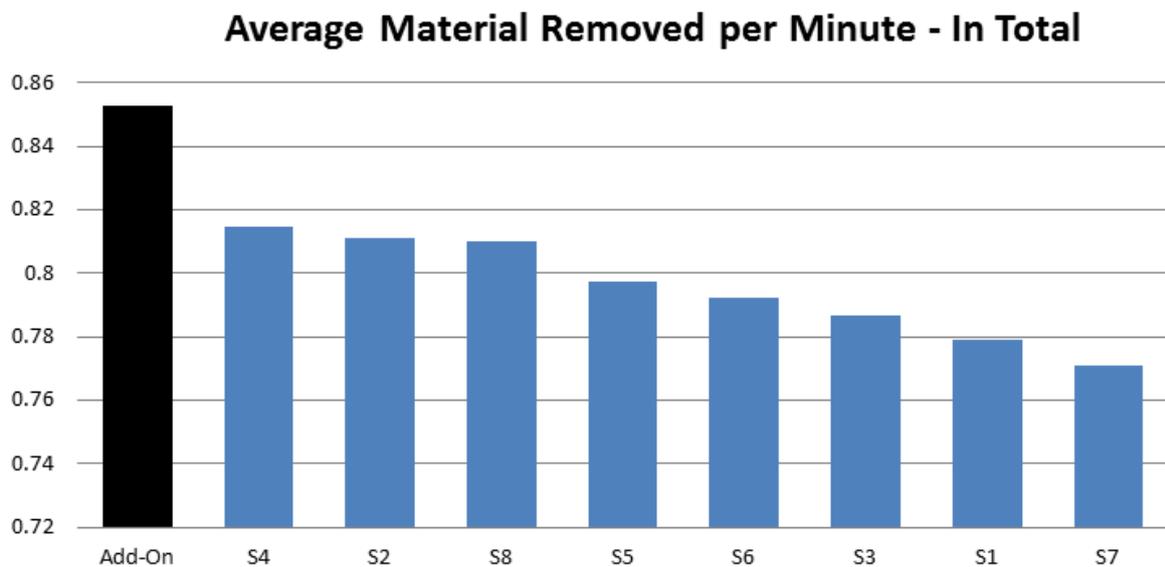


Figure 23. Average Material Removed per Minute - In Total for both Parts and all angle challenges

Data show that the Add-On suggestions overall removed most material in shortest time compared to the performance of the test subjects – the Add-On was **6.72%** faster and removed **0.631%** more material than average test subject. On the same note, the Add-On performed **4.4%** faster and removed **0.182%** more material than best performing test participant (S4).

8. Discussion

This chapter discusses the results from the experiment and assesses the success of the implemented Add-on functionality performance.

Analysing the inputs for the rotary machining, selected by the test participants and the automated Add-On – the latter seem to come out on top in most of the cases. As Figure 23 show, Machining orientations, angle sequencing and type of Rest Machining chosen by the Add-on consistently outperformed operations generated by the subjects.

As the experiment involved two different geometrical shapes to be machined, results yield some specifics at what the Add-On excels most at and where it lacks additional logic. Part I was modelled with more distinguished and easily recognised features. Some of the machining orientations were obvious to excel over the others by the possible tool reach and the stock removed. The Add-On logic of how to sequence the angles, heavily relies on weighing the “stock to be removed” from angles of interest and had an advantage with the Part I geometry. Thus, just by rearranging the order of same angles chosen, the Add-On managed to outperform the test participants.

The Part II geometry was symmetric and the difference between the Stock and the Part II volumes was considerably smaller. Most of the chosen angles to machine the part at, would remove the similar amount of the material, thus making the logic of how to sequence angles by the Add-On trivial. The difference of the performance by the test participants and the Add-On while choosing how to machine Part II was more subtle. As the angle sequence did not matter much, best operations were determined by the types of Rest Machining.

On the other hand, Add-On was not as good as experienced test participants at selecting 2 machining orientations. It was due to the resolution set for the data extraction and related to the number of “angles of interest” in the code.

9. Conclusion

This report started out by investigating Makers Culture, Movement, Makers spaces, tools and ways it could be improved. The focus of research became the integration of high tech skill requiring CnC machinery to that community through attempt to ease its complex workflow.

Literature concerning CnC router/mill optimisation techniques of rapid manufacturing and prototyping was reviewed with intentions to combine the findings with elements from Computer Aided Process Planning. Investigation led to design and implementation of Add-On tailored for Fusion 360 software, to assist the users with choosing optimal sets of parameters related to rotary machining:

- Angle (orientation) selection
- Sequencing and ordering of selected orientation angles
- Choosing Type of Rest Machining

An experiment to evaluate the functionality and performance of implemented Add-on was designed and implemented. A small sample of 8, mostly experienced CnC users were asked to fill information regards rotary machining of two objects and the parameters they would use. Data gathered from the test subjects as well as the Add-On recommendations were used to create virtual machining simulations, findings of which were compared and analysed.

The experiment results show that machining orientations recommended by Add-On slightly outperform submissions from the small sample of test participants by both overall materials removed and total machining duration. Additionally, the results hint towards an alternative implementation of the Add-On, where given orientations selected by the user, it would only focus on identifying most optimal angle sequences and few major parameters, such as Rest Machining type.

Despite showing promise, functionality test should be expanded by accumulating more test participants and analysing more objects varying in shapes and complexities.

The Add-On was implemented with the user of Makerspace/FabLab in mind and due to time restrictions certain features were implemented but not tested. The User experience testing is required to identify usefulness and performance of such features.

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