

THE DECISION PROCESS OF TRANSITIONING FROM A 3-AXIS TO A 4-AXIS OR 5-AXIS MILL  
MACHINE

A Senior Project submitted  
In Partial Fulfillment  
Of the Requirements for the Degree of  
Bachelor of Science in Manufacturing Engineering

the Faculty of California Polytechnic State University,  
San Luis Obispo

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May 2013

Graded by: \_\_\_\_\_ Date of Submission \_\_\_\_\_

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## Abstract

Companies are always looking for new ways to increase productivity and help the company save money. The way this is done is by researching new and more efficient ways to produce whatever it is the company is selling. Since there are always new technologies coming forward it can be difficult to distinguish which ones are viable and which ones are not. This paper looks at the decision of moving a company from a traditional 3-axis milling set-up to a 4-axis or 5-axis milling set-up. Through research and analysis this report will guide a company through the decision making process and help decide whether a move to 4-axis or 5-axis machinery is the correct move for them. In the end, every company is different and a switch to a 4-axis or 5-axis machine may not be for every company but it can be the right decision for some.

## Acknowledgements

Dr. Dan Waldorf

Eric Melsheimer of Melfred Borzall

Haas Automation Inc.

Dr. Jose Macedo

Ladd Caine

Martin Koch

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## Introduction

The topic of this report is the decision process of transitioning, for a company, from a 3-axis mill machine to a 4-axis or 5-axis mill machine.

## Background

The motivation behind this project came from an attempt to acquire a mill with 5-axis capabilities for the advance material removal lab in building 41 on the Cal Poly San Luis Obispo campus. How much would it cost? Is it necessary to have a 4-axis or 5-axis machine? These questions eventually gave birth to this project. Instead of applying these questions to the school itself, this project will look at manufacturing companies and whether it would benefit the company to move from a more standard operation (3-axis machines) to 4-axis or 5-axis machinery.

Machines with 4-axis or 5-axis create more complex geometries faster as well as cheaper. These machines provide vast improvements in efficiency by reducing set-up times, cycle times, tool wear, and increasing capability. When it comes to 3-axis machining there can be many separate operations involved with just as many set-ups, especially with complex parts. Conversely, with 4-axis and 5-axis these operations and set-ups can be significantly reduced which saves time and money. When it comes to 5-axis CNC machining the part that generally comes to mind is a turbine or impeller. The reason being that machining a turbine requires the simultaneous movement of all 5 axes to create the desired geometry. There are specific parts that require 5-axis technology but that do not limit the use of a 5-axis mill for 3-axis parts. For example, in the aerospace industry there are contours that can be machined by a 3-axis

machine but the process becomes much simpler with a 5-axis machine, ultimately saving the company money.

## **Purpose**

The project aims to answer the question: What is the decision process for a company to transition from a 3-axis mill to a 4-axis or 5-axis mill? Every company is different and there may be different answers for different companies but this will give a set of guidelines that can help almost any company through the decision making process. The purpose of this project is to analyze the 4-axis and 5-axis technology and assess if a company should move from a traditional 3-axis milling machine to a 4-axis or 5-axis milling machine. This will take into account the product being developed, justification of upgrading, time, initial investments, and additional investments in order to successfully analyze the situation.

## **Future Potential**

This project is very promising for the future because it will create a set of guidelines that can be used by companies to help them address their manufacturing needs. With technology constantly improving, it is critical for companies to continually improve their manufacturing processes and this report will help determine the need for a change or not. This project is not justifying moving every company to 4-axis or 5-axis, it is providing a guideline for companies to use in order to help in making the right decision for the particular company at the given time. The project will reveal knowledge of many aspects such as costs, time, justification, and pitfalls associated with deciding to transition from 3-axis milling to 4-axis or 5-axis milling.

## Problem Statement

When should a company consider upgrading from a 3-axis mill to a 4-axis mill or even to a 5-axis mill? Why move to a 5-axis milling machine? What issues or aspects should be considered in order to make the decision?

## Expected Deliverables

A guideline approach for deciding on transitioning from a 3-axis mill to a 4-axis or 5-axis mill.

## Technical Approach

The first thing to do is ask why 4-axis or 5-axis mills are needed. What aspects justify such machines and what common causes could potentially lead to purchasing a new mill when the need was not there.

Cost is a very important part of this project. First data must be collected on anything that will be needed to successfully move from 3-axis to 4-axis or 5-axis. Real cost information will be utilized whenever possible to provide a more accurate model of the associated costs. This includes any hardware, software, or operator training. Then all of these costs will be compiled into a spreadsheet for economic analysis. This analysis will include a breakeven analysis to show when the investment would pay off if the company were to change over.

When machining, part geometry is a big factor in deciding how the part will be produced. A complex part requires more sophisticated fixtures and set-ups. This will look at what parts actually require a 4-axis or 5-axis machine. Complex parts can be produced on a 3-axis machine but require multiple set-ups and fixtures. This analysis will yield an early indicator for the company because the company can look at the part itself and if it is very simple and

does not require a large amount of 3-axis set-up and fixturing then moving to 4-axis or 5-axis may not be the right decision. Conversely, a company with a high complexity part may want to look deeper into the possibility of a 4-axis or 5-axis process to develop their part. When using a 4-axis or 5-axis mill versus a 3-axis mill, parts with complexity tend to have fewer set-ups and lower cycle times.

### **Manufacturing Engineering Orientation**

This project will require skills learned throughout the Cal Poly Manufacturing Engineering curriculum. Utilizing courses such as IME 144, introduction to material removal, IME 241, process design I, IME314, engineering economics, IME 335, introduction to CNC machining, IME 341, tool & fixture design, IME 352, process design II, IME 417, supply chain management, and experiences gained through machining and process planning projects to accomplish this project.

Skills from courses mentioned above are listed below:

- Drafting
- CNC machining
- Supply chain
- Continuous improvement
- Computer-aided design (CAD)/Computer-aided manufacturing (CAM)
- Fixture design
- Process design
- Economic analysis

The project is aiming to come up with guidelines to assist companies in making the correct choice about capital investment in new equipment. Using analysis of general manufacturing processes, manufacturing systems, process design, continuous improvement, market economics, and process improvement will help create the guidelines.

## Literature Review

Multi-axis machining is becoming a bigger part of industry because of the benefits offered by multiple axis machines. The growing need for this technology is the constant pursuit of process improvement as well as the complexity of parts increasing and thus pushing the limits of technology. In order for companies using machining as a large part of their production to stay competitive cycle times, lead times, and cost are reduced anyway possible.

### 3-Axis

To fully understand the necessity for 4-axis or 5-axis machining requires knowledge of 3-axis milling. The 3-axis machine is the most commonly used CNC milling machine. The 3-axis system consists of 3 vectors in space. Two of the vectors are perpendicular to each other and in the same plane. These two vectors are commonly named X and Y. The third vector is normal to the plane established by two perpendicular vectors. The normal vector is commonly named Z. The X, Y, Z system is shown in **Figure 1**. The table in a CNC vertical mill moves along the X and Y directions while the spindle moves up and down in the Z direction. The X, Y, Z axes

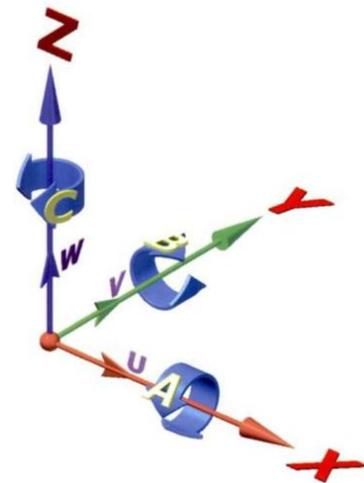


Figure 1: Axes Representation from *Secrets of 5 Axis Machining, Page 15 (Apro)*

approach works for a wide variety of parts. Geometries that are more complex require re-fixturing, increasing set-up time and adding time that the machine is idle.

## 4-Axis

The next level of capability is 4-axis milling. Defined by rotation about one of the 3 primary axes. Depending on which axis the rotation is about, the 4<sup>th</sup> axis is called A, if about the X-axis, or B, if about the Y-axis, or C, if about the Z-axis. The A, B, C axes are also shown in

**Figure 1.** In order for a machine to be considered 4-axis, the machine must be capable of motion in each axis simultaneously. A simulation of what a 4-axis machine using A-axis is shown in **Figure 2.** The 4<sup>th</sup> axis may be used while cutting or to rotate the part to machine a different surface, also known as indexing. Many machines can mount a separate piece of equipment to add a 4<sup>th</sup> axis or

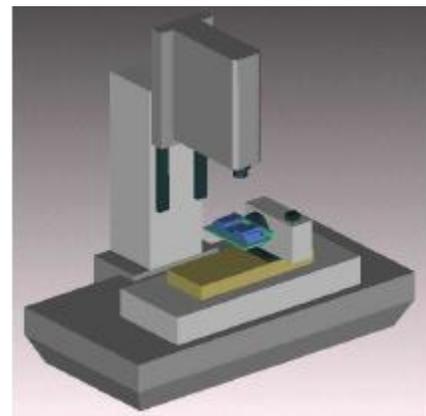


Figure 2: 4-axis Set-up (Qian)

machines can be purchased with 4-axis built into the machine. The addition of the 4<sup>th</sup> axis helps with machining more complex part geometries as well as reducing the number of set-ups for parts that run on a 3-axis machine but require more than one set-up to complete. Set-up time is a non-value added aspect of the manufacturing process, therefore minimizing time spent on set-up reduces non-value added time as well as overall cycle time of a product.

## 5-Axis

To further increase capabilities of a CNC mill a 5<sup>th</sup> axis is incorporated. A 5-axis set-up is more complex and there are two main methods of achieving 5<sup>th</sup> axis capability. The first method consists of a 4-axis set-up with using the A-axis or B-axis and the spindle unit tilts. The

second method for achieving a 5-axis set-up consists of what is called a trunnion. A Trunnion looks like a table that is driven by the A-axis, and a rotary attached on the trunnion that is driven by the B-axis shown in **Figure 3**. A trunnion system generally is less expensive than a tilt head system. Even though less expensive, a trunnion system adds some complexity if the part clamped to the rotary is not centered on the A-axis. As seen in **Figure 3** the part is below the A-axis line causing surfaces to move more from their previous location. A 5-axis set-up provides greater control of orientation of the machining envelope. This



Figure 3: Trunnion from *Secrets of 5 Axis Machining*, Page 24 (Apro)

allows for less re-fixturing for all parts and allows machining of very complex geometries such as an impeller in a single set-up. Instead of using a 4<sup>th</sup> axis indexing style of machining where a little bit of machining happened and the part is then indexed, using 5-axis simultaneous the tool does not leave the part until complete (Haftl).

## Types of 5-axis Mill Machines

There are three major groups of 5-axis machines, table/table, head/table, and head/head. Table/table machines provide the 4-axis and 5-axis through a single or double rotary table for 4-axis or 5-axis respectively (Apro). For example if a company had a 3-axis mill and purchased a dual rotary table that mounted to the table in the machine, the type of machine would be a table/table. Table/table machines is the only group that machines can add 4-axis or 5-axis capability in the future, the other two groups require the 4-axis and 5-axis mechanisms be built into the machine. Therefore, table/table machines generally are the

lowest in price of equipment among the groups. Machines in the group of head/table have a rotary table of some kind and a tilting head. Head/head machines utilize rotary/pivoting motions by the spindle head to provide 5-axis machining (Apro).

## Types of 5-Axis Mill Machining

When machining with 5-axis there are two main types of machining that differing by how the 5<sup>th</sup> axis is utilized. The first type is cutting while simultaneous moving the 5 axes. This type is known as true 5<sup>th</sup> axis, or simultaneous 5<sup>th</sup> axis, or contouring machining. Simultaneous 5<sup>th</sup> axis machining refers to when the part is being physically machined with the movements of all the axes (Waurzyniak, Five-Axis Programming). The other type of machining behaves like a 3-axis machine while cutting and the other two axes are used to change position of the part and index. This type of 5-axis machining is commonly referred to as 3+2 machining. The 3+2 makes programming easier because once the part is repositioned then the rest of the programming is 3-axis movement.

## Mill Machine Set-ups for 5-axis

With any kind of CNC machining setting up the machine and part(s) is required. All machines require setting up tools no matter the number of axes. The other critical part of set-ups is establishment of coordinate systems. In a 3-axis machine, the machine has a predetermined and set coordinate system, which will be called the machine zero. A second coordinate is necessary though to locate the part. The coordinate system is defined during the CAD/CAM process but must represent a possible point in the machine. This coordinate system will be called the program zero, sometimes known as the part zero or work offset. In a 4-axis machine, there still is a machine zero but also a machine rotary zero. The machine rotary zero is

the centerline of the rotary located against the rotary face. Like the 3-axis machine, a program zero is required. In a 5-axis machine, the machine has a machine zero like a 3-axis machine and a machine rotary zero. The machine rotary zero is similar to the 4-axis machine but takes both rotary centerlines into consideration. The machine rotary zero is located where the centerline of both rotaries intersects. The above descriptions assume the machine is a table/table with a dual rotary for 5-axis. The coordinate systems concept is applied to the other types of machines but require different physical steps to determine centerlines and zeros that will not be discussed in this paper.

Many benefits come from using a 5-axis machine. The first benefit is the reduction of set-up time for very complex parts. When machining with only 3 axes there will be multiple stops and then doing a set-up for the next operation. By using 5<sup>th</sup> axis machining, most parts can be manufactured in one or two set-ups, eliminating the need for extra fixturing and time (Apro). This reduction of time will also reduce the cost per part that the company has because each part is now taking less time. With a reduced number of re-fixturing the part quality increases. Every time you move a workpiece from a fixture and have to re-fixture, there is a risk of misalignment, either during set-up itself or during operation. Some machines shops found the 5-axis set-up to be so efficient that it was economically smarter to let a part sit waiting to go into the 5-axis machine than set the part up on an idle 3-axis or 4-axis machine (Zelinski). It is easy to build up (stacked) errors between machined surfaces when they are milled in multiple set-ups (Apro). There is also a need for 5-axis in certain industries, such as the aerospace industry, because of the complex parts associated with the products produced. "In aerospace, it's primarily to eliminate the need for form cutters, because there are very few, if any, parts in

aircraft structures that have straight lines on them," said Randy Von Moll (Waurzyniak, 5-Axis Machining). For situations such as the aerospace industry 5<sup>th</sup> axis is required to manufacture parts while in other industries 5<sup>th</sup> axis is growing in use not because parts require the additional capability but is to increase efficiency of the manufacturing process.

### Growth of 5th Axis Machining Use

There is growing use of 5<sup>th</sup> axis machining, and therefore a growing demand for individuals knowing how to operate and optimize 5-axis processing. A great opportunity to start supplying that demand is by creating curriculums in college that cover multi-axis processing. By no means does every machining operation use multi-axis machining but the top shops are more likely than the other shops to perform advanced, albeit challenging, machining operations (Korn). From **Figure 4** seen above, there are a fair amount of shops using this technology. Of the top shops 30% use 5<sup>th</sup> axis for full simultaneous 5-axis machining and 20% use 5<sup>th</sup> axis for 3+2

	TOP SHOPS	OTHER SHOPS
High-speed machining	60%	46.1%
Hard turning	47.5%	37.9%
Hard milling	40%	35%
Lights-out machining	37.5%	25.6%
Five-axis machining (full contouring)	30%	21.5%
Large-part machining	25%	28.7%
Five-axis machining (positioning only)	20%	20.2%
Micromachining	15%	11.7%

Figure 4: Table 1 from *Top Machining Strategies and Equipment* (Korn)

machining. There is most likely overlap with these percentages, meaning some companies use both 5-axis machining and 3+2 machining. Also, there are shops that do not do as much advanced work than top shops but still have the capabilities. From the other shops 21.5% of

these companies do full contour 5-axis machining and 20.2% does 3+2 axis machining. The data is limited since there is no information stating what constitutes a top shop and a total for shops polled or data taken is lacking.

## CAD/CAM Software

Along with using the machine, knowledge of software used for creating part geometry and tool paths is required to go along with 5<sup>th</sup> axis machining. The reason multi axis machining is becoming more plausible is because of the advancements in CAD/CAM systems. In general, saving machining time or set-ups with five-axis machining did not offset the costs associated with learning to program and use them effectively (Price). Now, with the advancements of CAD/CAM systems such as MasterCam the costs seem less daunting.

The multi-axis machining industry has been expanding, and with that there have been advances in the software. There are many software packages available such as GibbsCAM, MasterCam, and Siemens. A primary advantage with solid models is that gaps or overlaps between part surfaces are avoided, providing a watertight model that is easier to machine. Solid models also let a designer create a digital mockup of a part instead of physically creating a real part (McCollough, Gowers and Mazakas). Creating a part at the computer is much more accurate than programming the part into the machine manually. Also, with 5-axis machining some of the movements can be very complicated so having a CAD/CAM system to help with design and manufacturing is a huge benefit. The problem has been that these software packages can be expensive but as the technology develops it is becoming cheaper and easier to use. Solid modeling software is becoming more commonplace for many reasons. PC-based CAD/CAM packages are affordable, easy to use, and run on PCs equipped with the popular

Windows NT or XP operating systems (McCollough, Gowers and Mazakas). With these advances more companies are using 5-axis machining because the software is much more reliable than it has ever been. Using CAM systems has not always been the easiest task even for advanced technical users, and many developers have included extensive usability enhancements (Waurzyniak, *CAD/CAM Software Advances*). Siemens offers extensive updates to its design, manufacturing and engineering analysis components, including usability enhancements and new ways to machine parts with new volume-based 2.5-axis milling functionality (Waurzyniak, *CAD/CAM Software Advances*). This shows that companies are continually making efforts to improve their software to make it more user-friendly and practical.

## Steps for Deciding

1. When to consider upgrading to 4-axis or 5-axis
2. Determining work opportunities
3. Does the work really require more than 3-axis
4. Looking into alternatives
5. Type of multi-axis machine to buy
6. How much initial investment is required
7. Other implications (triple bottom line)
8. CAD/CAM software

The report assumes a company is considering 4-axis or 5-axis mill machining and provides guidelines for a company to follow through the decision process.

## When to Consider Transitioning to 4-axis or 5-axis

Sometimes the case is obvious in the sense that work currently running takes more time than necessary due to multiple set-ups to achieve the desired geometry. For example, a part takes 5 different set-ups for a single part and the job is for 30 parts.

### Geometry

A very direct indicator a company should consider 4-axis or 5-axis milling is complex part geometry. Generally complex surfaces requiring simultaneous motion in more than just 3 axes indicate the need for upgrading. An example of geometry requiring 5-axis milling is an impeller. Each fin or blade uses simultaneous 5-axis milling to create the feature. To create the fins would be difficult and time consuming to do with specialized set-ups.

## Multiple Fixture Set-ups

A product does not need to use simultaneous 5-axis milling to indicate the need or opportunity for improvement of the production through upgrading the equipment. Another indicator that a company could benefit from upgrading a 3-axis mill to 4-axis or 5-axis is the number of set-ups. Any part that requires multiple set-ups or even multiple fixtures adds cycle time to the process. The time adding is time the machine is not cutting and the operator is spending time, sometimes large amounts, setting up to make parts. In general, set-up time is considered non-value added time or waste. By utilizing 4-axis or 5-axis milling, the number of set-ups are greatly reduce, which eliminates waste. With that time saved the operator can move to another machine for set-up and start running another job while the first machine cuts.

## Surface Finish

A reason 4-axis or 5-axis mill machines can be a benefit to the company is the part quality. Any kind of feature that is not constrained in two axes will require a ball end mill to maintain high surface finish and therefore part quality. Even with a ball end mill, smaller depths of cuts are necessary in order to minimize forces on the tool due to the reduced rigidity intrinsic to ball end mills.

Better surface finish is accomplished by providing a more ideal cutting situation for the tool by changing the way the forces are applied to the tool. With 4-axis or 5-axis milling the tool can always be placed such that the tool is normal to the surface being machined as shown in **Figure 5**. The tool being normal to the surface causes the forces

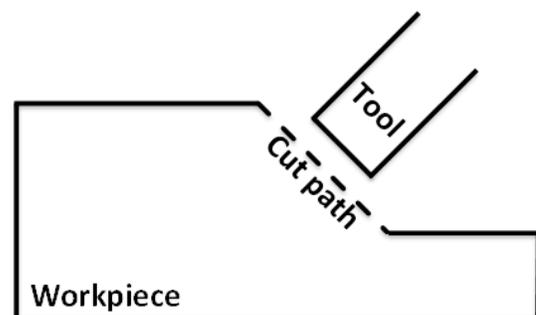


Figure 5: 5-axis Tool Orientation

to be applied axially as opposed to laterally. The cut being normal to the surface also removes the machine interpolation that is done with a 3-axis mill and therefore reduces error in approximations of geometry.

On a 3-axis mill, when milling a non-flat surface the machine creates the surface by moving in steps, as shown in **Figure 6**. These steps can be eliminated by having the cutter perpendicular to the cutting surface. Using a 4-axis machine can easily rotate the part to create that flat surface.

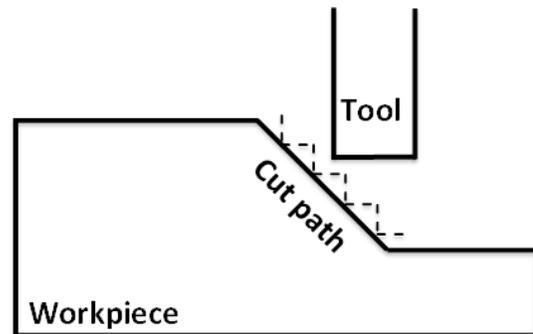


Figure 6: 3-axis Tool Orientation

Surface finish is another consideration when making this decision. If the part being produced needs to have a high quality surface finish (such as molds or mating surfaces) then this would be something to look at. On the other side, if the part does not need a high quality surface finish to help it function then there is no need to consider surface finish in the decision-making.

## Tolerances

Difficulty meeting tolerances on features is also an indicator that the company may benefit from transitioning from 3-axis milling to 4-axis or 5-axis milling. Tolerances are not as clear of an indicator as the previously mention indicators. The reason tolerances is not as clear or obvious of an indicator is the wide range of causes for not meeting tolerances. Some causes are tool deflection, excessive heat in the tool or part, tool breakage, dull tool, improper speeds and feeds, operator error, ambient temperature, and non-rigid set-up or fixturing. The list goes

on and the point being the cause of missing tolerances is easily affected by multiple variables and therefore is not a great indicator. That being said tolerances should not be ignored when considering transitioning from 3-axis to 4-axis or 5-axis but should be a complementary indicator.

## Determining Work Opportunities

The first step to deciding if upgrading a mill machine is to determine opportunities for jobs not currently coming to the company.

### External

Gathering information on such jobs may be difficult since competing companies unlikely will share information on jobs received that other companies could not do. The company would be giving away advantages in the market to their competitors. To better understand the opportunities in the market and the needs of the customer ask major customers or long time customers if there are jobs being sent out to other shops due to a lack of capability. The convenience of a single stop shop for a customer can be quite appealing. The supply chain for the customer also simplifies by reducing the number of suppliers involved in the chain.

### Internal

The above-mentioned opportunities primarily point to external work, do not forget to investigate work opportunities in a more internal sense. Upgrading a milling machine from 3-axis to 4-axis or 3-axis to 5-axis will benefit cycle times on jobs currently running through a shop. For example, the company works on a job for 1000 Widget As currently running on a 3-axis mill. The mill requires 5 set-ups; each set-up takes 10 minutes at the beginning of a job. Each cycle of the program on the mill produces 10 Widget As. For simplicity, the time to

machine each Widget A will remain constant. The shop then upgrades the mill with a 4-axis rotary table. Now the same job has 1 set-up with 4 sides able to fixture 2 Widget As per side. The set-up time for 1 set-up is still 10 minutes. A 40-minute reduction from 50 minutes in non-value added time is significant. In a more realistic situation where machining time would not be the same between the two machines as well as a shorter cycle time with a 4-axis merely by the reduction of cutter travel per set-up the benefits would magnify. The physical cutting motions of both machines are identical but the set-up possibilities and flexibility is much greater with 4-axis. The same point applies to using a 5-axis mill given the same situation. One of the greatest benefits of 4-axis or 5-axis milling is the efficiency gains in running parts that normally can run on a 3-axis mill with much less set-ups necessary.

The key to the step of determining work opportunities is finding out the current potential for more work that 5-axis mill machining enables. Communicate with long-term customers the company has a strong relationship with to determine work that could be coming to the company if the company possessed 4-axis or 5-axis capability. Also investigate work currently going through the company for reduction in set-up times for complex geometries.

## **Does the Work Really Require More than 3-axis?**

Beware of falling into the trap of “needing” more than a 3-axis mill just to have a sophisticated and hi-tech mill machine with 5 axes. This trap will be known, as The Want Becomes Need trap. With mills such as a 5-axis mill being a large initial investment especially compared to a more traditional 3-axis mill, care needs to be taken when making the decision to upgrade. The pitfall can be avoided by looking at the market opportunities without bias, some

in-depth researching, following the guidelines provided in this report, and considering alternatives to upgrading past 3-axis milling.

## Looking Into Alternatives

Just like other decision making processes, investigate alternatives. Some alternatives to consider are listed below:

- Utilizing CAD/CAM software more
- Specialized fixturing for large jobs/regular jobs
- Investing in specialized cutting tools
- Changing the process plan sequences
- Different processes

A list is great but without more detail this list is not very helpful. Let us first look at software.

### Utilizing CAD/CAM Software

CAD/CAM software is constantly advancing and CNC programmers may not be current on the capabilities. Work that appears to need 5-axis milling due to excessive cycle times or tight tolerance or unusual geometry may be possible with new cutting techniques or more advance cutting operations utilizing 3 axes.

### Specialized Fixtures

Perhaps specialized fixturing or clamping eliminates the need for upgrading. The fixturing alternative works primarily when a finite number of custom fixtures are needed with the likelihood of multiple-time use. In general, fixturing can take time and require investment

dependent on complexity of the fixture as well as tolerances allowable in the fixture. Given the potentially high investment of time and money, one-time use fixtures are not economical or very beneficial. Fixtures costs however are magnitudes cheaper than upgrading a 3-axis mill.

### **Specialized Tooling**

Along a similar line, looking into specialized cutting tools may eliminate the need for a 4-axis or 5-axis mill. Many people with some knowledge of CNC machining or mill machining in general are aware of the common cutters, flat end mills, face mills, ball end mills, and tapered end mills. Some cutters not as well known are t-slot mills, woodruff key seat cutters, dovetail cutters, thread mills, and others.

### **Changing the Process Plan Sequences**

Another option to consider as an alternative to upgrading from 3-axis to 4-axis or 5-axis is the order of sequences within the process plan. The main question to ask is will changing the order of steps on how we create the part change the needs for multiple set-ups. A simple example of changing sequences is drilling a hole along the axis of a hexagonal bar and then placing the hex bar into a lathe to turn down a portion of the outer diameter to create a round. Such a situation requires additional support at the end of the bar if the wall thickness created by the hole drilling is structurally able to deform from cutting forces. One solution is to turn the outer diameter first and if the hole must be drilled in the mill that will be the second sequence, if not the part could be made entirely on a lathe. The alternative does not apply if the part geometry is a complex surface such as a turbine blade or impeller.

## Different Processes

Last alternative to consider is the processes being used to create the part. Can the process be changed to eliminate set-ups and cycle time, while still achieving the desired part geometry? Again this alternative primarily comes into play when not dealing with complex surfaces requiring simultaneous 5-axis machining.

## Type of Multi-axis Machine to Buy

Looking at the decision matrix on the right there can be decisions made very early. Now this decision matrix is not something that will be 100% correct 100% of the time. What this matrix will do will give an idea of where to focus the attention first. For example, if the company produces complex parts at a very high volume a dedicated 4 or 5-axis machine would be the first alternative that should be analyzed. This is because with a complex part there are many areas where the cycle time can be reduced, and when these savings are taken over a high production volume then there is a possibility for significant savings. Similar logic can be applied to the other 3 conditions. If the part is complex and a low volume production rate then a flexible multi-axis machine may be a good place to start the research. This is due to the fact the low production volume will make it hard to justify a completely dedicated machine. Instead, if the machine is set-up such that it can still machine other parts quickly and easily, the company can have the benefits of a multi-axis machine without overpaying for it. During the interview with Eric Melsheimer at Melfred Borzall he said that the 5-axis machine does the part that requires 5-axis 80% of the time. The other 20% is spent doing other, simpler, parts. This can help a company start looking in the right direction instead of blindly looking, whether it is upgrading an older 3-axis machine or buying a new machine research must be done.

If a new machine is to be purchased, the new machine will take up space and change the footprint of the facility and can cost in the area of \$100,000 (The cheapest HAAS 5-axis machine costs \$113,000). This brings in the size of the machine. If a product can be done on a smaller machine then it should be done because the larger the machine the much more expensive it becomes. In addition, the larger it becomes the

High Volume	<b>Dedicated 3-axis Machine</b>	<b>Dedicated Multi-axis Machine</b>
Low Volume	<b>Flexible 3-axis Machine</b>	<b>Flexible Multi-axis Machine</b>
	Simple	Complex

Figure 7: Decision Matrix

more it can affect the layout and affect the processes around this machine. For a company like Melfred Borzall a large machine was necessary to fit the large ground drills they were machining. Although there is time saved in the set-ups and cycle time upgrading to a 4-axis or 5-axis machine may not be the best move due to the initial cost.

Assuming there is already a 3-axis machine on the floor making the part, there are additional costs to moving to 4-axis or 5-axis. 4-axis drive and wiring costs \$2000 and if the company wants to move to 5-axis it is an additional \$6,200 (numbers from HAAS website). Also, in order to use the equipment properly there needs to be training for the machine itself and in the new software that programming the machine will require. The cost of the CAM upgrade can be in the thousands depending on the software to be selected. Just using these rough numbers it can be seen that there has to be a payoff somewhere down the road and this decision all depends on where that payback is.

In the end cost is the most important part. If there is not a return on the investment then there was no point in making the investment initially. This aims to eliminate any mistakes by pointing out where to look when it comes to a decision regarding 4-axis or 5-axis machining. Companies like Melfred Borzall upgraded to 5-axis machines because of the increased part quality and time savings. These time savings and quality improvements were enough to justify buying a new 5-axis machine. This may not be true for every company because not every company makes the same products.

## How Much Will this Cost

### Cost

4-axis or 5-axis machining have their benefits when it comes to reducing cycle time and reducing the number of set-ups but the company has to be willing to put forth the initial cost in order to save further down the road. When looking at the costs of moving to a 4-axis or 5-axis machine there are certain things to consider when choosing the correct machine.

A simple example will be used in order to illustrate the process of the cost decisions involved as shown in **Figure 8**. A company makes a wide variety of parts but their main product is an aluminum business card holder. There are 2 pieces. One is the base that actually holds the business cards and the other is a stand, which screws into the holder.

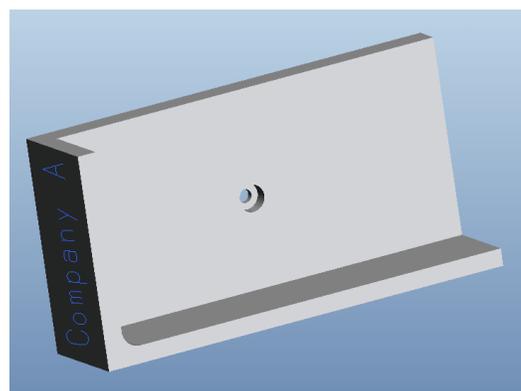


Figure 8: Part Example Front

The base portion will be done on a 3-axis CNC mill.

The base requires 3 set-ups to successfully finish the part. The first set-up will put the business card holder on its side where the company can engrave their name. The second set-up mills out

a pocket will the cards will go and bore a hole in the center where the screw head will sit. The third is on the opposite side where it will drill a pocket for the stand to screw into and engrave the company Logo as shown in **Figure 9**.

Using a 4<sup>th</sup> axis machine to allow for access to all sides in one set-up will be key in reducing the set-ups from 3 to 1. Assuming the one set-up takes slightly longer on a per set-up basis, but would most likely save time overall. For example, if each of the 3 set-ups takes 1 minute and the one set-up takes 1.5 minutes the company is saving 1.5 minutes per part, which can add up fast in a high production volume facility. It may not always be the

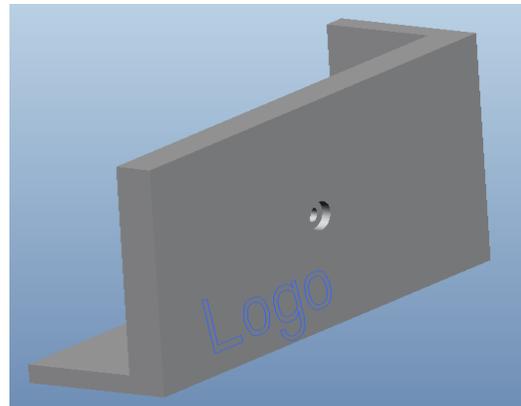


Figure 9: Part Example Back

best idea to convert a current 3-axis up to a 4-axis or 5-axis machine because there may be situations where 3-axis machines are better but for a specific product a 4-axis may save a lot of money in which other considerations must be made. When speaking with Eric Melsheimer at Melfred Borzall, he indicated to that the 5-axis machine they purchased was used for only one product. The rest of the products were created on 3-axis or 4-axis machines.

## Cost Analysis

When it comes to any decision, cost is often the most important part. For this project a spreadsheet was constructed in order to help analyze all the costs involved. Looking at **Figure 10** below the investments for this theoretical situation can be seen. The spreadsheet itself can be adjusted so that the values reflect what the company needs. For this report these numbers

will be used. These numbers are assuming that the company is moving from a 3-axis to a 5-axis set-up. This means that the company already owns the 3-axis and needs the extra add-ons.

## INVESTMENTS CALCULATIONS

Assets	Quantity	Unit Value	Total Value
4th Axis Drive	1	\$ 1,995	\$ 1,995
5th Axis Drive	1	\$ 6,195	\$ 6,195
Table	1	\$ 4,000	\$ 4,000
Training	1	\$ 2,200	\$ 2,200
Cad/Cam	1	\$ 5,000	\$ 5,000

Figure 10: Investment Inputs

The first thing to notice is the high initial cost of the switch and because of this the future benefit must outweigh the initial cost. To quantify this we will look at the payback period of a few scenarios. In order to look at payback period a few assumptions must be made:

- Part A is being sold such that the company makes \$0.50 per part
- Production Volume is 10,000 per year
- Production isn't at 100% until the 3<sup>rd</sup> year
- Every Part made is sold

Now using all of these numbers and assumptions, a breakeven point can be calculated as shown in **Figure 11** below.

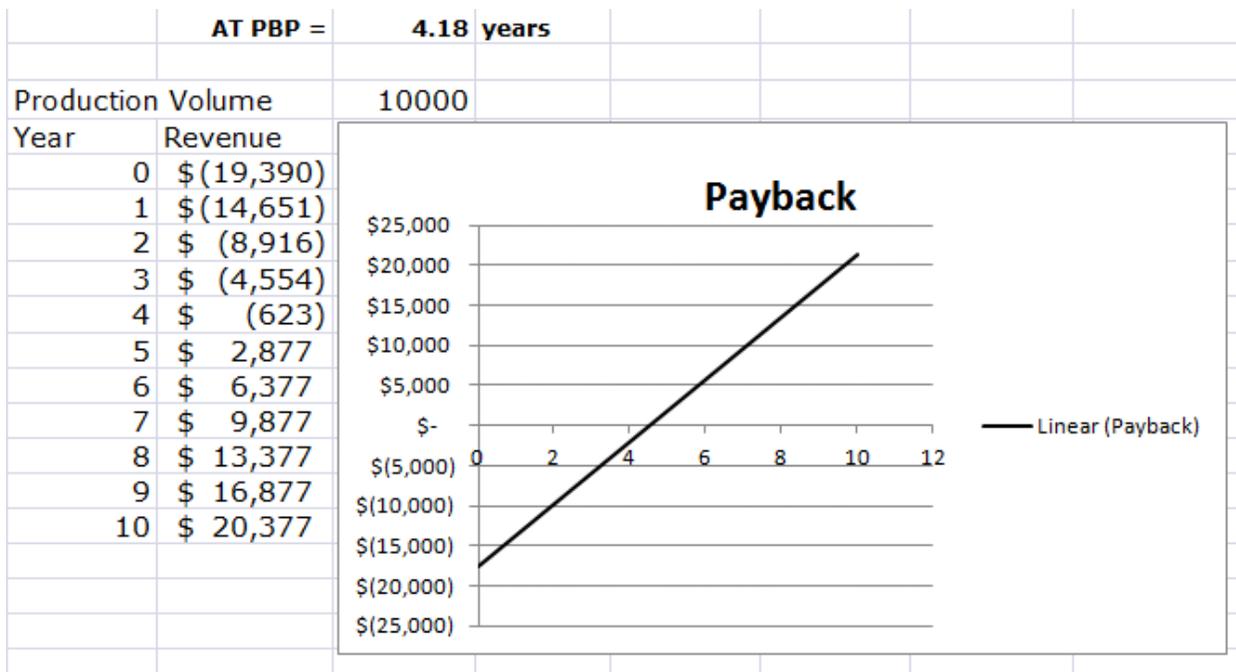


Figure 11: Payback Scenario 1

The payback period for this scenario is 4.18 years. It seems that 4 years is a long time to wait for an investment to pay off but if the company plans on using that machine for many years after that then maybe 4 years is reasonable.

The next scenario will be similar except there will be a few changes to the assumptions.

- Part A is being sold such that the company is making \$3.00 per part
- Production volume is 3,000 per year

Putting the new numbers in the spreadsheet will yield different results. As shown in **Figure 12** below the payback period is 2.45 years. This is a much shorter period than in the first scenario. These 2 scenarios are to reflect how different companies would receive different results. In the first scenario the company had a much higher production volume but a lower profit margin per part. Conversely, in the second scenario the company had a high profit margin with a lower production volume. Just because the payback period in the second scenario was

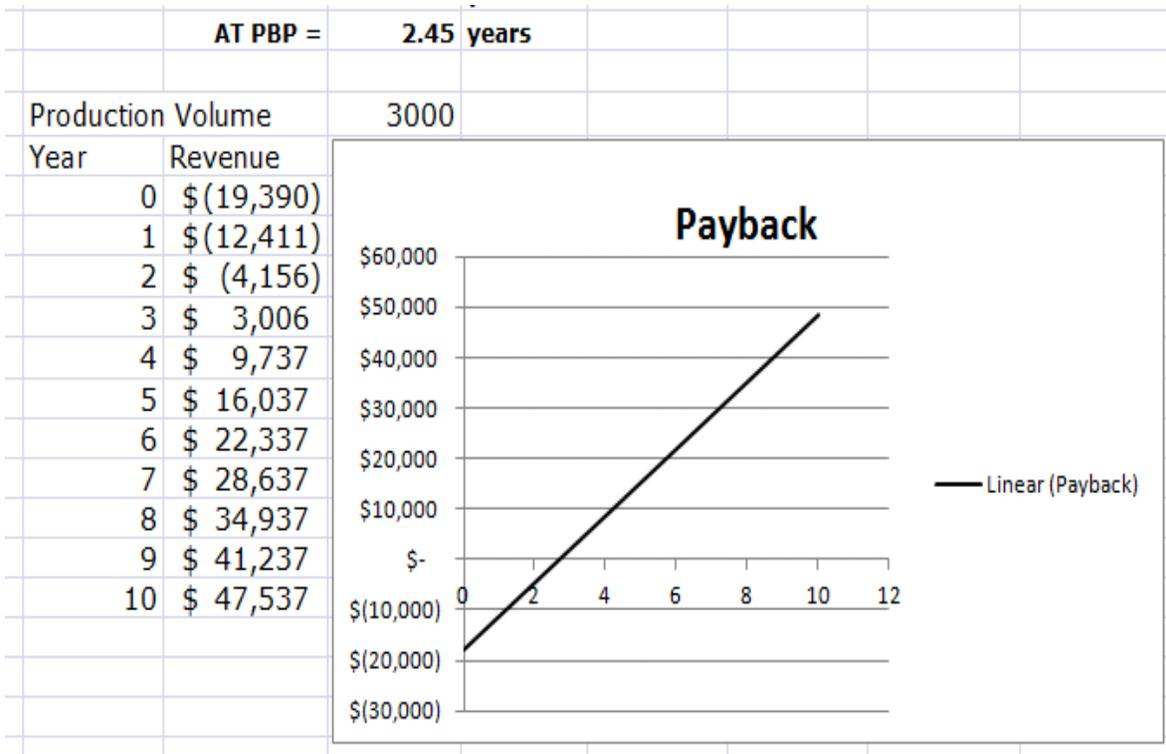


Figure 12: Payback Scenario 2

shorter does not mean that the 5-axis machine is better for the 2<sup>nd</sup> company. Remember that every company is different and every situation should be analyzed independently.

Finally, we are going to look at production volume. Keeping the profit margin constant, it can be seen that a company with a higher production volume will be better off with an investment like this than a similar one with a lesser production volume.

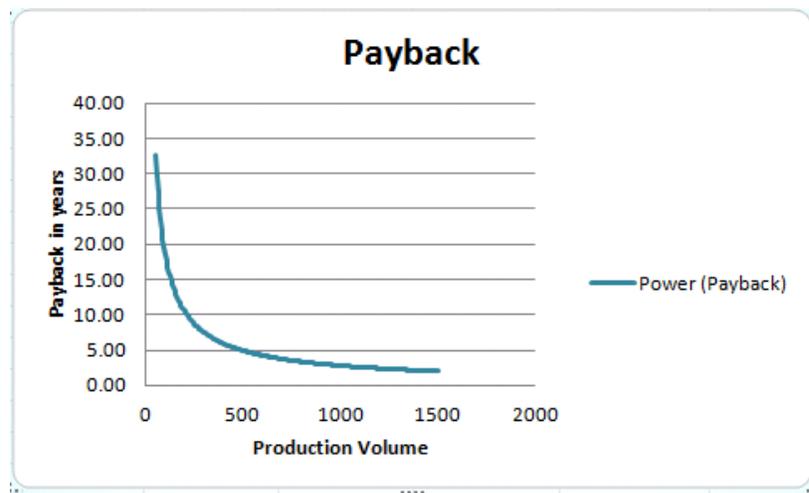


Figure 13: Payback by Production Volume

## Other Implications (Triple Bottom Line)

### People

In order to benefit the employees and the company, training for this new system would be a smart plan. If adding a 4-axis or 5-axis machine to the production line there are going to be a new set of issues that arise. In an effort to keep the

company, machines, and most importantly employees as safe as possible a training program that teaches the operators how to safely and effectively use the machines. Ultimately this will keep the employees and the company as a whole satisfied.

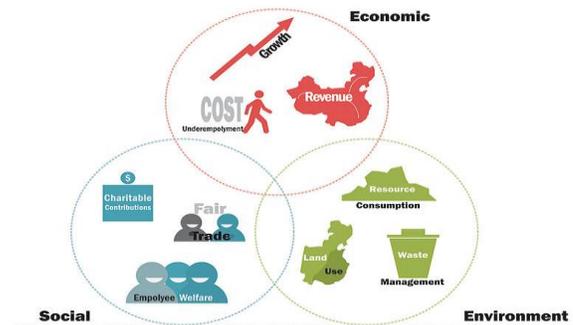


Figure 14: Triple Bottom Line  
[en.wikipedia.org/wiki/File:Triple\\_Bottom\\_Line\\_graphic.jpg](https://en.wikipedia.org/wiki/File:Triple_Bottom_Line_graphic.jpg)

### Planet

Although adding a 4-axis or 5-axis may not directly help the environment it can have its benefits. If the company is saving money and time with the addition of a 4-axis or 5-axis machine then there is extra money to expand the company. In this instance, a percentage of the money saved could be put toward making a more effective use of the scrap metal that is created in the machining operations. This could be reusing the material themselves or just recycling it correctly. In the end there is no effect on the planet when moving from 3-axis to 4-axis or 5-axis machines but if there are savings they can be used accordingly.

## Profit

There is a great possibility of saving money if using 4-axis or 5-axis machines, but it is not for everyone. If the company uses 4-axis or 5-axis machines then there is going to be money savings, which will allow the company to expand itself economically by possibly lowering prices and increasing production volume. On the other hand, if the company looked at moving to 4-axis or 5-axis machines and deemed that it was not a smart move then the company can use the money that would have been used for a new machine to help develop other areas of the company.

In the end, the TBL should be addressed when making any decision within a company. Every area of TBL may not be directly affected with every decision but looking at each section critically when making a decision could help the company move forward.

## CAD/CAM Software

When it comes to CAD/CAM software it depends what the company currently is using and what potential the current software has for growth. When making such a capital investment make sure the company is using software that is currently capable of generating 4-axis or 5-axis tool paths or an add-on can be purchased to enable the capability. The main features to look for in CAM software is usability, provided training, customer service, and flexibility. Flexibility is important for future growth. Perhaps the company only needs 3+2 machining but want to be able to buy the capability for simultaneous 5-axis after the company gets experience with 3+2. The CAM software company should also provide some training programs to get people at the company familiar with the software.

## Conclusion

Throughout this decision making process it should be kept in mind that this is an example that is to help set the framework for a company to make a similar decision. A company that uses 3-axis machines for very simple parts may not even need to address this decision, but there are companies that need the new technology to help satiate the growing need for their product. For these companies it is necessary to look at every option available. 4-axis and 5-axis machines are just one of many alternatives that could possibly help increase productivity. Ultimately, this is a process that will hopefully guide companies to the right decision.

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