Cycle Time Reduction for CNC Machining Workcells in High-Mix Low-Volume Manufacturing

by

Brandon Christopher Sun

Bachelor of Science in Mechanical Engineering
Tufts University, 2023

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Abstract

The demand for the product under investigation exceeds the available manufacturing capacity, with the CNC milling workcell identified as the bottleneck operation. This research, conducted in an active, high-mix, low-volume production environment, focuses on evaluating and implementing improvements to CNC machining parameters to enhance the workcell's capacity. Key areas of investigation include machining speeds and feeds, depth of cut, machine settings, toolpath strategies, stepover percentages, and alternative tooling. The study specifically targeted the initial roughing operation, which uses a feed mill and is the longest milling process. Addressing the challenges of high mix and low volume, the research successfully optimized machining and CNC programming parameters, reducing total machining cycle times by 25% and resulting in a 33% increase in throughput.

Additionally, the methodologies and findings from this work have provided a framework for implementing further milling process improvements outside of the roughing operation, demonstrating their applicability to similar production scenarios.

Disclaimer: The content of the thesis is modified to protect the identity of the project company. Company name and confidential information are omitted or disguised.

Thesis supervisor: Brain W. Anthony
Title: Principal Research Scientist

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Chapter 1: Introduction

1.1 Company Overview

Company X is a world-leading multinational company that provides technology, information solutions, and integrated project management solutions to its clients. Company X produces multiple different technologies and products at different locations around the world. Its engineering, manufacturing, and sustaining plant in Houston is equipped with a foundry, machine shops, quality inspection equipment, and additional specialty process equipment. The facility employs a make-to-order (MTO) manufacturing model due to the nature of its products, which are often designed custom to meet a specific customer's needs. While Company X's product portfolio is broad, the facility involved focuses on a single product line.

1.2 Product Introduction and Manufacturing Processes

The product manufactured by Company X is designed custom for the customer and comes in a wide range of sizes with different features and materials. As a result, Company X's manufactured products are high in mix and low in volume. Each customized product is produced in order quantities seldom larger than two. The products range in size rather dramatically and are cylindrical in nature. Hence the size is often characterized by the diameter of the production. The product typically ranges from 6 - 28 inches in diameter. The overall manufacturing time of these products is directly tied to their size with larger products taking significantly longer to produce than their smaller counterparts.

The manufacturing process begins with raw materials provided by Company X's suppliers. This raw material undergoes a bandsaw step where it is cut to length. After cutting, the stock moves to a lathe where the profile of the product is turned. After turning, the profiled product goes to the CNC mills where the remaining features are introduced to the product. From there the product is close to the final form but undergoes numerous specialized surface treatment processes and assembly before moving to quality inspection and delivery to the customer.

1.3 CNC Milling Process

The CNC milling process has numerous operations that each require multiple different machining processes and tooling and are often dedicated to producing a certain feature on the product. While some tooling is reused between multiple product features, the milling procedure is driven by features. Some products are designed without a given feature which eliminates a set of procedures from the manufacturing process. The roughing and finishing operations are always present on every product. A brief overview of the types of operations are provided.

Roughing

The roughing cycle is the first set of operations performed on the product and removes the majority of the bulk material. Roughing begins with a feed mill which is the primary tool used in this process. The feed mill removes the greatest volume of material from the product but is often unable to reach everything. As a result, smaller cutting tools are used to remove the remaining hard-to-reach material. The roughing step does not machine any high-tolerance features and gets the product to approximate shape and form. These operations, particularly the feed mill, often represent the greatest share of machining time for the product.

Finishing

The finishing cycle is used to clean up the sharp edges and any material missed by the roughing pass and occurs in the middle of the overall operation. These operations often involve running a small ball-nose end mill across all non-critical features and surfaces of the product and can represent a sizable share of the machining time.

Other Feature Milling

Other feature milling is a lump category encompassing all other operations related to producing features for the product. Most of these operations are performed after roughing and around the finishing operations. Some operations have quick cycle times and others can take multiple hours. As the product can vary significantly in feature variety and quantity, this group of operations likewise varies in machining time quite dramatically. Some products omit some of these features entirely.

1.3.1 Sample Product Time Study- 17.5-inch Diameter

A time study was performed on a sample 17.5-inch diameter product which was fairly representative of an average-sized product with most features included. The goal of the time study was to evaluate roughly what operations take the most machine time. The results of the time study revealed that the roughing operation represented the largest share of the machining time. The finishing operation was the second largest single operation with many of the other operations responsible for producing product features.

CNC Milling Operation	A	B Roughing	C	D	E Finishing	F	G	H	Total
Machine Time (hh:mm)	0:11	13:02	1:35	0:08	7:08	2:10	0:20	3:35	28:09
Percentage of Total Time (%)	0.7	46.3	5.6	0.5	25.3	7.7	1.2	12.7	100.0

Table 1: Cycle times of machining operations from 17.5-inch diameter product

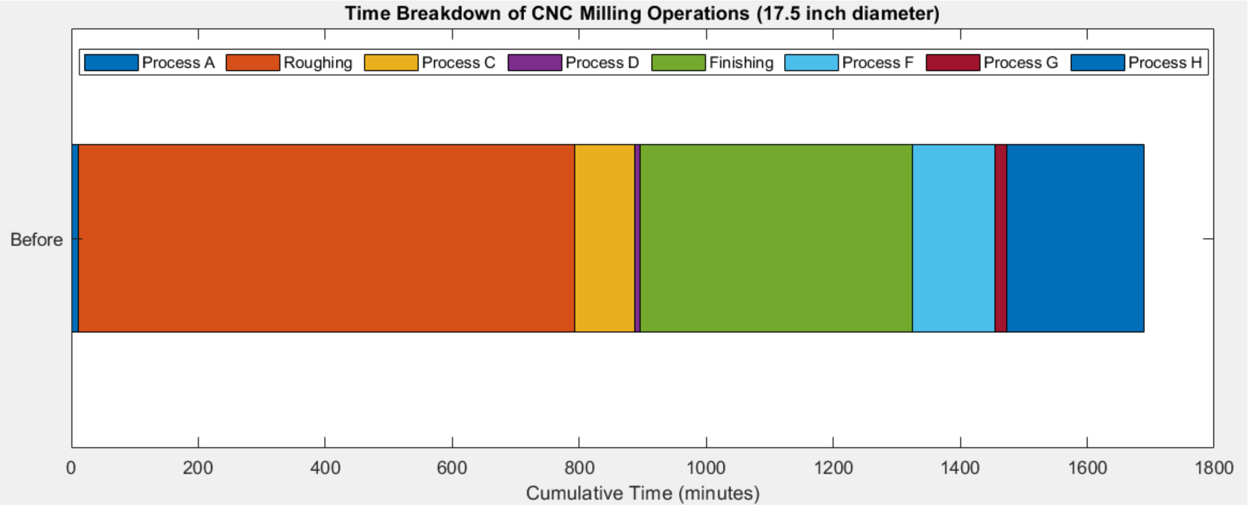
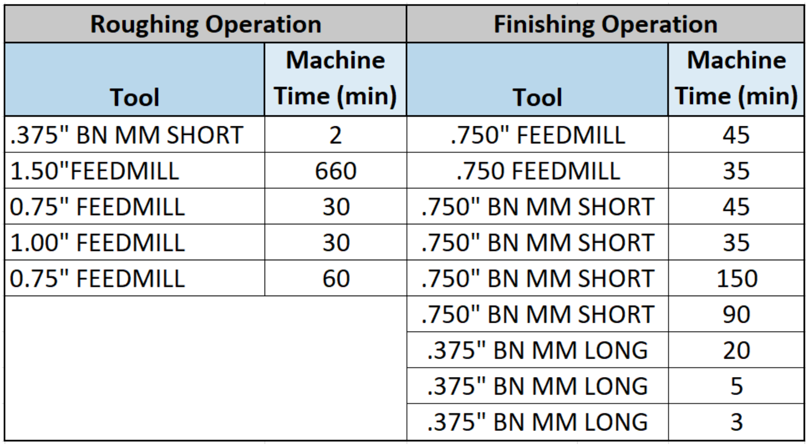


Figure 1: Bar graph of machining operation cycle times from 17.5-inch diameter product

Each operation requires numerous different machining processes. A breakdown of the tooling and processes within roughing and finishing are included in Table 2.



Roughing Operation		Finishing Operation	
Tool	Machine Time (min)	Tool	Machine Time (min)
.375" BN MM SHORT	2	.750" FEEDMILL	45
1.50"FEEDMILL	660	.750 FEEDMILL	35
0.75" FEEDMILL	30	.750" BN MM SHORT	45
1.00" FEEDMILL	30	.750" BN MM SHORT	35
0.75" FEEDMILL	60	.750" BN MM SHORT	150
		.750" BN MM SHORT	90
		.375" BN MM LONG	20
		.375" BN MM LONG	5
		.375" BN MM LONG	3

Table 2: Tooling and cycle times within roughing and finishing operations

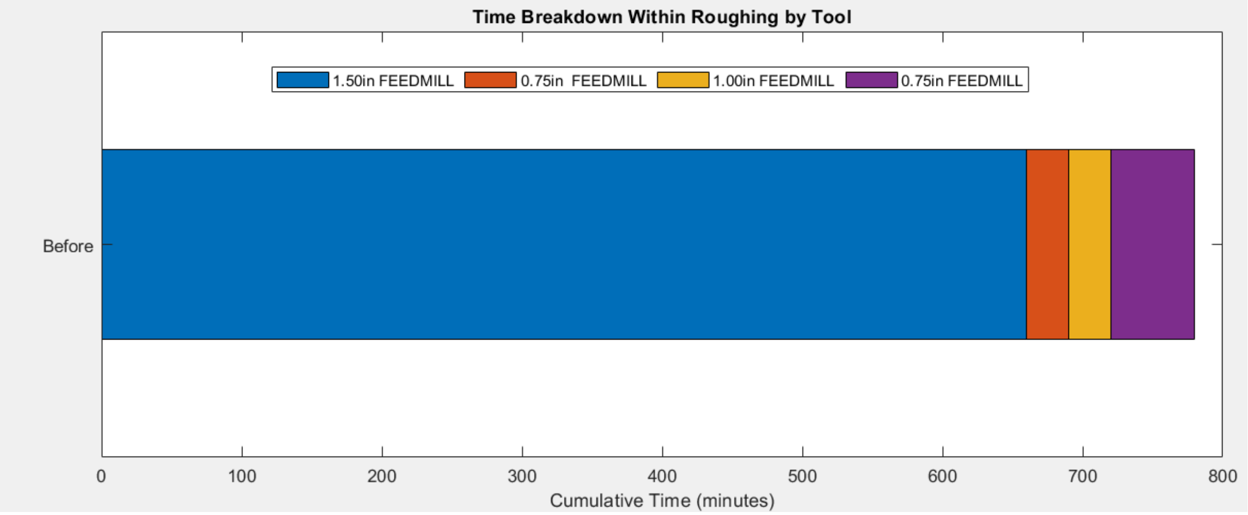


Figure 2: Cycle Time Breakdown Within Roughing by Tool for 17.5-inch diameter product

From the results of this time study, it was determined that the single longest operation performed in the CNC milling process is the 1.5-inch feed mill which alone represented 84% of the roughing time and 39% of the total machining time. This trend remained consistent with other sized products, with the roughing feed mill representing the lion's share of total machining time.

The specific feed mill that is used depends on the size of the product. Products that are smaller than 12.5 inches in diameter often use the 1-inch feed mill. Products in the 12.5-inch to 17.5-inch diameter range often use the 1.5-inch feed mill. Finally, products greater than 12.5 inches in diameter use the 2-inch feed mill.

As the roughing operation is necessary for all of Company X’s products, it was identified as a suitable first operation for improvement. It is the long-term goal of Company X’s manufacturing engineering team to eventually reduce cycle times across all CNC milling operations but the first area targeted for improvement would be the feed mills used in the roughing passes given the impact potential.

Chapter 2: Problem Statement

2.1 Introduction

At Company X, a manufacturing bottleneck has been identified in the CNC milling stage. Demand for this product as a whole is greater than the facility's manufacturing capacity, restricted primarily by the throughput of this CNC milling stage. As a result, additional orders are either backlogged or are lost entirely. This bottleneck has sparked considerable interest in launching improvement initiatives aimed at increasing manufacturing capacity without the need for acquiring additional equipment. The focus of this thesis will be on improving processes and parameters to increase throughput, thereby addressing current production constraints.

A challenge hindering Company X's path to process improvement is the requirement to operate within a dynamic production environment where the cost of damaged products is high. Additionally, as the product is custom in nature with low order quantities, there are few opportunities to quantitatively evaluate the effect of process changes as products are seldom identical, and apt comparisons cannot be made.

Despite these challenges, Company X has been presented with a unique opportunity to pursue process improvement as an atypical order of 20 identical 8.5-inch diameter products was placed. This unique, higher-quantity order provides an opportunity for process improvements to be made and quantitatively evaluated using the 8.5-inch product as a baseline.

2.2 Objectives and Scope

This thesis will focus on pursuing improvements that aim to reduce cycle times in the CNC milling stage. The scope of the project will encompass CNC programming in addition to CNC milling process parameters for the 1-inch and 1.5-inch feed mills used in the first roughing operation. The size of tooling used is dependent on the size of the product. As testing will occur on production products, availability for testing will be dependent on the production schedule. Improvements will be evaluated with respect to economic impact, effect on Material Removal

Rate (MRR), and cycle time. Improvements will also be evaluated against possible drawbacks such as tool wear, tool breakages, and machine chatter. Attention to the following parameters for process improvement will be investigated.

Increasing Feeds, Speeds, and Depth of Cut (DOC)

Existing parameters will be evaluated for improvement potential by comparing them with tooling vendor recommendations.

Evaluating Alternative Tooling

Multiple tooling vendors will showcase their tooling on production products to determine if improved performance can be achieved by switching.

Improve Machine Settings

Machine settings will be reviewed to ensure that the equipment is being utilized to its fullest potential.

Change tool path strategies

Improved tool path strategies and parameters will be pursued to increase machine utilization and removal rates.

Chapter 3: Literature Review

3.1 Introduction

This chapter will review two key areas related to this thesis's work. A brief background on Machining including equations and terminology relevant to the problem this thesis addresses will be reviewed. A review of how CNC machines operate with G-Code will be covered to provide background on specific areas in which cycle time improvements will be made.

3.2 Machining and Cycle Time

3.2.1 Machining Introduction

Machining is the manufacturing process in which a desired part or shape is produced through the controlled, subtractive removal of material using cutting methods. This process involves various techniques such as turning, milling, drilling, and grinding to achieve precise dimensions and surface finishes. Machining is widely used in industry for its ability to create complex geometries and high-tolerance components from a range of materials, including metals, plastics, and composites. By carefully controlling factors such as cutting speed, feed rate, and tool geometry, machining ensures the production of parts with exceptional accuracy and quality.

3.2.2 Machining Operating Mechanisms and MRR

The mechanism in which machining operates is through cutting. In the case of milling, this is accomplished by fixing cutting tools to the machine spindle which carves away material as the tool is moved into the stock material. A mill has several parameters that are important to its operation: feed rate, spindle speed, tooling geometry, and depth of cut. These parameters will dictate how material is being removed when the machine is in operation and can be quantified by the term MRR which is the material removal rate with units of volume of material removed per unit time. For the purposes of this thesis, MRR will be defined in two ways: theoretical MRR and operational MRR. One will calculate MRR with respect to tooling capability in an ideal cutting environment and one will calculate MRR with respect to real operating conditions which include the effects of additional inputs such as tool-pathing efficiency and machine dynamics.

$$MRR = (Feed\ Rate) * (Depth\ of\ Cut) * (Width\ of\ Cut) \quad (1)$$

$$MRR = \frac{Volume\ of\ material\ removed}{Cycle\ time} \quad (2)$$

Theoretical MRR

The theoretical MRR is calculated using the vendors' recommended feed, speed, DOC, and stepover percentages together in Equation 1. This value is theoretical as it assumes a constant cutting environment and is seldom replicated in the machine shop. Theoretical MRR, however, helps compare the capability of tooling to one another. A tool whose theoretical MRR cannot exceed the incumbent is unlikely to realize any improvement when used in production.

Operational MRR

The operational MRR is evaluated by dividing the total volume of material an operation removes by that operation’s cycle time, as seen in Equation 2. This calculation of MRR takes into account external factors such as tool pathing efficiency and the cutting demands of the product into account. This value is the one that matters as it realizes the impact of the tooling with respect to cycle time which has a significant impact on the economics of the machine shop.

3.2.3 Climb & Conventional milling

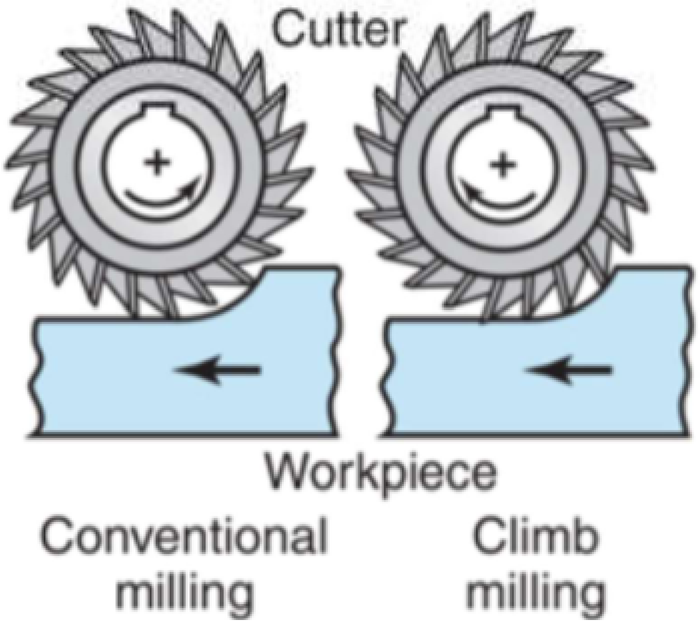


Figure 3: Diagram depicting Conventional and Climb milling [1]

Climb milling and conventional milling, depicted in Figure 3, are two distinct approaches in the machining process, each with unique characteristics and applications. In climb milling, also referred to as down milling, the cutting tool rotates in the same direction as the feed of the workpiece, meaning the cutter engages the material at the top of the cut and exits at the bottom. This technique tends to produce a smoother surface finish and requires less force, making it ideal for high-precision and high-speed operations. Conversely, conventional milling, also referred to as up milling, involves the cutter rotating against the direction of the feed. This method typically results in a rougher surface as the tool engages the material at the bottom of the cut and exits at the top. The choice between climb and conventional milling depends on factors such as material type, desired finish, and machine capability.

3.2.4 Effects of Tooling (Feed Mills)

$$SFM = \frac{(Spindle\ Speed) * (Tool\ Diameter)}{3.82} \tag{3}$$

$$Feed\ Rate = (Spindle\ Speed) * FPT * (Number\ of\ teeth) \tag{4}$$

Specifics related to tooling are important when evaluating the operation of a mill as they can dictate what feed rate, spindle speeds, and depth of cut can be used. The primary tooling used in this thesis are feed mills which have replaceable carbide cutters mounted in a tool head. Tooling vendors of feed mills will often provide a recommended depth of cut, surface speed, and feed per tooth to inform how best to operate their tooling. Surface speed (SFM) is related to the diameter of the tool and the spindle speed as shown in Equation 3. Feed per tooth (FPT) can be used with the spindle speed and number of teeth in the tool to determine the feed rate as shown in Equation 4.

3.2.5 Cycle Time

Cycle time is a key performance indicator (KPI) that is often used in manufacturing environments and is defined as the time it takes to complete a manufacturing operation from start to finish, including non-productive time. The MRR can be related to the expected cycle time and vice versa, as described in Equation 2, so long as the volume of material to be removed is known. When aiming to improve how much product can be manufactured, reducing the cycle time is key and can be done by maximizing MRR and eliminating non-productive time.

3.3 CNC Machine Operating Principles and G-Code

3.3.1 CNC Introduction

CNC (Computer Numerical Control) milling machines have the same operating principles as manual milling machines where material is removed by manipulating a cutter into the workpiece. The difference lies in that a CNC machine is controlled by a computer using servo motors on the various translation and rotation stages with feedback control [2]. As a result of this computer control, CNC machines offer significant advancements in precision and automation compared to their manual counterparts.

3.3.2 CNC Controllers

The CNC controller is a specialized computer built into the machine that controls its operation and movements. The controller is programmed and tuned to the dynamics of the specific milling machine so that automated actions can be performed. Additionally, the controller is where machine configurations and settings are set. The controller executes CNC programs which are written in g-code.

3.3.1 G-Code

G-code programs provide the CNC machine information on how to operate. The program will provide line-by-line instructions on what the machine should do and the controller executes these commands in order. In a program, before any material is removed, operation parameters are set such as what specific tool is selected, the feed rate, spindle speed, and tolerances. After these parameters are set, operation begins and the controller is fed a stream of stage positions for the machine spindle to hit. When that target position is met, the next position is set and the machine moves until it is reached. The controller uses its understanding of the machine dynamics and the acceptable tolerance range to control how the spindle is moving in space to meet these positions within tolerance, while also attempting to achieve or maintain the feed rate.

3.4 Summary

With the above literature review, background information on the relevant machining equations and an understanding of the inner workings of a CNC milling operation have been reviewed for future reference.

Chapter 4: Changing Machine Parameters

4.1 Introduction and Background

This chapter will focus on machine parameter changes that were pursued on existing tooling that include feeds, speeds, DOC, and other machine settings. When improving the cycle times of a machining process, the feeds and speeds are among the main criteria that influence the MRR of the process. Increasing feeds and speeds often come with the drawback of increased tool wear. At Company X, however, machine operators would change to fresh tooling inserts before a roughing operation and seldom need to change them before the completion of the rough. Given the cost of tooling inserts is low compared to Company X's shop rate of $150/hr, improving feeds and speeds at the cost of potentially increased tooling usage was the first strategy pursued.

Existing Tooling

The current tooling being used in the primary roughing operation consists of 1-inch, 1.5-inch, and 2-inch feed mills. Typically a given product would only be milled by one of these three. These feed mills use carbide inserts from Iscar and have 3, 5, and 5 inserts respectively. The specific insert is FFQ4 SOMT 090412T grade IC808. These inserts are square in profile allowing for four cutting faces.

Existing Speeds and Feeds

Company X's feeds and speeds were identified in the past to produce products of sufficient quality on all the milling machines. This was done to aid production flexibility and streamline the CNC programming process. Parameters were set very conservatively so as to avoid the possibility of machine chatter and tooling replacement during the operation.

Existing Depth of Cut (DOC)

For the roughing cycle, the DOC was determined to be 30 thousandths of an inch as this minimized the refinishing paths needed when continuing to rough with subsequent feed mills. This DOC falls below the manufacturer's recommended value of 40 thousandths.

MT-LINKi

MT-Link*i* is an operational management software developed by FANUC, designed to connect and manage machines in a factory setting through Ethernet [3]. MT-Link*i* can collect, manage, and visualize various types of information from CNC milling machines [3]. The machines must connect to a PC running the MT-LINKi server which provides a web interface for accessing and visualizing data. This software was used to aid in quantifying process performance.

CNC Machines

Company X has numerous different CNC milling machines used to produce their products. Of most relevance to this thesis are the Doosan VC 630/5AX CNC mills (630Vs) and Doosan DVF 8000 CNC mills (V8000s). The 630Vs are smaller and are less powerful which lend themselves to smaller diameter products in the 4-10 inch diameter range and use the 1-inch feed mills in roughing. The V8000s are larger and are more powerful than the 630Vs so they typically produce products in the 10-18 inch diameter range. These machines are controlled by FANUC controllers and have sensor readings that can be collected and monitored remotely using MT-LINKi.

4.2 Methodology

Before new feeds and speeds are tested, a time study was performed to determine a baseline from which improvements could be judged. To collect baseline info on the feed mills, time studies on the roughing operation of multiple-sized products were performed. The 8.5-inch diameter product used the 1-inch feed mill while a 17.5-inch product used the 1.5-inch feed mill. These time studies would be performed not only on the stock settings but also when improvements were being evaluated.

Data collected from the time study included the following:

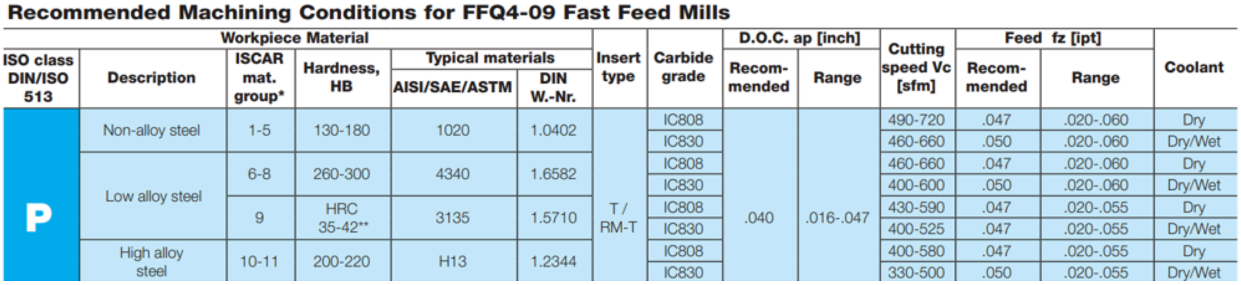
- Cycle time (operation start to operation end)
- Spindle speed
- Feed Rate
- Tool diameter
- Number of Inserts

MRR Calculation

To calculate the average MRR of the operation, the volume of material removed is needed. To determine the volume of material removed, STL models of the product pre and post-operation were generated from the CAM software for comparison. From the differences, the volume of material removed could be inferred and the average MRR calculated.

4.2.1 Speeds and Feeds Selection Process

The inserts used in both the 1-inch and 1.5-inch feed mills were Iscar FFQ4 SOMT 090412T IC808 cutting a high alloy steel with a hardness of 220 Rockwell. The generalized cutting parameters given these operating conditions were given by the manufacturer in Table 3. The spindle speed was calculated using Equation 3 and the feed rate was calculated for a target chip load using Equation 4.

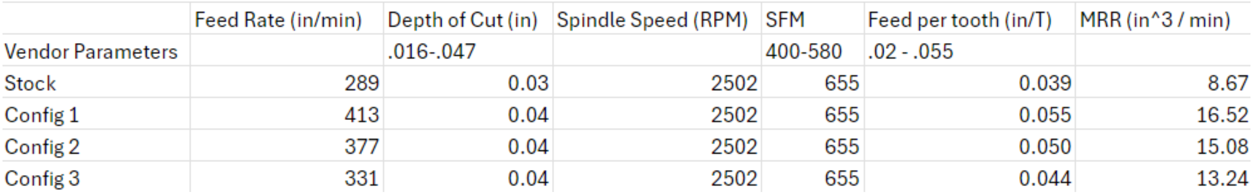


Recommended Machining Conditions for FFQ4-09 Fast Feed Mills

Workpiece Material						Insert type	Carbide grade	D.O.C. ap [inch]		Cutting speed Vc [sfm]	Feed fz [ipt]		Coolant
ISO class DIN/ISO 513	Description	ISCAR mat. group*	Hardness, HB	Typical materials				Recom-mended	Range		Recom-mended	Range	
				AISI/SAE/ASTM	DIN W.-Nr.								
P	Non-alloy steel	1-5	130-180	1020	1.0402	T / RM-T	IC808	.040	.016-.047	490-720	.047	.020-.060	Dry
							IC830			460-660	.050	.020-.060	Dry/Wet
	Low alloy steel	6-8	260-300	4340	1.6582		IC808			460-660	.047	.020-.060	Dry
							IC830			400-600	.050	.020-.060	Dry/Wet
		9	HRC 35-42**	3135	1.5710		IC808			430-590	.047	.020-.055	Dry
							IC830			400-525	.047	.020-.055	Dry/Wet
	High alloy steel	10-11	200-220	H13	1.2344		IC808			400-580	.047	.020-.055	Dry
							IC830			330-500	.050	.020-.055	Dry/Wet

Table 3: Feeds and Speeds table for Iscar FFQ4-09 feed Mills

Company X was operating this tooling at an increased surface speed of 655 sfm compared to the manufacturer’s recommended max value of 580 sfm. The increased value was kept as it reduced chip load and performed well in production. An increased depth of cut of 40 thousandths was chosen as it is the manufacturer’s recommended DOC and would reduce the number of tool paths considerably while increasing MRR. Furthermore, pushing DOC to the maximum value can spell disaster should the tool encounter any extra material. Hence selecting DOC values slightly under maximum was the chosen strategy should all other factors remain constant. Numerous feed rates pushing higher chip loads were chosen for testing to evaluate the cycle time reduction. The operating parameters for testing on the 1-inch feed mill are given in Table 4.



	Feed Rate (in/min)	Depth of Cut (in)	Spindle Speed (RPM)	SFM	Feed per tooth (in/T)	MRR (in^3 / min)
Vendor Parameters		.016-.047		400-580	.02 - .055	
Stock	289	0.03	2502	655	0.039	8.67
Config 1	413	0.04	2502	655	0.055	16.52
Config 2	377	0.04	2502	655	0.050	15.08
Config 3	331	0.04	2502	655	0.044	13.24

Table 4: Feeds and speeds for testing on a 1-inch feed mill

A similar process for selecting feeds and speeds was performed for the 1.5-inch feed mill.

4.2.2 Failure Criteria

When evaluating increased feeds and speeds, there are a number of different failure criteria that need to be taken into consideration such as machine chatter, sparking, tool failures, and chip quality.

Machine chatter

Machine chatter, also known as cutting chatter, is excessive vibration that can be caused when the cutting frequency matches the natural frequency of the tool, machine, or part. This chatter can cause accelerated machine wear and failure and cause unexpected downtime. Chatter can occur when due to poor machine rigidity, when machining the unsupported end of a workpiece, when tool overhang is high, when tooling is wearing, and when feeds and speeds are inappropriately chosen. It is important to reduce chatter whenever possible to avoid unnecessary damage to the milling machine.

Sparking

Sparking can occur when feed rates or spindle speeds get too high and is a sign that tooling may be wearing out or chipping. Some harder materials are more prone to sparking during machining. While an occasional spark may be okay, it is best to avoid operating primates that result in regular sparking.

Tool failures

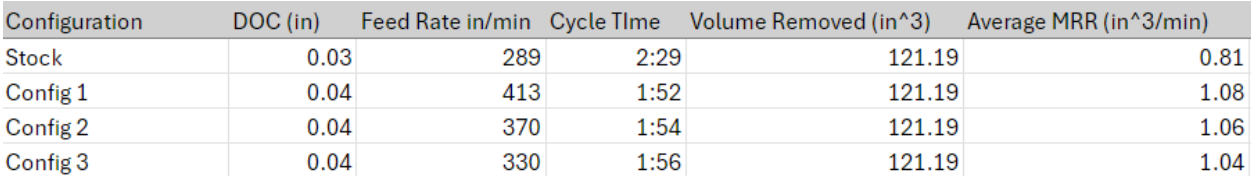
Tool failures, as the name implies, are unexpected dramatic failures of the inserts in a tool that could damage the tool head in addition to the inserts. Ideally, the inserts wear down in a controlled manner, and cutting edges are switched out before an insert fails to prolong tool life and avoid waste. If cutting conditions are too poor, the tooling may fail suddenly and unexpectedly.

Chip quality

Examining the quality of the metal shavings, also known as “chips”, can be a good way of gauging whether or not the operating parameters are appropriate. Color is important as it can indicate whether or not the heat generated by cutting is going into the chips or into the tool and part. Chips that are blue or purple in color are good. Chips that look dark grey or are burnt are not desirable and can be indicative of pushing parameters that are too aggressive. Chip shape is important too. From a feed mill, a chip that curls into itself, resembling a “6” or a “9” is indicative of good operating parameters. Finally, when examining the edge of the chip, a clean straight edge is ideal. Rough edges that resemble a saw blade are indicative of tearing which happens when operating parameters aren’t appropriately set.

4.3 1-Inch Feed Mill Testing and Results

The 1-inch feed mills were evaluated on an 8.5-inch product which required 121.19 cubic inches of material to be removed in the roughing pass. The first couple of test results are included in Table 5.



Configuration	DOC (in)	Feed Rate in/min	Cycle TIme	Volume Removed (in^3)	Average MRR (in^3/min)
Stock	0.03	289	2:29	121.19	0.81
Config 1	0.04	413	1:52	121.19	1.08
Config 2	0.04	370	1:54	121.19	1.06
Config 3	0.04	330	1:56	121.19	1.04

Table 5: Time studies using a 1-inch feed mill evaluating the effect of speeds and feeds and DOC

The primary takeaways from this time study were the significant effect of increasing DOC on the cycle time and the much smaller effect of increasing feed rates on cycle time. While both DOC and feed rates were changed in this time study, implementing Config 1 increased operational MRR over the Stock configuration by 33.3%

4.4 Machine Setting Changes

4.4.1 Observed Problem

While supervising the CNC milling machine in operation on the 8.5-inch products with the 1-inch tool, it was observed that the machine would very seldom achieve the targeted feed rate, even on longer straight line passes where the machine should be operating at maximum feed. Increasing the target feed rate did not affect these passes. This observed behavior significantly increased the cycle times of operations with little ability to effect changes. Machine capability was ruled out as some tool passes would achieve the targeted feed rate. CNC programming was consulted before identifying the issue as a machine code setting.

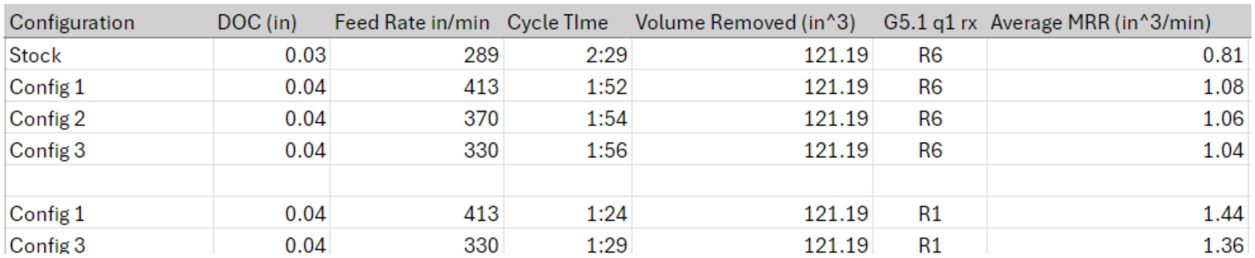
4.4.2 FANUC AICC/AIAPC

FANUC-controlled CNC milling machines have a high-speed machining settings called AI Contour Control (AICC) and AI Advanced Preview Control (AIAPC) that enable the controller to look ahead in the CNC program to improve the performance of the machine. For these acronyms, AI does not refer to "Artificial Intelligence". AI represents FANUC's Alpha I Series Servo System. The syntax enabling AICC/AIAPC is “G05.1 Q1 Rx” where Rx provides the user with the option of selecting from 10 fixed settings (R1 -R10) which contrast Tool Path Speed (feed rate) with Positioning Accuracy. A value of R10 will greatly prioritize positioning accuracy at the expense of feed rate while a value of R1 will greatly prioritize feed rate at the expense of positional accuracy.

4.4.3 Solution and Impacts

Both Doosan CNC Milling Machines were controlled with FANUC controllers and would automatically implement AICC/AIAPC at a setting of R6 after every tool change if no alternative AICC/AIAPC setting was indicated. This would slow down the feed rates when the controller anticipated challenges meeting the tolerance threshold. The following line of code was inserted with every tool change related to a roughing program to remove the slowing behavior: “G5.1 Q1 R1”.

Additional time studies were performed using the 1-inch feed mill on the 8.5-inch diameter product to observe the effect of setting the AICC/AIAPC parameter to R1 with data recorded in Table 6, note the “G5.1 q1 Rx” column.



Configuration	DOC (in)	Feed Rate in/min	Cycle TIme	Volume Removed (in^3)	G5.1 q1 rx	Average MRR (in^3/min)
Stock	0.03	289	2:29	121.19	R6	0.81
Config 1	0.04	413	1:52	121.19	R6	1.08
Config 2	0.04	370	1:54	121.19	R6	1.06
Config 3	0.04	330	1:56	121.19	R6	1.04
Config 1	0.04	413	1:24	121.19	R1	1.44
Config 3	0.04	330	1:29	121.19	R1	1.36

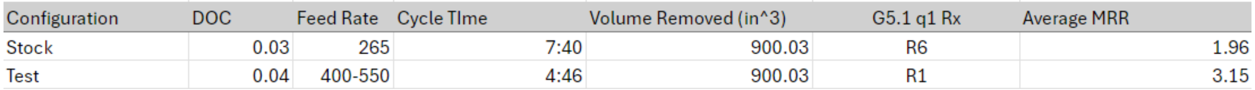
Table 6: Time study demonstrating effects of AICC/AIAPC setting

Evaluating the difference in cycle time of Config 1 before and after changing the AICC/AIAPC setting to R1 reveals an additional 33.3% increase in MRR. Compared to the stock configuration, changing the AICC/AIAPC parameter and changing feeds and speeds to Config 1 improved MRR by 77.8%. As noted earlier, the effect of increasing feed rates had little effect on the overall cycle time. During this test of Config 1, a tool break was recorded. Given the little cycle time improvement between config 3 and 1, config 3 was selected as a standard for future roughing operations using the 1-inch feed mill. Between the stock configuration and config 3’s feeds and speeds, the MRR was increased by 67%.

The effect of making the AICC/AIAPC change was so dramatic, that Company X immediately implemented the change across all FANUC roughing cycles and would be included in all new CNC programs and tests.

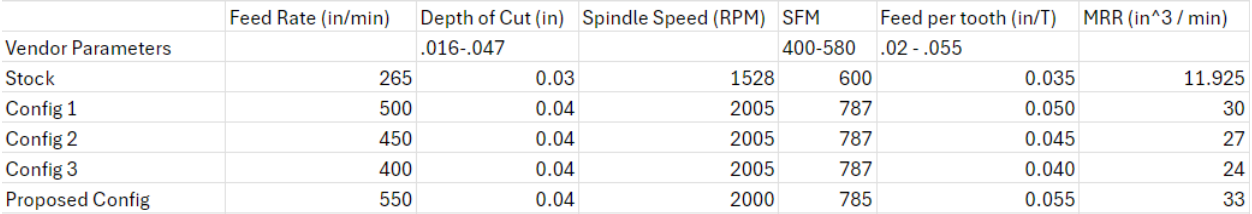
4.5 1.5-Inch Feed Mill Testing and Results

The 1.5-inch feed mills were evaluated on a 17.5-inch product which required 900 cubic inches of material to be removed in the roughing pass. The first couple of test results are included in Table 7.



Configuration	DOC	Feed Rate	Cycle TIme	Volume Removed (in^3)	G5.1 q1 Rx	Average MRR
Stock	0.03	265	7:40	900.03	R6	1.96
Test	0.04	400-550	4:46	900.03	R1	3.15

Table 7: Time studies on 1.5-inch feed mill evaluating feeds and speeds and DOC increases



	Feed Rate (in/min)	Depth of Cut (in)	Spindle Speed (RPM)	SFM	Feed per tooth (in/T)	MRR (in^3 / min)
Vendor Parameters		.016-.047		400-580	.02 - .055	
Stock	265	0.03	1528	600	0.035	11.925
Config 1	500	0.04	2005	787	0.050	30
Config 2	450	0.04	2005	787	0.045	27
Config 3	400	0.04	2005	787	0.040	24
Proposed Config	550	0.04	2000	785	0.055	33

Table 8: Feeds and Speeds tested on a 1.5-inch feed mill

When evaluating the 1.5-inch feed mills, there were only 3 identical products in production. The first product was used to establish a cycle time baseline with the second product used to increase the depth of cut and identify a suitable operating feed rate. The second test also received the AICC/AIAPC code change. As this was a larger product with a longer cycle time, a given feed rate was tested with 30 minutes of operation before evaluating the next feed rate. Tested feeds and speeds for this 1.5-inch tool are given in Table 8.

When testing, it was observed the tool ran better at a higher spindle speed of 2000 rpm which was implemented into the remaining tests on this tool. It was determined that a feed rate of 550 ipm and a DOC of 40 thousandths was the hardest this tooling could be pushed before noticeable sparking occurred. During these tests, some machine chatter was observed but was not unrelated to the speeds and feeds and was due to the product geometry and tool pathing.

From the baseline, the operational MRR was increased by 60.7%. This was performed by increasing DOC, implementing the AICC/AIAPC change, and increasing feeds and speeds. Given this product was manufactured using varied feed rates, the reduction in cycle time would likely be greater if it were run at the proposed 550 ipm for the entirety of the product.

4.7 Summary

Changing the feeds, speeds, DOC, and AICC/AIAPC parameters on the existing machines and tooling had an enormous effect on increasing MRR values and reducing cycle times. While many of these changes were made together and without a more organized DOE, the cycle time reductions realized by these combined changes are in excess of 41% across both the 1-inch and 1.5-inch feed mills on the 8.5-inch and 17.5-inch products respectively.

Chapter 5: Changing Tool Pathing

5.1 Introduction and Background

As the project progressed, the scope increased to encompass more than machine parameters. Improvements to CNC programming and tool pathing were identified as another promising area for cycle time reduction. The primary parameters that were investigated were the toolpathing algorithm itself and the stepover percentage from toolpath to toolpath. These changes were tested on 1-inch and 1.5-inch feed mills.

5.1.1 Tool Pathing Algorithms

The tool-pathing algorithms are the strategies that a CAM software will use when generating the tool-paths. When generating a roughing pass, there are many different strategies that have different sub-variations one can choose from. For the feed mill, there are two primary strategies that were up for consideration, Lace and Concentric, with three sub-variations for each of them, climb, conventional, and optimized.

The sub-variants climb, conventional, and optimized are related to the choice of milling to be performed when surfacing the model. Choosing climb or conventional will add additional tool paths to ensure model surfacing and sometimes bulk removal is performed with the specified milling type. Selecting optimized will disregard the preference for one over the other and will minimize additional tool paths. The choice of this sub-variant is dependent on factors such as material type, desired finish, and machine capability.

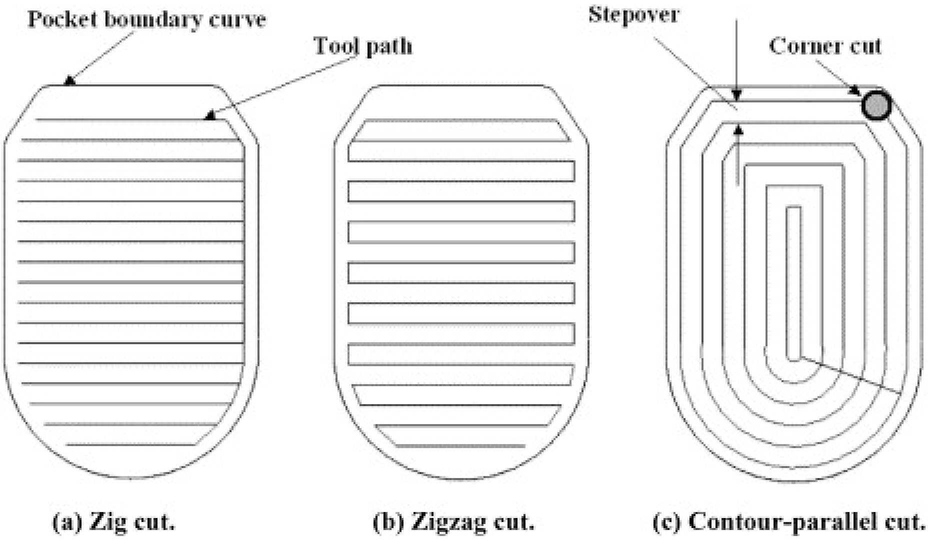


Figure 4: Example pocketing toolpaths. (a) Zig cut; (b) Zigzag cut; and (c) Contour-parallel cut [4].

Lace Strategies (Zig & Zig-Zag)

Lace is characterized by following a back-and-forth toolpathing strategy. This geometric approach is good at removing material quickly and methodically and shrinking the size of the CNC programs. It is also preferred when machining parts that have simpler geometries. When operating with the lace strategy, the choice of milling (climb, conventional, and optimized) is presented.

A lace-optimized toolpathing strategy results in a zig-zag operation where both climb and conventional passes are taken and is depicted in Figure 4 (b). This toolpath strategy is good at rapidly removing material as it cuts in both directions, reducing tool paths.

Selecting either lace-climb or lace-conventional will result in a zig cut where the cutting paths are only in one direction as depicted in Figure 4 (a). Zig cut toolpathing provides additional control over the cutting conditions.

Concentric Strategies (Contour-parallel)

Concentric is characterized by creating tool paths that run parallel to the contours of the part. This toolpathing strategy can be efficient with complex and organic geometries. Concentric tool paths have more consistent tool engagement during the toolpaths which can improve tool life and reduce machine chatter. When operating with the contour strategy, the choice of milling (climb, conventional, and optimized) is also presented.

A concentric-optimized strategy results in the formation of parallel contours that, when milling a pocket, will form closed shapes. When milling open geometries, such as a fin, the strategy will form parallel concentric rings growing in the radial direction, away from the feature. The optimized sub-variant will not prioritize either climb or conventional cutting and will use both to minimize the tool paths needed.

A concentric-climb or concentric-conventional strategy will prioritize the selected cutting strategy for the surfacing pass but, unlike the lace counterparts, will continue to use both cutting methods when removing bulk material far from the surface boundary.

All three of the concentric sub-variants will resemble the tool paths indicated in Figure 4 (c).

5.1.2 Stepover Percentage and Scallops

Another way to increase MRR is to increase the width of the cut which is chosen in programming. The width of the cut is often represented as a percentage of the diameter of the cutting tool. For finishing passes, it is often best to choose a value less than 50% and a value greater than 50% for roughing. The specific value is often determined based on factors including machine power, material, desired surface finish, and rigidity. As a rule of thumb, a stepover value of exactly 50% should be avoided as the cutter is faced with maximum forces when cutting at the centerline. For end mills, up to 100% stepover is feasible but for feed mills with curved profiles, a different approach is needed to calculate the maximum stepover due to the effect of scallops.

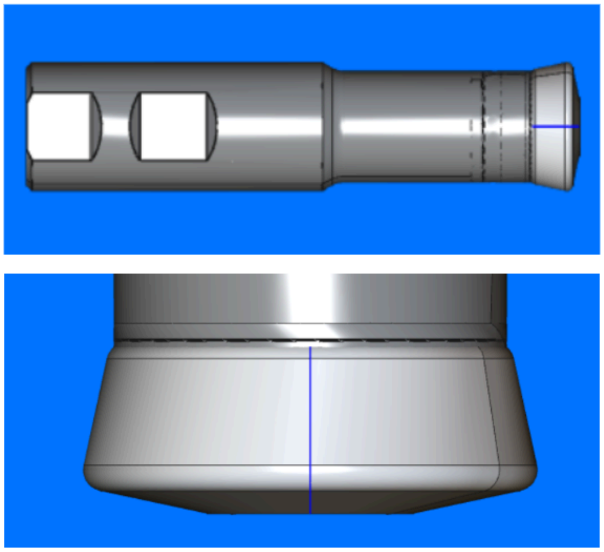


Figure 5: 3D representation of Iscar 1-inch feed Mill (top), 3D cutter profile (bottom) [5]

A scallop is the material left behind by cutting tools with curved profiles. The tool profile of a feed mill does not have a flat bottom for the full cutting area like a more common end mill cutter. The arrangement of the cutters in a feed mill results in a unique profile that is flat near the center of the tool with chamfers and a radius near the outer edge of the tool and is depicted with a 1.5-inch Iscar tool in Figure 5 (bottom).

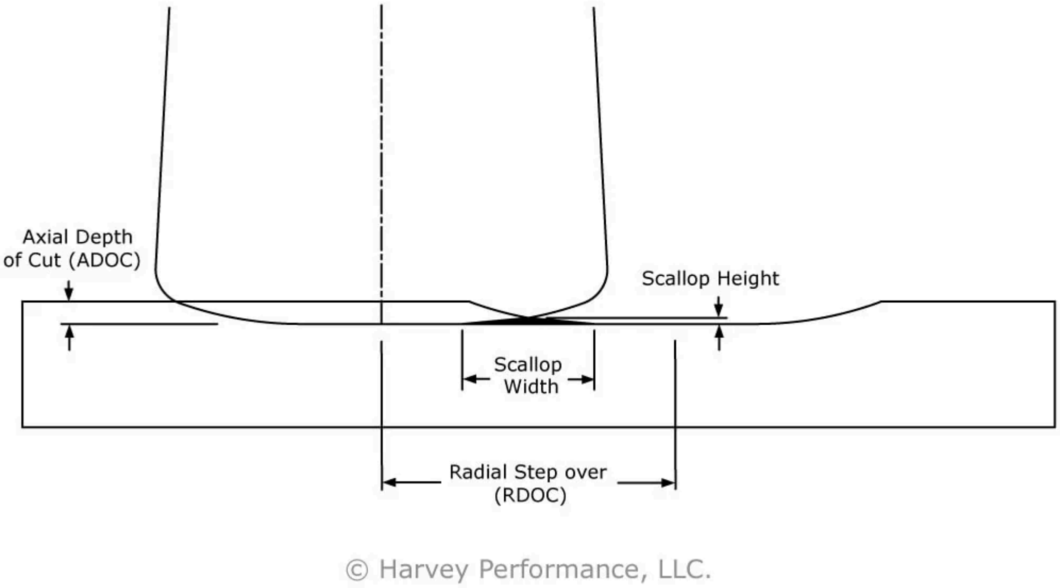


Figure 6: Side view showing scallop profile after two roughing passes [6]

Scallops affect more than the surface finish left behind. As scallops are areas of excess material left behind from cutting, it can result in areas of increased DOC which could damage the tool if it exceeds the maximum DOC [6]. The size of the scallop is dependent on the depth of cut and the stepover distance.

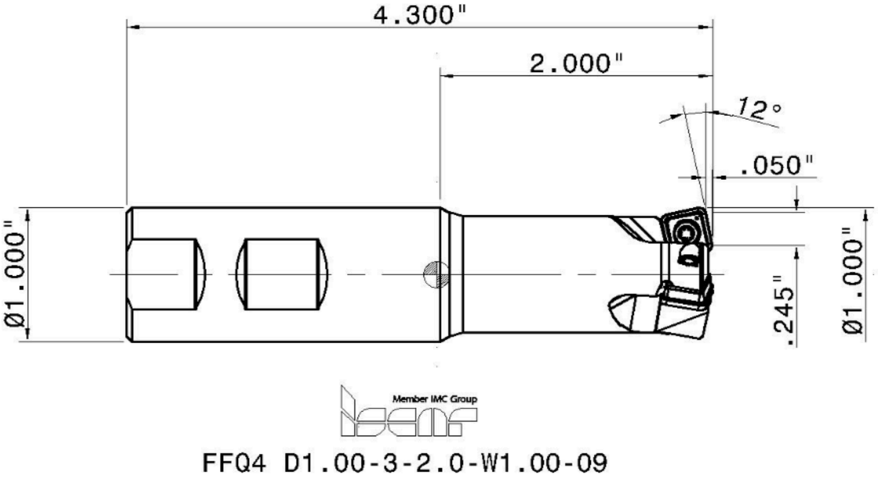


Figure 7: Annotated drawing of the 1-inch Iscar feed mill [5].

Company X decided that avoiding the creation of scallops entirely would be the preferred method of setting the maximum stepover. In that case, the stepover percentage would need to be calculated from the geometry of the feed mill as the ratio between the total diameter of the tool to half of the diameter plus the distance between the centerline and inner edge of the cutter. In the case of the 1-inch feed mill, that value comes out to .755 or 75.5%. This value differs from feed mill to feed mill and is related to the ratio of the diameter to the size of the cutter.

5.2 Methodology

Similar to the evaluation of testing feeds and speeds, improvements were evaluated based on their effects on cycle times which required a time study to be performed. Due to the limited availability of identical products from which testing could occur, a baseline cycle time would be acquired followed by a test in which multiple variables were changed. The time studies performed changing tool paths often included changes to feeds and speeds as well so the specific effect of the tool paths wasn't always available.

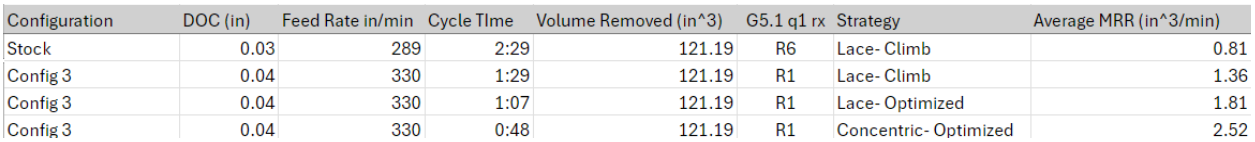
The following information was gathered and recorded during the time studies.

- Cycle time (operation start to operation end)
- Programming strategy (Lace-climb, Lace-optimized, Concentric)
- Spindle speed
- Feed Rate
- Tool diameter
- Number of Inserts
- Percent Step-over

5.3 1-Inch Feed Mill Testing and Results

As the 1-inch feed mill was used on the 8.5-inch product at a greater order quantity, more tests could be performed allowing for better characterization of the individual effect of different tool pathing strategies as well as increasing stepover percentage.

First, the effect of changing different tool pathing strategies was evaluated. Company X had been using the lace-climb strategy as their default. The feeds and speeds used in Config 3 were preferred as they offered increased performance while reducing the risk of tool breakage. The strategies Lace-climb, Lace-optimized, and Concentric-optimized were evaluated. The conventional strategies in addition to concentric- climb were omitted as they were not expected to yield improved results.



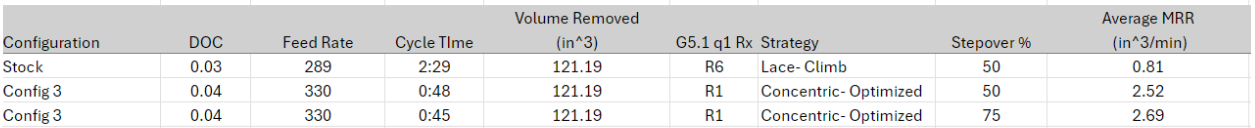
Configuration	DOC (in)	Feed Rate in/min	Cycle TIme	Volume Removed (in^3)	G5.1 q1 rx	Strategy	Average MRR (in^3/min)
Stock	0.03	289	2:29	121.19	R6	Lace- Climb	0.81
Config 3	0.04	330	1:29	121.19	R1	Lace- Climb	1.36
Config 3	0.04	330	1:07	121.19	R1	Lace- Optimized	1.81
Config 3	0.04	330	0:48	121.19	R1	Concentric- Optimized	2.52

Table 9: 1-inch feed mill tool-pathing testing results

From the tool pathing tests tabulated in Table 9, concentric-optimized yielded the greatest increase in MRR over the other strategies. The config 3 Lace-climb run was used as the basis of comparison to eliminate the effects of the increased DOC and feed rates. Changing the toolpathing strategy from lace-climb to concentric optimized had the greatest increase in MRR with an 85.3% increase. Lace-optimized had an improved performance over lace-climb with an

MRR increase of 33.1% but it couldn’t compare to the improvements realized by changing to concentric optimized.

Changing the stepover percentage was another target area for improvement. For this test, the basis of comparison was config 3 with a strategy of concentric-optimized using a 50% stepover. The maximum stepover percentage without realizing the creation of scallops was calculated to be 75.5% as was calculated at the end of section 5.1.2. For testing, a value of 75% was used and results were tabulated in Table 10.



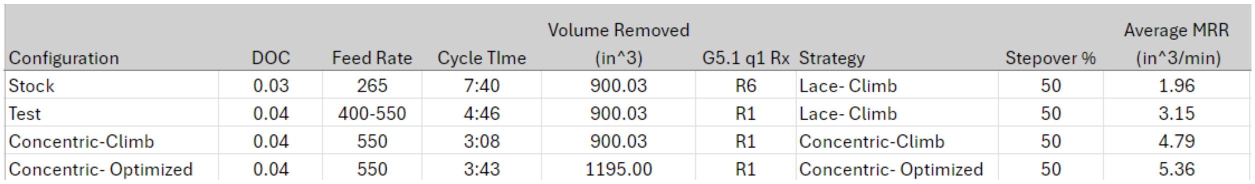
Configuration	DOC	Feed Rate	Cycle TIme	Volume Removed (in^3)	G5.1 q1 Rx	Strategy	Stepover %	Average MRR (in^3/min)
Stock	0.03	289	2:29	121.19	R6	Lace- Climb	50	0.81
Config 3	0.04	330	0:48	121.19	R1	Concentric- Optimized	50	2.52
Config 3	0.04	330	0:45	121.19	R1	Concentric- Optimized	75	2.69

Table 10: 1-inch feed mill stepover percentage testing results

The results of increasing stepover were rather lackluster compared to the previously implemented improvements. While an increasing stepover percentage from 50%-75% should theoretically increase MRR values by 50%, the real improvements were much less due to the nature of the 8.5-inch product. With few side-by-side passes needed on each layer of the operation, the effect of increasing the stepover percentage was not significant. For the 1-inch feed mill, increasing the stepover percentage from 50%-75% increased MRR by 6.7%.

5.4 1.5-Inch Feed Mill Testing and Results

The 1.5-inch feed mill was evaluated on the 17.5-inch product which had a much smaller order quantity of 3 which had to be shared with speeds and feeds testing. With the reduced test number, there was some mixing of testing variables and the tests were performed before the stepover percentage was considered. Furthermore, the concentric-optimized tool pathing strategy was tested on a different 17.5-inch diameter product with a greater volume of material to remove.



Configuration	DOC	Feed Rate	Cycle TIme	Volume Removed (in^3)	G5.1 q1 Rx	Strategy	Stepover %	Average MRR (in^3/min)
Stock	0.03	265	7:40	900.03	R6	Lace- Climb	50	1.96
Test	0.04	400-550	4:46	900.03	R1	Lace- Climb	50	3.15
Concentric-Climb	0.04	550	3:08	900.03	R1	Concentric-Climb	50	4.79
Concentric- Optimized	0.04	550	3:43	1195.00	R1	Concentric- Optimized	50	5.36

Table 11: 1.5-inch feed mill tool-pathing testing results

The MRR achieved by the Test Lace-climb run was 3.15 in^3/min which will be the standard from which concentric-climb and concentric-optimized will be evaluated. Unfortunately, that test run is the same one where feeds and speeds were being evaluated so the actual MRR is likely higher resulting in smaller magnitude differences in the comparison to concentric-climb and concentric-optimized. That said, switching to concentric-climb resulted in an MRR increase of 52%. More impressively, switching from lace-climb to concentric-optimized resulted in an MRR increase of 70%. These improvements dramatically improved MRR rates which will reduce cycle times across the board.

An unexpected improvement of transitioning to concentric from lace is that the incidence of machine chatter was reduced significantly. This improves machine life in addition to reducing required operator interference. The

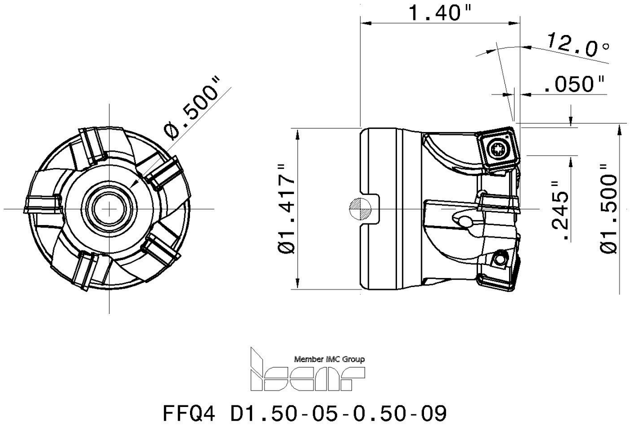


Figure 8: Annotated drawing of the 1.5-inch Iscar feed mill [7]

While the stepover percentage was not evaluated on the 1.5-inch feed mill, the theoretical maximum stepover percentage was evaluated using the annotated drawing in Figure 8 to be

83.6% before the formation of scallops. Future testing evaluating the machine’s ability to accomplish this increased stepover will need to be conducted.

5.5 Summary

Changing the tool pathing strategies from lace-climb to concentric-optimized resulted in the greatest reduction of cycle times or increases in MRR across both the 1-inch and 1.5-inch tools. It will become the formal recommendation to switch from lace-climb to concentric-optimized for all roughing processes. Increasing the stepover percentage from the original value of 50% to the maximum capability of the tool will be the recommended change.

Chapter 6: Objectively Evaluating Alternative Tooling

6.1 Introduction and Background

In addition to the improvements made, changing the tooling that is being used could allow for increased MRR and improved cycle times. The primary way in which new tooling may improve cycle times is through the tooling's ability to handle more aggressive speeds and feeds, assuming the machine is capable enough to provide that power. By evaluating a new tool's theoretical MRR, evaluating the operational MRR on a production part, and evaluating tooling on an economic basis, the decision on whether or not to invest in changing tools can be made.

The scope of the tooling evaluation was limited to four new tools for the 1-inch feed mill.

Economic Model

Evaluating a tool on the basis of economic impact is a strategy that can be used to take into account additional tooling differences such as number of inserts, cutting edges per insert, insert cost, and the cost of shop time to identify if a new tool is actually worthwhile to pursue. After all, at the end of the day, increasing profits is the real goal.

A Matlab script was built to calculate the operational costs of a product related to tooling, see Equation 5 for a simplified depiction. The actual code is available in Appendix 2. The equation boils down to the total time of the operation multiplied by the shop rate added to the cost of the tooling edges used. This equation hopes to capture the effects of tools that wear quickly, have differing numbers of inserts on the tool head, and the cost of the inserts itself, in addition to any time savings realized by an improved MRR.

$$Total\,Cost = ShopRate * (MachiningTime + ToolChangeTime) + ToolingCost \tag{5}$$

$$Tooling\,Cost = (CostOfInsert * InsertNumber * NumToolChanges)/\,InsertEdges \tag{6}$$

$$ToolingChangeTime = NumToolChanges * TimePerToolChange \tag{7}$$

$$MachiningTime = VolumeRemoved/MRR \tag{8}$$

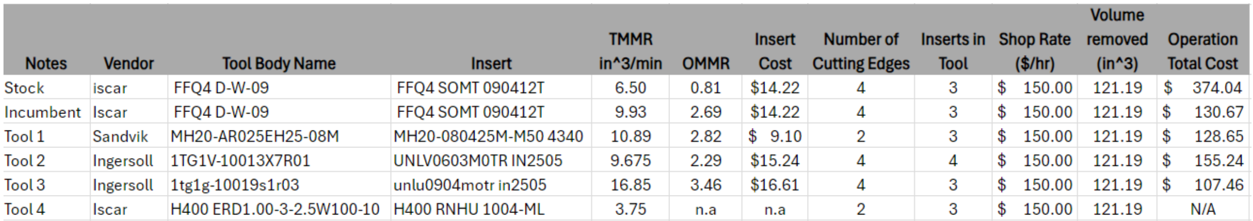
This script can be used to calculate an effective “cost per operation” and can be used to quantify the operational cost savings that cycle time reductions have had for Company X.

6.2 Methodology

When evaluating this new tooling, first the theoretical MRR was calculated on realistic operating parameters to evaluate whether or not the new tooling would, on paper, be able to outperform the existing tooling. If the theoretical MRR represented favorable improvements over our existing tooling, the tool was then purchased and tested on a production part with realistic operating parameters. The test production part’s CNC program will have many of the tool-pathing improvements implemented already, such as a switch to concentric-optimized and a programmed stepover of 75%. The DOC and feed rate will be run at the most aggressive, operationally stable configuration that is able to be achieved in person. A time study would determine the cycle time and the operational MRR and a quote on the inserts would be requested to evaluate the final economic impact making a switch might represent compared to our existing best tooling.

6.3 Results

There were four different 1-inch feed mills evaluated: two from Ingersoll, one from Iscar, and one from Sandvik. See Table 12 for more detailed information.



Notes	Vendor	Tool Body Name	Insert	TMMR in^3/min	OMMR	Insert Cost	Number of Cutting Edges	Inserts in Tool	Shop Rate ($/hr)	Volume removed (in^3)	Operation Total Cost
Stock	iscar	FFQ4 D-W-09	FFQ4 SOMT 090412T	6.50	0.81	$14.22	4	3	$ 150.00	121.19	$ 374.04
Incumbent	Iscar	FFQ4 D-W-09	FFQ4 SOMT 090412T	9.93	2.69	$14.22	4	3	$ 150.00	121.19	$ 130.67
Tool 1	Sandvik	MH20-AR025EH25-08M	MH20-080425M-M50 4340	10.89	2.82	$ 9.10	2	3	$ 150.00	121.19	$ 128.65
Tool 2	Ingersoll	1TG1V-10013X7R01	UNLV0603M0TR IN2505	9.675	2.29	$15.24	4	4	$ 150.00	121.19	$ 155.24
Tool 3	Ingersoll	1tg1g-10019s1r03	unlu0904motr in2505	16.85	3.46	$16.61	4	3	$ 150.00	121.19	$ 107.46
Tool 4	Iscar	H400 ERD1.00-3-2.5W100-10	H400 RNHU 1004-ML	3.75	n.a	n.a	2	3	$ 150.00	121.19	N/A

Table 12: Economic Evaluation of the 1-inch tooling

6.3.1 Tool 1: Sandvik MH20-AR025EH25-08M

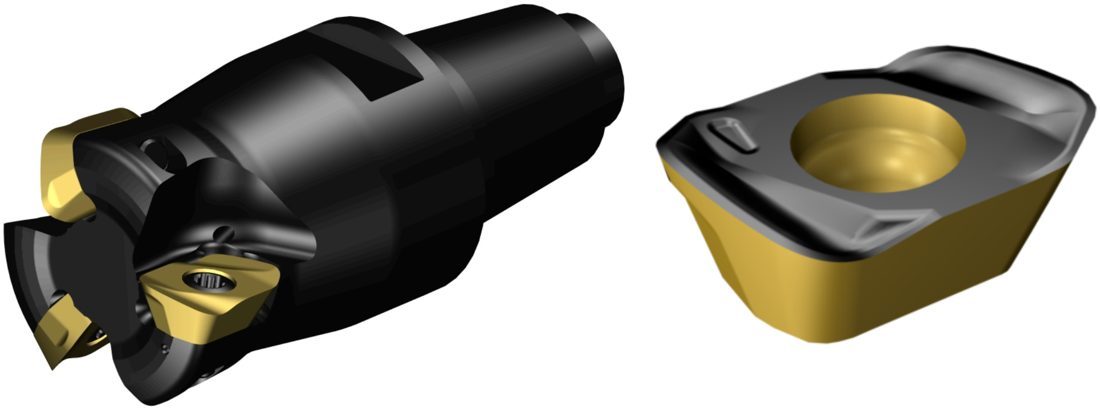


Figure 9. Graphic of Sandvik MH20-AR025EH25-08M tool body (left) and insert (right) [8]

The Sandvik tool had operating parameters that were on paper superior to the incumbent. While the DOC of the cutter would remain the same at 40 thousandths, the tool could handle a greater surface speed enabling a higher feed rate. A feed rate of 360 in/min was an improvement over the incumbent's 330 in/min. This resulted in an improved theoretical MRR of 10.89 in^3/min over the incumbent's 9.93 in3/min.

The tool was tested on an 8.5-inch diameter product with a cycle time recorded. The operation resulted in an operational MRR of 2.82 in^3/min, an improvement over the incumbent's 2.69 in^3/min. The Sandvik tool's insert had only 2 cutting edges compared to the incumbent's 4 and at a price of $9.10 per insert, the price per edge was greater than the incumbent's price per edge. Overall, the time savings proved to have a greater effect than the increased tooling cost which resulted in an overall reduced operation cost of $128.65 compared to the incumbent's $130.67.

6.3.2 Tool 2: Ingersoll 1TG1V-10013X7R01

Figure 10: Image of Ingersoll 1TG1V-10013X7R01 tool assembly (left) and insert (right) [9]

The Ingersoll 1TG1V-10013X7R01 tool head was the first of two of Ingersoll's proposed tooling. This particular tool's operating parameters on paper weren't superior to the incumbent's. The tool's primary advantage was the addition of a 4th insert enabling greater feed rates for a given chip load. Although this tool was able to operate at an impressive feed rate of 430 in/min (compared to the incumbent's 330) the tool was limited to operating at a 30 thousandths DOC. These effects combined to result in a reduced theoretical MRR compared to the incumbent: 9.675 in^3/min to 9.93 in^3/min. The Ingersoll sales engineers recognized this shortcoming but wanted to run the tooling anyway.

As the theoretical MRR would have predicted, the part was not able to improve upon the performance of the incumbent tool. With an operational MRR of 2.29 in^3/min, the part took longer to complete the operation than the incumbent. Additionally, the tooling consumes an additional cutting edge per operation. With the cost of an insert at $9.10 per, the cost of running this tool to rough the 8.5-inch product came to be $155.24, substantially greater than the incumbent's $130.67.

6.3.3 Tool 3: Ingersoll 1TG1G-10019SLR03

The Ingersoll 1TG1G-10019SLR03 is the second of Ingersoll's proposed toolings. After recognizing that their previous tooling was inadequate on paper, this new tool was suggested. Unlike Tool 2, this tool head accommodates 3 cutting inserts. What sets it apart, is the increased DOC of 50 thousandths and increased surface speed enabling a slightly greater feed rate of 337 in/min. This results in a theoretical MMR of 12.63 in^3/min, improved over the incumbent's 9.93 in^3/min.

With a promising theoretical improvement, the tool was tested on an 8.5-inch diameter product, and an operational MRR of 3.46 in^3/min was realized. With respect to tooling, the inserts have 4 cutting edges each and cost $16.61 per insert, slightly more than the incumbent's. When evaluating the overall cost of the operation, the time savings overcame increased tooling costs with a final operation cost of $107.46, a significant improvement over the incumbent's $130.67.

6.3.4 Tool 4: Iscar H400 ERD1.00-3-2.5W100-10

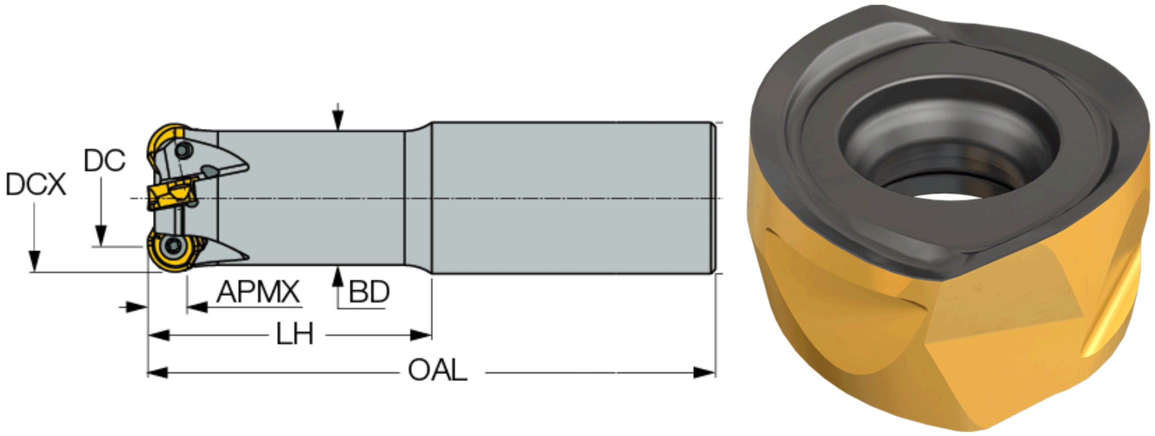


Figure 11: Drawing of Iscar H400 ERD1.00-3-2.5W100-10 tool and Button cutter insert graphic [10]

The Iscar H400 ERD1.00-3-2.5W100-10 is a feed mill head with 3 button cutters. The button cutters are theoretically capable of operating at a much greater DOC, up to 295 thousandths. Despite this, the feed per tooth must be greatly reduced to around 8 thousandths. A test run at 100 thousandths DOC revealed that the cutter couldn't perform at such a DOC. At an operating feed rate of 50 in/min and DOC of 100 thousandths the theoretical MRR was 3.75 in^3/min. With such poor theoretical performance, a test run on a production part was not pursued.

6.3.5 Summary

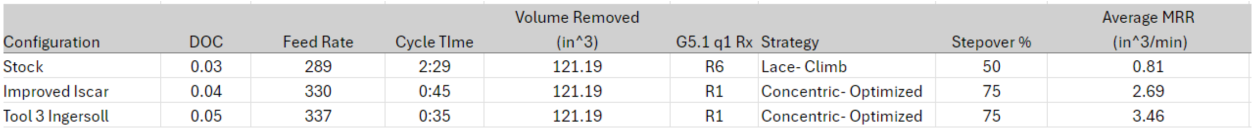
Of the four, 1-inch tools evaluated, Tool 3, Ingersoll's 1TG1G-10019SLR03 tool head performed the best and resulted in the greatest cost savings. Despite its increased cost per insert, it was able to reduce the overall cost per roughing operation by 17.8% over the incumbent Iscar tooling. If the tool is able to perform similarly across all CNC machines at Company X, then it will likely become the new standard tooling.

Chapter 7: Results and Recommendations

7.1 MRR Improvements

Numerous parameters including feeds and speeds, DOC, AICC/AIAPC settings, tool pathing strategies, stepover percentages, and alternative tooling were all evaluated to maximize the operational MRR of the roughing process and likewise reduce cycle times. The production schedule featured many identical 8.5-inch diameter products which enabled a thorough evaluation of the effects these varied parameters had on MRR and cycle times. While a more organized DOE should have been performed to better quantify the effects of each treatment and evaluate combination effects, the chosen operating parameters offer greatly improved performance, even if not truly optimized.

7.1.1 1-Inch Feed Mill Results



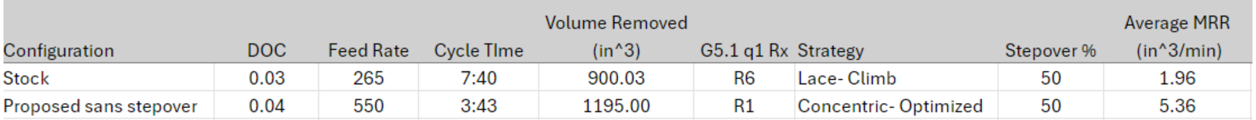
Configuration	DOC	Feed Rate	Cycle TIme	Volume Removed (in^3)	G5.1 q1 Rx	Strategy	Stepover %	Average MRR (in^3/min)
Stock	0.03	289	2:29	121.19	R6	Lace- Climb	50	0.81
Improved Iscar	0.04	330	0:45	121.19	R1	Concentric- Optimized	75	2.69
Tool 3 Ingersoll	0.05	337	0:35	121.19	R1	Concentric- Optimized	75	3.46

Table 13: Operating parameters for 1-inch feed mill, original and the proposed alternatives

For the 1-inch feed mill, roughing an 8.5-inch diameter product, changing from the stock parameters to the improved Iscar parameters detailed in Table 13 increased operating MRR from .081 in^3/min to 2.69 in^3/min, resulting in a cycle time savings of 104 minutes or a 69.8% cycle time reduction. If willing to transition from the existing Iscar tool to a different Ingersoll tool, additional improvements could be realized, achieving an MRR of 3.46 in^3/min, further reducing cycle times by 10 minutes.

A 69.8% cycle time reduction was realized in the 1-inch feed mill roughing cycle by improving operating parameters on the existing Iscar tooling. By additionally changing to Ingersoll's tooling, a cycle time reduction of 76.5% is achievable.

7.1.2 1.5-Inch Feed Mill Results

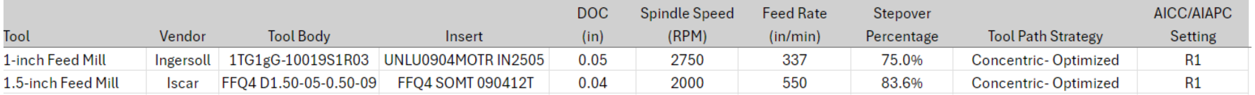


Configuration	DOC	Feed Rate	Cycle TIme	Volume Removed (in^3)	G5.1 q1 Rx	Strategy	Stepover %	Average MRR (in^3/min)
Stock	0.03	265	7:40	900.03	R6	Lace- Climb	50	1.96
Proposed sans stepover	0.04	550	3:43	1195.00	R1	Concentric- Optimized	50	5.36

Table 14: Operating parameters for 1.5-inch feed mill compared with original

The 1.5-inch feed mill had fewer products to test various configurations and as a result, evaluating the effect of increasing stepover percentage to the theoretical 83.6% was not tested. There were fewer opportunities for A-B testing using this feed mill, with most operating parameters determined from lessons learned from the more involved 1-inch feed mill testing. Despite this, by changing to the operating parameters detailed in Table 14, the operational MRR was able to be increased to 5.36 in^3/min from the original 1.96 in^3/min, an increase of 173.5%. A greater improvement is predicted if the stepover percentage were increased to 75% or the maximum of 83.6%.

7.2 Formal Recommended Operating Parameters



Tool	Vendor	Tool Body	Insert	DOC (in)	Spindle Speed (RPM)	Feed Rate (in/min)	Stepover Percentage	Tool Path Strategy	AICC/AIAPC Setting
1-inch Feed Mill	Ingersoll	1TG1gG-10019S1R03	UNLU0904MOTR IN2505	0.05	2750	337	75.0%	Concentric- Optimized	R1
1.5-inch Feed Mill	Iscar	FFQ4 D1.50-05-0.50-09	FFQ4 SOMT 090412T	0.04	2000	550	83.6%	Concentric- Optimized	R1

Table 15: Formal recommended tooling and operating settings

Global parameters

All of Company X's roughing operations performed on the machines controlled by FANUC controllers should set the AICC/AIAPC to a value of R1 to prioritize the feed rate. The tool path strategy should be set to Concentric-Optimized for all feed mill roughing operations which offers much improved tool pathing efficiencies over Lace-climb.

1-Inch Feed Mill

The formal operating parameters to run the new Ingersoll tool at 337 inches per minute at a 50 thousandths depth of cut. The spindle speed should be set to 2750 RPM as this provides an adequate chip load while not initiating any sparking or machine chatter. A 75% stepover should be used when roughing with this tool as it maximizes the MRR without leaving behind any scallops.

1.5-Inch Feed Mill

The formal operating parameters to run on the existing 1.5-inch feed mill is to run the tool at a feed rate of 550 inches per minute at a 40 thousandths depth of cut. The spindle speed should be set to 2000 RPM. A maximum of 83.7% stepover is to be used to maximize MRR without the effects of scalloping.

Chapter 8: Impact and Future Work

8.1 Impact on CNC milling operations

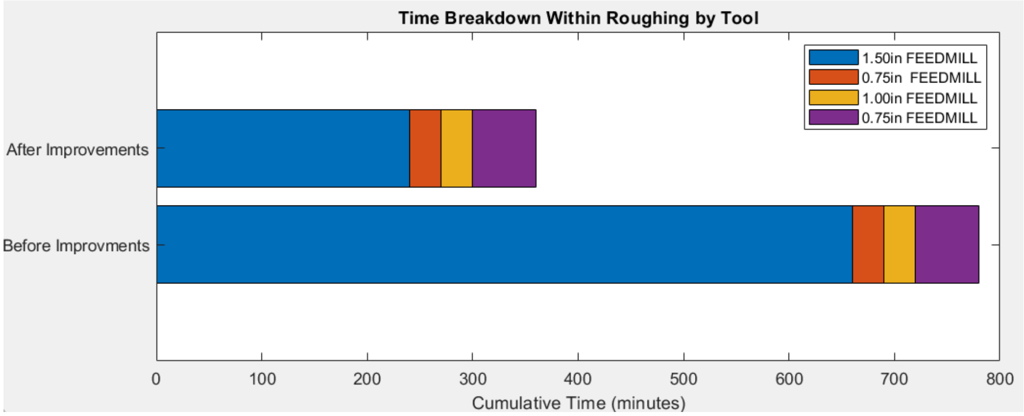


Figure 12: Breakdown of roughing operation cycle times before and after improvements

To contextualize the impact of the MRR increases and the corresponding cycle time reductions, cycle time comparisons with the original 17.5-inch diameter product time study were performed. As a result of the improved operating parameters, the MRR of the 1.5-inch feed mill increased by 173.5%, resulting in a cycle time reduction of 420 minutes or 63%: from an initial 660 minutes to 240 minutes. The total roughing operation cycle time was reduced by 54% from an initial 782 minutes to 360 minutes as visualized in Figure 12.

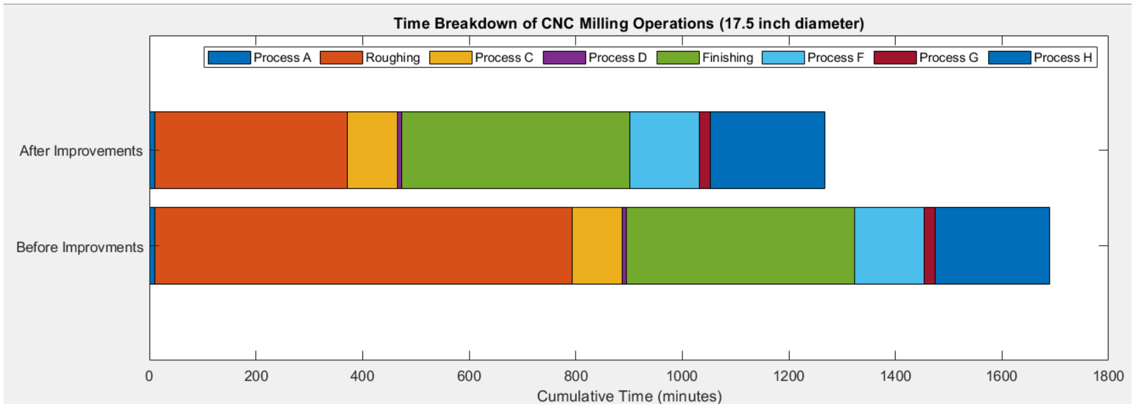


Figure 13: Breakdown of CNC machining operation cycle times before and after improvements

Putting the improvements made to the roughing operation into context with the entirety of the machining process realizes an overall reduction of machining time of 25%. This reduction in cycle time corresponds to an increased throughput of 33% through the CNC work cell.

8.2 Future Work

8.2.1 1.5-Inch Feed Mill

The 1.5-inch feed mill wasn't fully tested at maximum operating parameters as increasing stepover percentage was not tested. The MRR values used in the impact section were the MRR values operating at a 50% stepover rather than the maximum 83.7% stepover. Theoretically, an additional 67% increase in MRR could be realized if this parameter were changed. This parameter change would be a good place to start when further pushing MRR values to their maximum for the 1.5-inch feed mill.

Tooling from other vendors was not evaluated for the 1.5-inch feed mill. Further improvements to DOC and feeds could be realized if alternative tooling can outperform the incumbent.

8.2.1 2-Inch Feed Mill

The 2-inch feed mill wasn't evaluated at all and is the largest feed mill used at Company X. Providing this 2-inch feed mill the same treatment provided to the 1-inch feed mill would likely provide MRR improvements greater than what was realized for the 1-inch or 1.5-inch feed mills.

Improvements to both feeds and speeds and DOC could be performed to increase MRR in addition to the CNC programming changes like increasing stepover percentage and switching to the concentric-optimized toolpathing algorithm.

Tooling from other vendors could also be evaluated to determine if new tooling would offer increased performance over the current feed mill.

8.2.3 Ball-nose end mill + Finishing

The ball-nose end mill is the next category of tool that experiences significant usage in Company X's CNC machining operations. Present in both roughing and finishing operations improvements to the standardized operating parameters of this tool could dramatically reduce cycle times further.

8.2.4 Reducing non-productive times

One area of Company X's CNC machining operations that wasn't within this thesis's scope was the prevalence of non-productive machining time. The cycle time of the 17.5-inch product only represented spindle-on time. In reality, the product took around 50 hours to produce if non-productive time was included. This corresponds to an average spindle-on time of around 50%. Reducing non-productive time would also go a long way toward improving the capacity of Company X's CNC machining operations.

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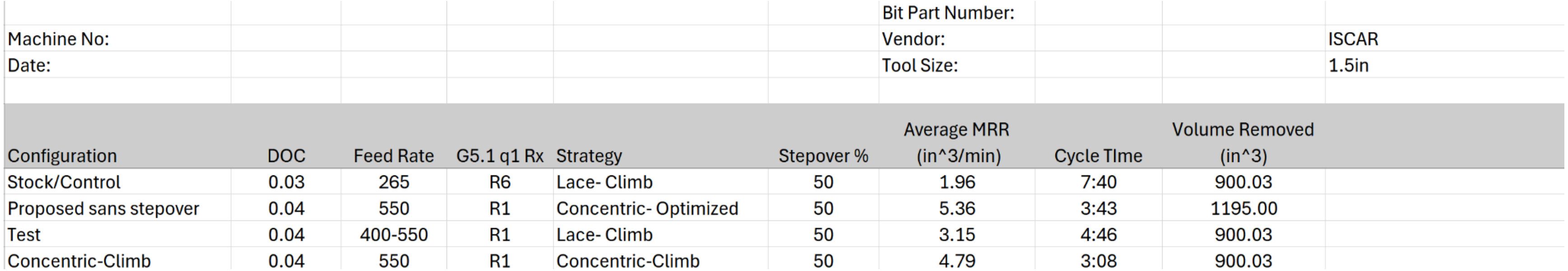
Appendix 1: Full Time Study Results

The following spreadsheets include a summary of the numerous time studies performed and run-by-run parameters.

1-Inch Feed Mill

Machine No:							Doosan VC 630/5AX		
Date:								Tool Size:	1in
Configuration	DOC	Feed Rate	Volume Removed (in^3)	G5.1 q1 Rx	Strategy	Stepover %	Cycle TIme	Average MRR (in^3/min)	
Control/Stock	0.03	289	121.19	R6	Lace- Climb	50	2:29	0.81	
Config 3	0.04	330	121.19	R6	Lace- Climb	50	1:56	1.04	
Config 2	0.04	370	121.19	R6	Lace- Climb	50	1:54	1.06	
Config 1	0.04	413	121.19	R6	Lace- Climb	50	1:52	1.08	
Config 3	0.04	330	121.19	R1	Lace- Climb	50	1:29	1.36	
Config 1	0.04	413	121.19	R1	Lace- Climb	50	1:24	1.44	
Config 1	0.04	413	121.19	R1	Lace- Climb	50	1:25	1.43	
Config 3	0.04	330	121.19	R1	Lace- Optimized	50	1:07	1.81	
Config 3	0.04	330	121.19	R1	Concentric- Optimized	50	0:48	2.52	
Config 3	0.04	330	121.19	R1	Concentric- Optimized	75	0:45	2.69	
New Ingersoll 1	0.03	430	121.19	R1	Concentric- Optimized	75	0:53	2.29	
New Ingersoll 2	0.05	337	121.19	R1	Concentric- Optimized	75	0:35	3.46	
New Sandvik	0.03	330	121.19	R1	Concentric- Optimized	75	0:54	2.24	accidentally ran old code
New Sandvik	0.04	363	121.19	R1	Concentric- Optimized	75	0:43	2.82	
New Iscar	bad								

1.5-Inch Feed Mill



						Bit Part Number:			
Machine No:						Vendor:			ISCAR
Date:						Tool Size:			1.5in

Configuration	DOC	Feed Rate	G5.1 q1 Rx	Strategy	Stepover %	Average MRR (in^3/min)	Cycle TIme	Volume Removed (in^3)	
Stock/Control	0.03	265	R6	Lace- Climb	50	1.96	7:40	900.03	
Proposed sans stepover	0.04	550	R1	Concentric- Optimized	50	5.36	3:43	1195.00	
Test	0.04	400-550	R1	Lace- Climb	50	3.15	4:46	900.03	
Concentric-Climb	0.04	550	R1	Concentric-Climb	50	4.79	3:08	900.03	

Appendix 2: Economic Model Matlab Script

```
clear;
clc;
%Job Parameters
V=121.19;               %Volume to machine. Units: in^3
%Shop Parameters
ShopCost= 150;      %Cost of Shop Time. Units : dollars/hour
ToolReplaceTime= 3; %Time needed to replace a Tool. Units: min
%Tool Changes
numToolChanges=1; %Number of tool changes performed
%Tool Parameters
InsertNumber=3;     %Number of inserts in a tool. Unitless
InsertFaces=4;      %Number of cutting faces in insert. Unitless
CostOfInsert=20;    %Cost of a tooling Insert. Units: dollar
%Theoretical MRR
DepthOfCut=.04;     %Cut depth Units: in
ToolDiameter=1;     %Diameter of cutter Units: in
StepoverPercentage=.75; %percentage stepover Units: unitless
FeedRate= 400;      %Feed rate of tool Units: in
tMRR=  FeedRate*ToolDiameter*DepthOfCut;         %MRR at target speeds+feeds Units: in^3/min
%Operational MRR (if acquired)
oMRR=2.6931; %Operational MRR Units: in^3/min
%Choose which MRR you want to use (comment out one or the other)
MRR= oMRR;
%MRR= tMRR;
%Intermediate Variables
MachiningTime=V/MRR;                        %Units time(min)
ToolChangeTime= numToolChanges*ToolReplaceTime;  %Expected time spent changing tools Units: time(min)
ToolingCost= (CostOfInsert*numToolChanges*InsertNumber)/ InsertFaces; %Cost of worn insert faces
%Total Cost Equation
TotalCost= ShopCost*((MachiningTime + ToolChangeTime)/60) + ToolingCost
```