Optimization of Tool Wear Versus Tool Change at Affordable Interior Systems

A Major Qualifying Project Submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements for the degree of
Bachelor of Science

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Submitted on:
April 11th, 2024

Abstract

The objective of this paper is to understand the lifespan and wear characteristics of the tooling used at Affordable Interior Systems (AIS), our project focused on the creation and running of an experiment that focused on creating baseline metrics for AIS. We did this due to the need for standardization on the shop floor of AIS, a high-volume custom furniture manufacturer who uses CNC routers to machine hundreds of particle boards per day. To do this we used sensitivity analysis along with DOE methods to run capacity experiments on the current tooling that AIS uses. This along with interviews with shop floor workers allowed us to recommend a baseline lifespan that will allow engineers at AIS to inform their workers better as to when to changeover endmills. The results of our testing ended up being quite similar to what is currently being done, which works nicely as it solidifies that what we determined was a good quantification of what is already being done. In some cases, there was a decrease in changeovers, which was monetarily represented in a financial analysis. This analysis showed that the cost of the equipment required to implement standardized distances across all machines would pay for itself within 1 year. The conclusion is that there is a monetary gain to be had if AIS standardizes their changeover indicators, which will in turn remove the amount of variability that is currently occurring when it comes to when operators changeover the end mills.

Acknowledgements

Our MQP team would like to thank our project advisors, Professor Walter Towner Ph.D. and Christopher Brown Ph.D. for their guidance and unwavering support throughout our project. We would also like to thank AIS Inc. for allowing us to collaborate with their company and execute our project in their facilities. This includes Jason Truscott (WPI ‘94), Fernando Perez (WPI ‘13), Steve Savage (WPI ‘85), Brianna Ankstitus (WPI ‘23), Keith LaBlanc, Larry Scangas, and Adolfo Ortiz. Lastly, we would like to thank James Eakin Ph.D. for training us and coordinating the availability of the WPI LEAP lab.

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Project Objective

The goal of our project is to understand the changeover rate that occurs with the end mills used to cut the worksurfaces. The end mills are used on the CNC routers that manufacture exclusively work surfaces, which are characterized as desk surfaces as well as any large particle board components.

Background

AIS- About the sponsor

Affordable Interior Systems (AIS) is a leading manufacturer of commercial office furniture in North America. The company is known for having a catalog of customizable products available for order at great value. AIS headquarters is located in Leominster, MA, where it boasts a 600,000 square foot warehouse and office space. Its warehouse is split into a worksurfaces space and case goods space. The warehouse itself staffs over 500 of the 800 total employees of AIS.

As of recent, AIS financial performance has been great eclipsing over $200 million dollars in sales as of 2019. They can do all this business while also keeping true to their values of lean manufacturing and sustainability. Because of their dedication to great performance and those initiatives, AIS has won an OFDA award every year since 2010.[1]

CNC Process Closer Look

One of the value adds of AIS is their ability to produce custom dimensioned products with a turnaround time of 2 weeks. All orders are made to order meaning they carry no inventory of finished products. To do this AIS runs 12 CNC routers 3 shifts a day 5 days a week. This is achieved using a German parametric CAD/CAM system that produces one off CNC programs

[1] Deranian

for each unique design. The CNC routers are like handheld routers used at home, but instead of being controlled by a human, the spindle is attached to stepper motors and a computer that is controlled by G-code. This automated process makes the processing of 4x8 sheets of plywood considerably faster than being cut by hand.

Currently, to do the majority of their cutting on work surfaces, AIS is using a 2 flute 1/2in diameter coated carbide compression end mill manufactured by FS-tool. A compression end mill is different from a normal end mill in that it “has an up-cut flute geometry from the tip to usually about 1/3 of the cutter length at which point it converts into a down-cut flute.”[2]. A down cut flute in short is a flute that twists in the opposite direction. This can be seen in figure 1. The utility of this is that it avoids the delamination of the laminate layers while cutting. With a regular twist end mill the cutting forces are trying to pull up the tool or positive Z direction due to the angle of the cutter. This helps with the evacuation of the chips out of the gullet or flute of the end mill. This works well with metals due to the homogenous or layer less composition of the material. When cutting laminate fiberboard on the other hand, the upward facing cutting forces will pull apart the laminate layers. The counter rotating flutes on compression end mills counteract this by adding an opposing force that prevents delamination as well as reducing the upward forces. The reduction of upward forces also means that a vacuum plate can be used to hold the workpiece down on the machine.[3] The boards are held down to the machine using a vacuum plate that uses a negative pressure pump and ports cut into a MDF board.

Figure 1: New 1/2in compression endmill

Finally, when it comes to the CNC machine, to attach the end mills to the spindle of the machine, a tool holder is needed. Currently AIS is using hydraulic tool holders. A cutaway image

[2] (Royer)
[3] (Royer)

is shown in figure 2. A hydraulic tool holder "uses a reservoir of oil to equalize clamping pressure around the tool. When you place the tool in the holder and turn the screw inwards, it increases the oil pressure, causing an expansion of the sleeve to grip the tool shank." [4]. Alternatively, in the case goods department, AIS uses heat shrink tool holders. The methodology for that is that the heat shrink tools offer more stiffness, which results in quieter cutting of the small and intricate designs. Heat shrink tool holders work by heating a machined diameter to increase the diameter allowing for the insertion of the tool. [5] The heating is done by an electric induction heater. Once the endmill is inserted the holder is let to cool allowing for the receiving end to shrink around the endmill. The value of heat shrink tool holders is that they have no moving parts while producing a tight fit around the endmill. The lack of moving parts and increased bracing material around the endmill allow for a reduction in vibrations which is why AIS uses heat shrink holders in their case goods department.

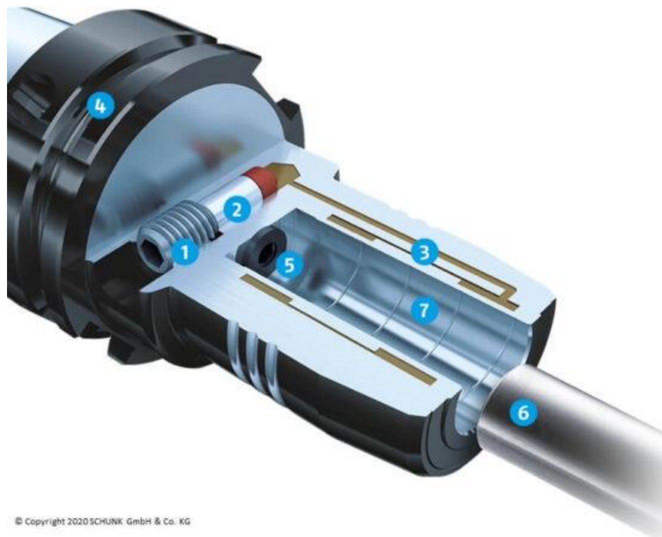

Figure 2: Cutaway of hydraulic tool holder.

Axiomatic Design

One principle taught throughout WPI industrial engineering courses is axiomatic design. Axiomatic design was created by MIT professor Nam Suh in the late 1970s as a tool to decompose processes. Our group decided a vertical axiomatic design structure would be the best way to break down our interview process. The way an axiomatic design structure starts is with a problem statement that defines the customer's needs (CN). The next step is adding the functional

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[4] (Triumph Tool)
[5] (GDP tooling)

requirements (FR), which are needed in the experiment to solve the problem statement. The third part of the structure are the design parameters (DP), and these explain what the process looks like. The last section is the process variables, (PV) and these are different things that could change the process.[6]

Tooling Wear Mechanisms

As the end mills process the fiberboard, the edges that cut the board dull reducing the efficiency and performance of the cutters. This wear materializes as unwanted changes in the geometry of the cutter. This wear occurs for many reasons. Firstly, abrasive wear is when the interaction between the carbide grains and wood particles results in the removal of the carbide grains from the cemented composite. For most cemented carbide mills this is a mixture of carbide and cobalt. Research has also suggested that three other wear mechanisms occur: corrosion, oxidation erosion, and electro-chemical wear.[7] All these mechanisms can be lumped into the removal of carbide grains from the cemented composite. This results in a change to the desired geometry of the tool resulting in a reduction of the performance of the end mill when processing the particle boards.

Resharpened End Mills

In order to extend the usability of the carbide end mills, AIS sends their used end mills to their tooling provider to be resharpened. The goal of resharpening is to reproduce the original geometry to 100% of the starting shape. This is done using a 5-axis CNC grinding machine designed for end mill grinding. When the tools are resharpened, the grinder is programmed to rework the primary and secondary edge, as well as the flute. The compression flutes get the same treatment as the primary flutes. The top face of the endmill is also ground to the original

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[6] Brown
[7] (Gisip)

specifications. This produces a tool that dimensionally is the same except for the outside diameter (OD). An alternative resharpening design is the leftmost image shown in figure 3. This resharpen program only refinished the flute of the endmill, to keep the coating in-tact. This condition was not tested, as it is only feasible for the first resharpen and 50% of samples for the second resharpen according to the tooling supplier. Every resharpen results in a reduction of the outside diameter by roughly .01 in. This is not a specified value rather an average because each resharpen is based upon laser measurements done by the grinding machine. The middle and right most images in figure 3 show a reground tool and a brand-new tool.

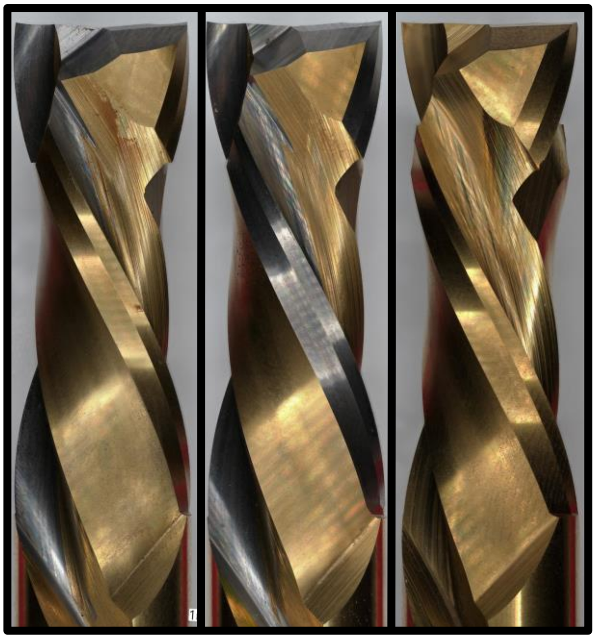

Figure 3: Left: flute grind, center: full geometry grind, right: brand new endmill.

Workpiece Material

One issue specific to AIS that is a key point for our upcoming tests was the laminate layer that most of their boards have. This layer is a colored decorative layer that is bonded onto the particle boards. This relates to tool wear, because the properties and material makeup of this layer is different to that of the particle board that it surrounds. AIS processes 3 different types of boards: high pressure laminate (HPL), thermally fused, and MDF. The MDF boards are not within the scope of this project as they do not make up a majority of orders processed by AIS. Both HPL and TFL have a 3-layer core which is made up of 2 different types of fiberboards. The two outer layers are made up of surface type material with the middle layer being "core" material. "Surface" material is often finer wood chips creating a stronger higher density layer. The inner core, however, is made up of larger, less refined particles. This is to save on costs as well as alternate the properties of each layer, increasing the strength of the completed board.[8] A cutaway image showing these different layers can be seen in figure 4. According to AIS engineers the core is where inconsistencies in material often show up. Inconsistencies are classified as non-homogeneous sections consisting of mostly glue or wood particles.

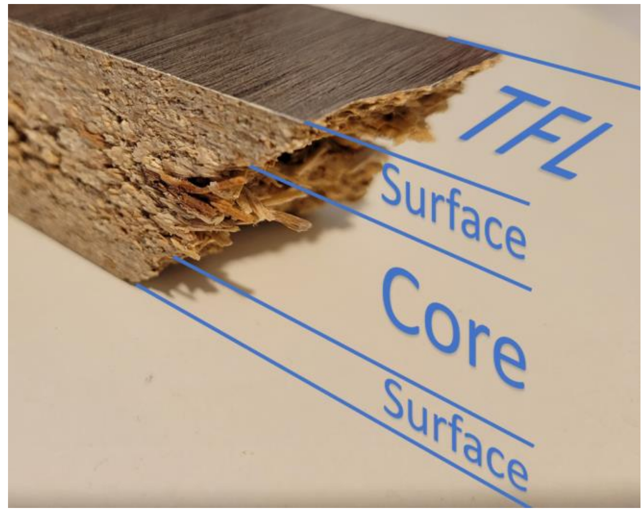

Figure 4: Composition of fiberboard layers.

Voids are also an issue that can occur, leading to poor quality of finished goods, whereas other inconsistencies can also create inconsistent wear on the endmill as well as affect the finished product. On top of consistency issues AIS engineers have also found foreign bodies such as fasteners, rocks, and staples. There are processes in place at fiberboard manufacturers to mitigate these quality issues, but historically AIS has seen a significant number of quality issues with incoming boards. Figure 5 shows magnified images of chunks of what is likely a non-homogeneous mixture of glue and wood.

Figure 5: Sample of non-homogeneous fiberboard material.

The main difference between the HPL and thermally fused is that the HPL is .020" in thickness while the thermally fused is .005" thick. The difference in thickness comes from the materials as well as the manufacturing process. The

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[8] (EPA)

decorative top and bottom layers on the HPL are made from “multiple layers of kraft paper [bonded] with phenolic resin.” with “A layer of printed décor paper is placed on top of the kraft paper before pressing”.[9] Comparing this to the thermally fused decorative layer which is made up of “a resin-impregnated sheet of décor paper directly to a substrate.”. [10] This paper layer is the same decorative layer that is added to the HPL, just without the other kraft paper layers. The value of the extra layers is durability. Those extra layers are high in silicates which make it very durable, at the expense of wearing the tools used to manufacture it. The thermally fused on the other hand, is still scratch and wear resistant enough for most applications. Thermally fused makes up the majority of AIS’ products due to the ease of manufacturing on top of its sufficient durability for most applications.

Sensitivity Analysis

The main objective of the project as stated earlier is to understand the cost of the tool wear and propose an action plan to reduce this cost. In order to do this, we need to understand the effect that certain conditions have on the resulting wear. These conditions include, but are not limited to material type, toolpaths, building environment, etc. The sheer amount of possible conditions to test is time and cost prohibitive, meaning we have to determine which conditions have the largest effect on the result to focus our study. Sensitivity analysis does just that. Sensitivity analysis allows researchers to test the extremes of a condition and compare the results. Condition Monitoring and Control for Intelligent Manufacturing by Lihui Wang and Robert X. Gao states that “Each factor will be studied at only two levels, traditionally called low and high”[11]. A large difference between the results of a pair of conditions compared to the other

[9] (Composite Panel Association)
[10] (Composite Panel Association)
[11] (Paul, Goodwin)

pairs indicates that that pair of conditions influences the results. This conclusion is not a final result, rather an indication that a certain condition is worth the time and resources to further investigate. Our application of sensitivity analysis will focus on deciding which end mill holders to use while also keeping wood type as a factor.

Methods

Employee Interviews

Our first step in understanding the CNC machining process at AIS required us to talk to operators in the warehouse. Looking at the axiomatic design in figure 6 below, the first step to creating the design was stating our CN. This portion of the design we wanted employees to give us their best description of their current tool changeover process with their tools. Next for our FRs, we wanted to look at different types of variables that can cause damage to the tool and if anything could be done to eliminate costs in that aspect. This includes the tool holder, type of material, as well as reground vs. new tools. For the DP section, we tried to get more perspective from the employees on performance and what they typically look for when changing out tools and if they have a standardized practice between them. Lastly, our PV section attempts to go more in depth in conversation with these operators and find potential solutions to their changeover issues.

CN: Quantify the current state of changeovers in order to have a baseline for experiments.

FR0: How much money can we save in the router process through the reduction of tool changeovers.

FR1: Quantify the current state tool life.
- FR1.1: Define training regarding changeovers.
- FR1.2 Quantify current changeover characteristics used by operators.

FR2: Define regound bit performance differences.
FR3: Evaluate cutting characteristics between tool holder types.
FR4: Evaluate cutting characteristics between wood types.
FR5: Quantify why errors and rejects occur.

DP1: Current actual changeover rate
- DP1.1: Employee perspective on changeover training
- DP1.2: List of what employees use as an indicator for worn tooling.

DP2: Employee perspective on reground tool performance
DP3: List of characteristics of each tool holder type as observed by operator.
DP4: List of characteristics for each wood type observed by operator.
DP5: Employee opinion on root cause of errors and rejects

PV1: When you are running this machine, how do you decide when to change the tool over?
- PV1.1: What were you taught to look for on the boards when they are done?
- PV1.2: Are there things that you notice during the lifespan of the tool?

PV2: Are there differences between using a reground tool as compared to a new tool when it comes to tool life and performance?
PV3: What differences in the cutting do you notice between the heat shrink and the hydraulic holders?
PV4: Do you find that there are differences in the cutting performance between the two different wood types?
PV5: What is causing chipping to occur to the finished surfaces and is there a way to lessen it?

Figure 6: List of FRs, DPs, and PVs used in axiomatic breakdown.

	Current actual changeover rate	Perspective on training	Indicators for worn tooling	perspective on reground tools	tool holder characteristics	wood type characteristics	main causes of error
	DP1	DP1.1	DP1.2	DP2	DP3	DP4	DP5
FR0	X						
FR1	X						
FR1.1		X					
FR1.2			X				
FR2				X			
FR3					X		
FR4						X	
FR5							X

Figure 7: Axiomatic design graphic breakdown.

Tool Wear Measurement Methodology

To quantify the wear on the end mills we used a high magnification digital microscope to record images of chipping as well as measure the edge recession in key positions. Edge recession was recorded using a 3d contour feature on the microscope. Edge recession was recorded in 2 positions on the end mill where the cutter was interacting with fiberboard. Visual observations at varying magnifications are done across all edges, and any chipping or inconsistent is recorded for later comparison. The 3d contour test is done at 200x with the end mill oriented at a standardized position. This standardized position was defined using a marking tool that indexed on the flute of the tool allowing for a line to be defined on the end of the shank using a slot and a marker. This can be seen in figure 9. Those markings then matched up with various markings on a stand that would then sit on the table of the microscope as pictured above. The contour feature allows us to draw a line across the edge to get the height map. This height map as seen in figure 8 is then compared against a control tool to calculate the recession of the used end mill. Using

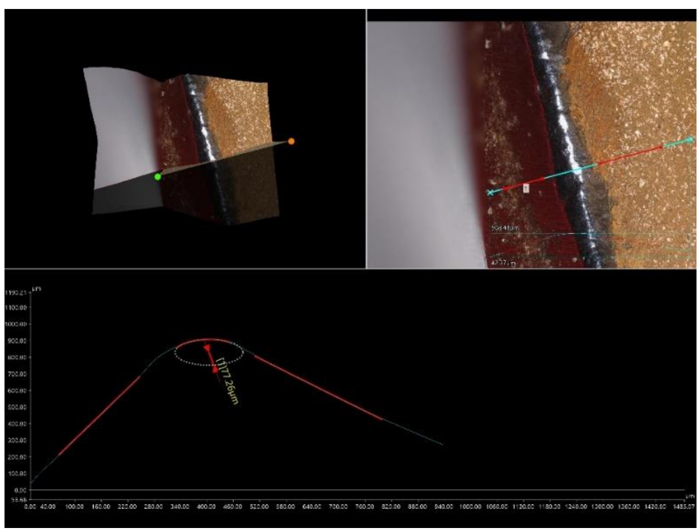

Figure 8: Left: Marking tool CAD image, right: microscope stand in use.

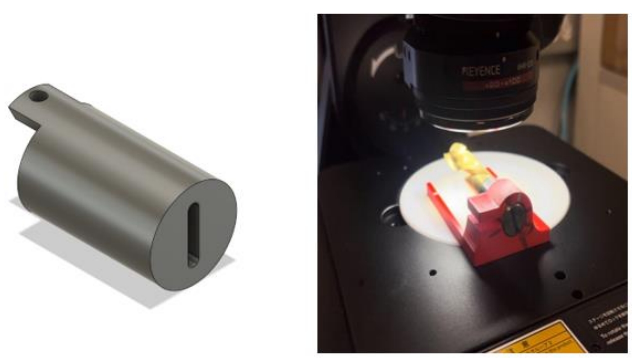

Figure 9: height map from topographic scan of endmill

that heightmap on the microscope we use the radius feature which allows us to select a region to be fit to an ellipse which is then measured and produces a radius value in microns. These annotations can be seen in figure 8. The wear occurring near or at the location where the laminate layer interacts with the tool is also run through the contour feature in a different standard position. For the resharpening experiment, we outsourced the OD measurement to the tooling supplier who measured the OD using the laser measurement system used before and after grind. A before and after OD is recorded for all tools going through the regrind process which also provides insight into the severity of the chipping as well as the wear on the edge. This only provides a maximum as that is what the CNC grinders use to calculate the depth of cut.

Stage 1: Tool Holder Sensitivity Analysis

To understand the tool life for the 1/2in compression router end mill we conducted 3 stages of testing. The first stage is a sensitivity analysis which is a test that measures the effect of a certain pair of conditions on a measurable variable. The results of this stage are not a definitive answer as to the best pair, rather a direction towards a condition that affects a result. We applied sensitivity analysis in a test of whether the tool holder type has a noticeable effect on the wear characteristics and quality of cut on the CNC router. The results of this will be presented to our sponsors as well as help decide which tool holder should be used for future stages of testing. In our test we needed to test two different tool holders on two different wood types which resulted in 4 different pairs needing to be collected as shown in figure 10 below.

Wood Type	Tool Holder
Thermally Fused	Hydraulic
Thermally Fused	Heat Shrink
High Pressure Laminate	Hydraulic
High Pressure Laminate	Heat Shrink

Figure 10: Pairs of test conditions for sensitivity analysis

When running each of these pairs we removed the tool from use for measurement at 125m which was the optimal removal time for the high-pressure laminate. Any longer, the risk of defects in the quality of cut was high according to our interviews with experienced operators. 125m was also well within the lifespan of the end mill cutting thermally fused. Due to our constraint of running the tests during production hours, the tool paths as well as color of the laminate layer was not controlled. We decided that the real-world application of this lack of control over these variables was acceptable for our test even though it limits the repeatability of results. To measure the tools and draw our conclusions we used our tool wear methodology as outlined previously.

Stage 2: Define Baseline Tool Life

According to our interview with the operators, we found out that the majority of tools on the floor are resharpened. AIS generally tries to get 3 resharpens out of each end mill. Each resharpen which is done by Atlantic Tooling. Each resharpen removes roughly .010in. of the edge. During this stage of the test, we are going to cut 500m of thermally fused boards as well as roughly 125m of HPL. In the case that the 125m mark was reached while only part of the way through processing a board, we would run the tool until the board was finished. Throughout each of the tests if the operator decides that the sound or quality of cut is not sufficient, the tool will be removed and measured to avoid any scrap parts being produced. This footage metric will be recorded as well as the indicators that were used in order to decide the removal. To measure the tools and draw our conclusions we used our tool wear methodology as outlined previously**.** Then we will send the tools to Atlantic Tooling so that we can resharpen the selected tools to be considered in the resharpen test.

Stage 3: Resharpened Tools Cost/Benefit Analysis

Finally, we want to test the lifespan of each of the 3 resharpens. To do this, we will resharpen the tools that were run to their distance limit as explained in the previous stages. We will then send them out to Atlantic Tooling to resharpen the tools to their normal specifications. The before and after OD will be recorded for later consideration. The tools will then be run to their previously defined number of boards. This length will be based upon previous knowledge that was gained from our interviews as well as metrics that are measured during the test such as sound, power consumption, and cut quality. Experienced operators will be accompanying us to help identify these indications. The cycle of resharpening and cutting will be repeated until the tools are below specification which is defined by the resulting OD being less than .470in. As mentioned earlier, this will likely result in 2 or 3 resharpens depending on the material being cut.

Cost Analysis

After the distance tests have concluded, and a baseline has been defined, we need to verify our results against the current state. To do this, we need to quantify the current state and compare it to our recommendations. The current state will come from employee interviews as well as time studies conducted by another research group. Analysis of recorded changeover data will also be used to verify the results of the interviews as well as support the comparison between the current state and our recommendations. This comparison will be a comparison of total downtime per day for one CNC machine.

Time Value of Money

In order to support our recommendations from a financial standpoint, our partnered process group will quantify the opportunity cost of a cutting machine. This figure will allow us to show any reduction in downtime and the future value of any investments in the process that are needed to facilitate the reductions. Time value of money calculations will be done to facilitate the future value calculations.

Results

Interview Results

Throughout our interviews, we learned many operators there did not have much previous experience working with CNC routers therefore, once hired they go through a training process. This training includes one month of supervised operation of the CNC machine. In order to be fully trained the operator must fully demonstrate their knowledge in a test run overseen by a supervisor. This test includes having competency in powering the machine, loading and unloading the wood boards, how to read documents and computer codes, and recognizing when to change out a tool. Lastly, operators must take a week-long course with AIS’s CNC machinist that consists of a presentation of special instances in tool wear. This course only occurs once every six months, therefore it is not necessary to operate the CNC machines at first.

When talking to the operators, we learned standard practice with the machines like how tools can consistently cut ten or eleven HPL boards or two and a half hours’ worth of TFL boards before needing to be taken out and resharpened. Operators are 75-85% of the time working with resharpened tools but noted that with a new tool they can get about 4 hours of work out of it. Tools can be used until they have been resharpened to the diameter of 0.475, when they are deemed unusable. Operators noted that the HPL material is more likely to give them issues because it is harder and shinier. Because of this, the tool becomes hotter while cutting and can cause burning. The other way tools can be worn quicker is by the type of cut they are doing. For example, the tool is making a grommet hole in the middle of a work surface, this will cause more damage to the tool than regular straight edge cuts.

We also learned a bit from the operational aspect of AIS. Currently, operators are just cutting boards fit to order, meaning that there is no standardization in the process. While most of their orders are made from TFL materials, there are instances when HPL orders are being cut with the same tool that has already cut TFL. This means that the distance cut should be shorter than the average 2.5 hours because the tool is working harder on the HPL. We also learned that 8% of all cut boards are damaged and need rework. Reworks typically take more time for operators to cut because they have to input new code into the CNC machine.

Tool Holder Sensitivity Analysis

Out of the 4 tools that were collected from the machine, as expected, the most wear occurred on the tools that were cutting HPL. As mentioned in interview results, the majority of the wear was due to the thickness of the laminate layer that sandwiches the surface and core fiberboard layers. Looking at the boards cutting thermally fused we found that little visible abrasive wear occurred where the laminate layer interacted with the end mill, with the majority of the wear showing as chipping along the edge. This is likely because 125m of cutting is a fraction of the expected lifetime of the end mill when cutting thermally fused. A closer look at the end mills cutting HPL we can see multiple types of wear. Closest to the shank of the tool a large divot in the edge coming from abrasive wear is likely from cutting the top layer of laminate as shown in figure 11. The impact location on the bottom of the tool can be seen in figure 12. This is defined as abrasive wear due to the smooth rounded edges along the cutting edge. The white material in the center of the divot is a mixture of wood and laminate material. Along the edge of the tool, small amounts of chipping has happened, but it is insignificant in comparison to the wear where the top laminate layer interacts with the endmill.

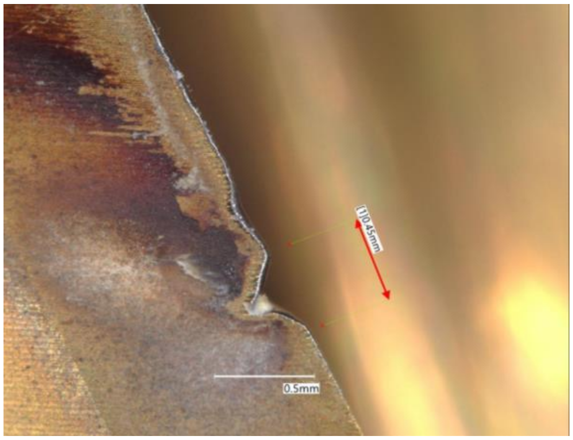

Figure 11: Chipping at top sheet layer on HPL endmill

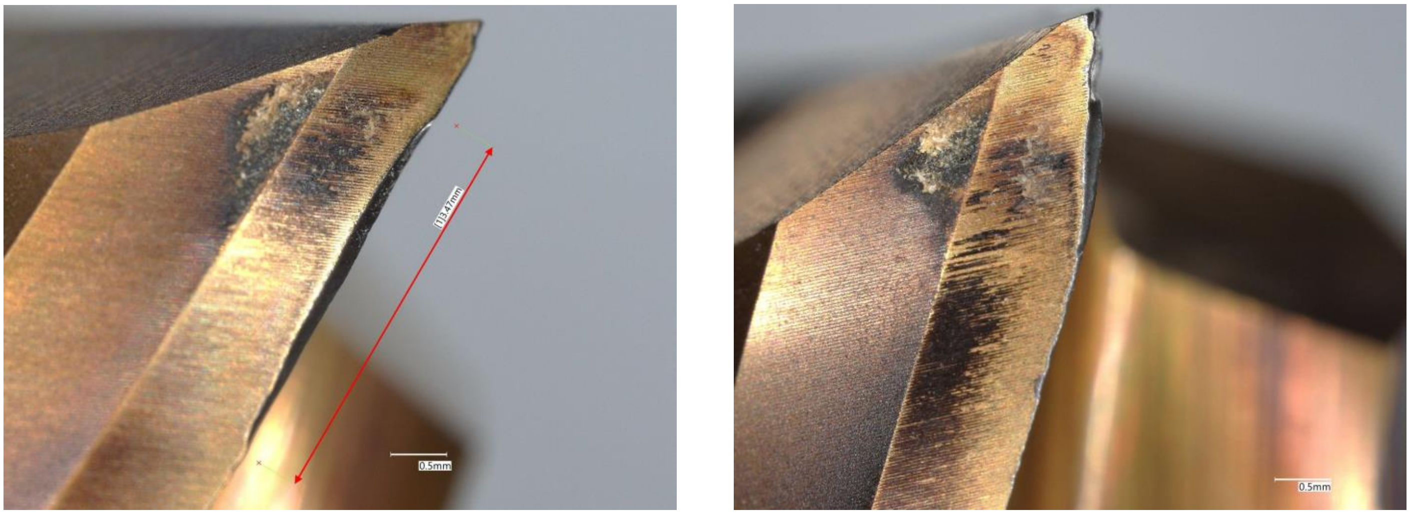

Figure 12: Tip of HPL sensitivity analysis test tools

Coming back to the sensitivity analysis of the tool holders, there was no significant difference between the two tool holder types in terms of wear throughout the endmill. The amount of chipping and abrasive wear was similar throughout the tools with the only difference being a large wear mark on one of the two flutes of the hydraulic tool holder. The other flute, which is shown in figure 12, did not show this wear which leads us to believe that this was due to a defect in the wood or a defect on the end mill.

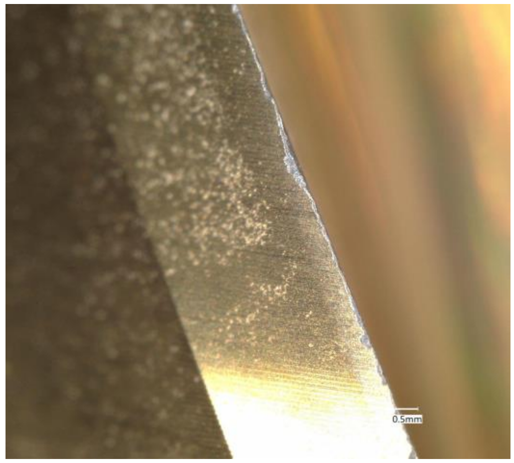

Figure 13: Wear at top sheet layer contact area on TFL sensitivity analysis tool

Looking at the tools that cut thermally fused boards, as expected, the wear was far less as compared to the tools that cut HPL. The regions of the flutes that cut the laminate layer of the thermally fused did not show inconsistent wear. The section where we think the laminate layer was in contact with the tool did show a small divot which is shown in the figure below, but the

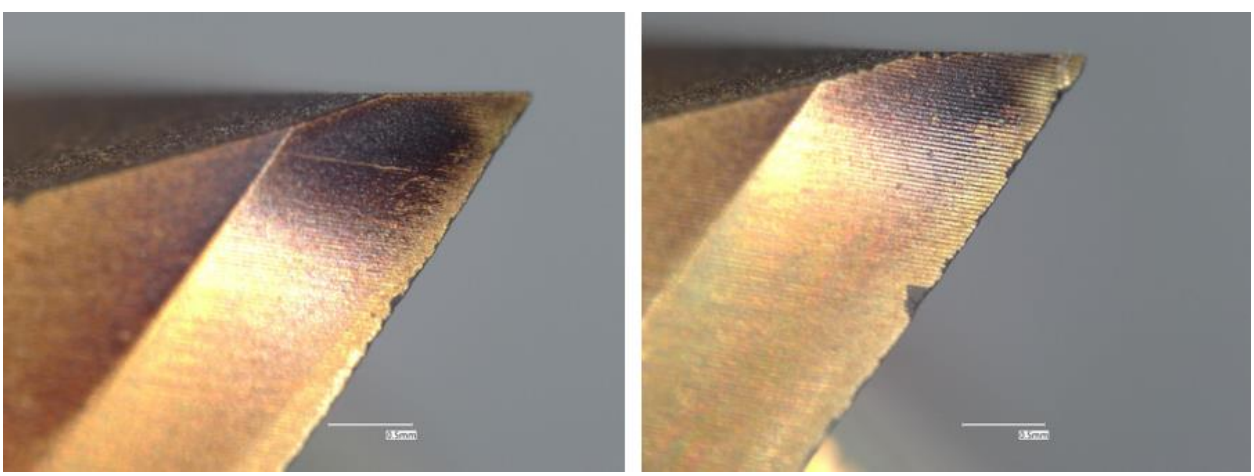

Figure 14: Chipping at tip of TFL sensitivity analysis tools

depth of this wear was not greater than other wear along the edge. Along the flute of the end mill small chips were seen evenly distributed throughout. Comparing the hydraulic to the heat shrink we found deeper chips along the tool using the hydraulic holders. The difference between the two was not significant in our opinion to warrant correlation between the tool holder and the wear. The difference is shown below in figure 14.

To compare the two holder types, below in figure 15 we can see that there is no significant difference between the two tool holder types on the TFL tools and the HPL tools. The only differences are seen when comparing HPL tools to TFL tools mainly in regard to the depth of the top sheet divot as seen in figure 15. This was expected due to the different material makeup between the two board types, and the different wear types that occur.

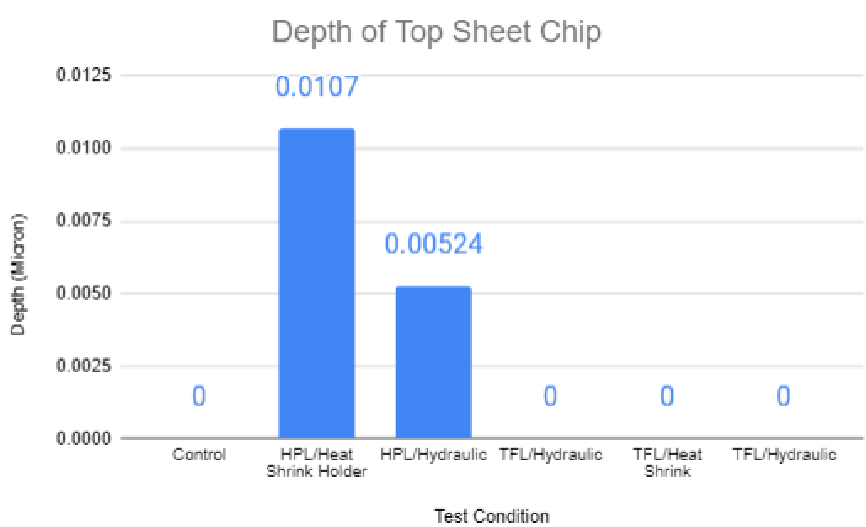

Figure 15: Depth of top sheet divot chart between tool holders

Baseline Distance Test

To preface the full distance test results, our measurements for the HPL tool will be done on the end mill that was used for the sensitivity analysis in the hydraulic holder because during that test we ran the tool to the specified distance by the company, so to reduce test time we will reuse the measurements and analysis done on that tool. However, the thermally fused tool was a new tool that ran 500m as mentioned earlier in the methods, because according to the manufacturing engineers and the operators this is the limit that they have specified for the end mills.

Looking at the thermally fused tool first, we found wear characteristics similar to that of the TFL as well as dissimilar wear. Firstly, unlike the HPL tools, burning on the outside of the end mill was more prevalent. Interestingly, it was likely wood or glue material that was heated to the point where it stuck to the end mill in a semi-permanent way. Figure 16 below shows that phenomenon.

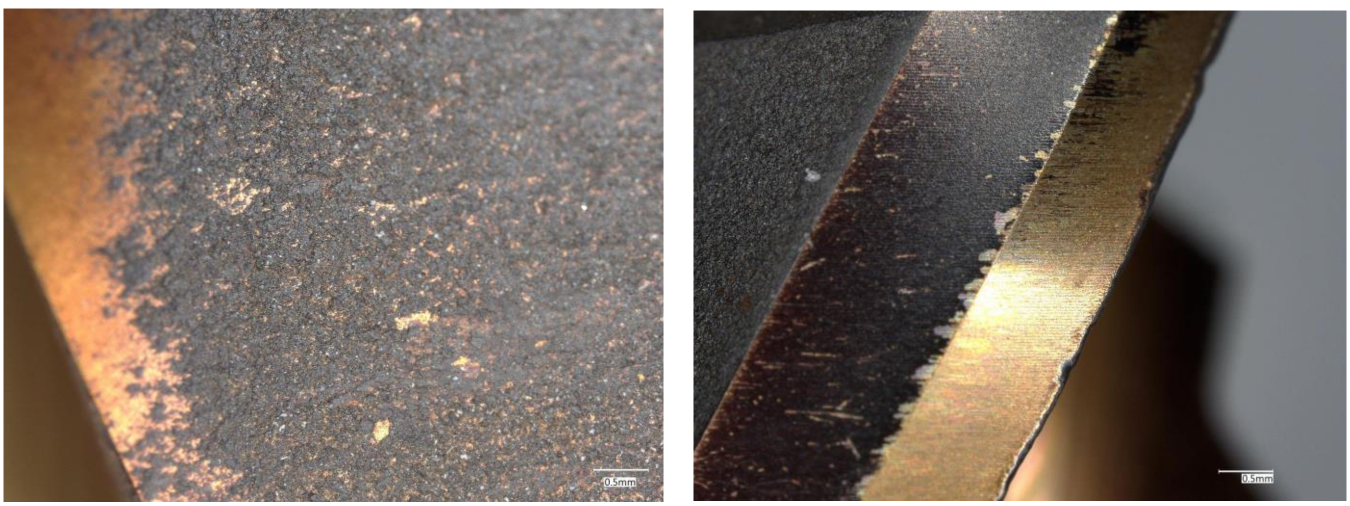

Figure 16: Side by side of different types of burning on endmill faces.

The image on the right of figure 16 shows the secondary angle which did not show the deposition of wood material, instead this is likely burning of the protective coating which is applied on the ground carbide during manufacturing.

Looking at the edge of the tool that cut thermally fused, unlike the HPL tools, we found consistent wear along both the compression edges as well as the main flutes. This wear was considerably greater than any of the other tools. The radius of the edge was 77 micron in comparison to roughly 14 micron on the other tools. The fact that there are no high wear sections of the tool means that the end mill can be run longer, which means that more wear will occur. As mentioned earlier, there was no inconsistent wear along the edge even where the top sheet interacted with the end mill. That section is shown in the below image.

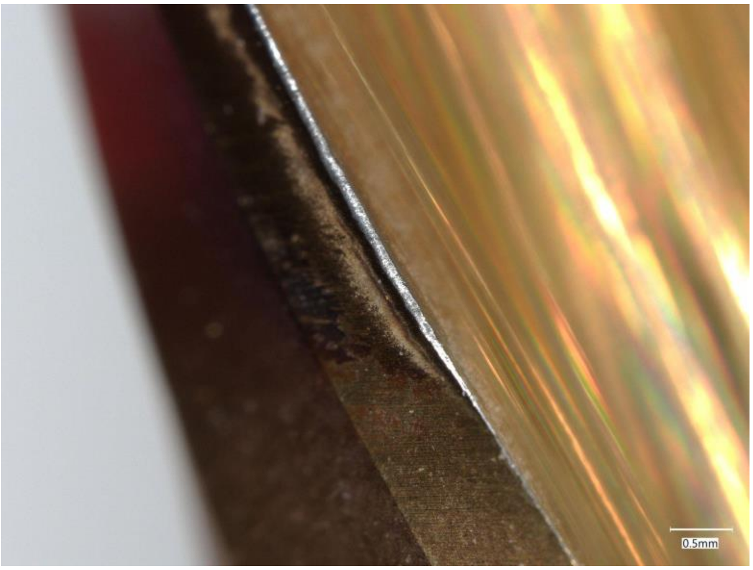

Figure 17: Contact area of top sheet of laminate layer on TFL tools

As we can see above, the unworn portion of the edge transitions smoothly to the worn section. This is due to the thermally fused layer being only .005in thick in comparison to the HPL which is .020in thick. Looking further down the tool on the reverse twist edges, we see similar wear to the main edge. This is characterized as mostly abrasive wear that has rounded the edge while also wearing away at the coating just behind the edge. Interestingly, unlike the primary direction edge, chipping can be seen in figure 18 below, which can be due to a host of reasons, but primarily will result in a large cut being needed to resharpen the tool, in turn reducing the number of resharpens that can be achieved on this tool. Another issue with these craters that can be seen is that if the tool were to be run longer than we ran it in this condition, the craters would only grow due to a reduction of supporting material behind the edge that is

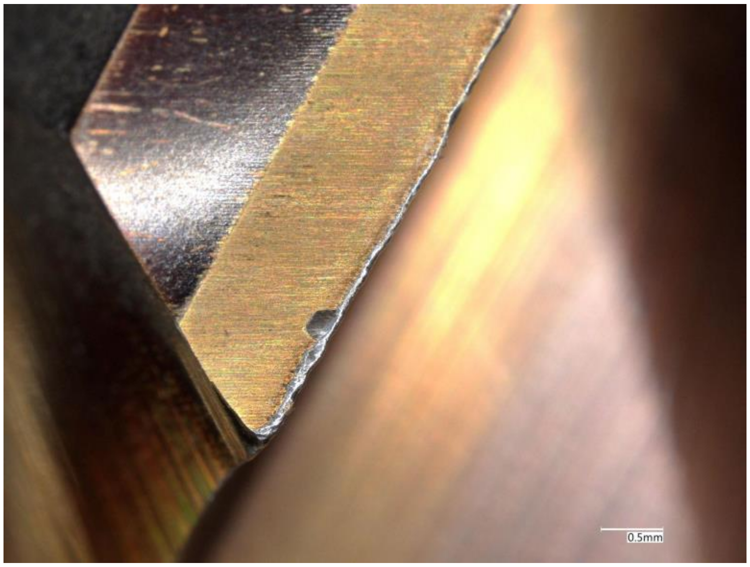

Figure 18: Chipping at beginning of reverse twist on full length TFL tool.

interacting with the material being cut. Interestingly this is what likely happened at the tip. Looking at the tip of the endmill, considerable fracturing as well as abrasive wear has occurred. This hasn't been seen on the HPL tools that cut to their specified maximum distance. We believe this is because the limiting wear on the HPL tools is occurring where the top and bottom sheet interact with the endmill. On the thermally fused tools on the other hand, the wear is consistent throughout the tool, so critical wear can occur in a host of various places. Below is a photo of the tip of a new tool is beside the used tool for reference.

Comparing the types of wear occurring in the worn condition on the left in figure 19, firstly, the majority of the abrasive wear is occurring on the edge of the tip. This is what is creating the .3mm radius that is annotated on the picture on the left. On the top face of the edge however, both fracturing and abrasive wear are likely occurring due to the interaction between the end mills and the MDF spoil board that the workpieces sit on. On the face of the tool this is where the majority of the fracturing is likely occurring. This seems to have materialized as removal of material only on the face of the end mill. This is not desirable, as it reduces the cutting performance by altering the geometry that was designed for optimal bracing of the cutting edge as well as reducing the efficiency of chip evacuation. Fortunately it seems like we can see the progression of the wear as well as different types of carbide removal the farther we look from the tip of the tool in figure 19. Starting at the furthest point from the tip we can see what can be described as essentially in new condition. The only wear indication is slight darkening of the coating due to the heating of the tool. Moving to the next point on the tool we can see removal of the coating from the carbide. As seen in higher power photos of other tools, we know that at high wear zones of the end mill, the coating is the first thing to go, which is not desirable as the coatings are added to increase the lubricity between the cut chips and the end mill reducing friction and ultimately heat. Moving one step closer to the end mill we see

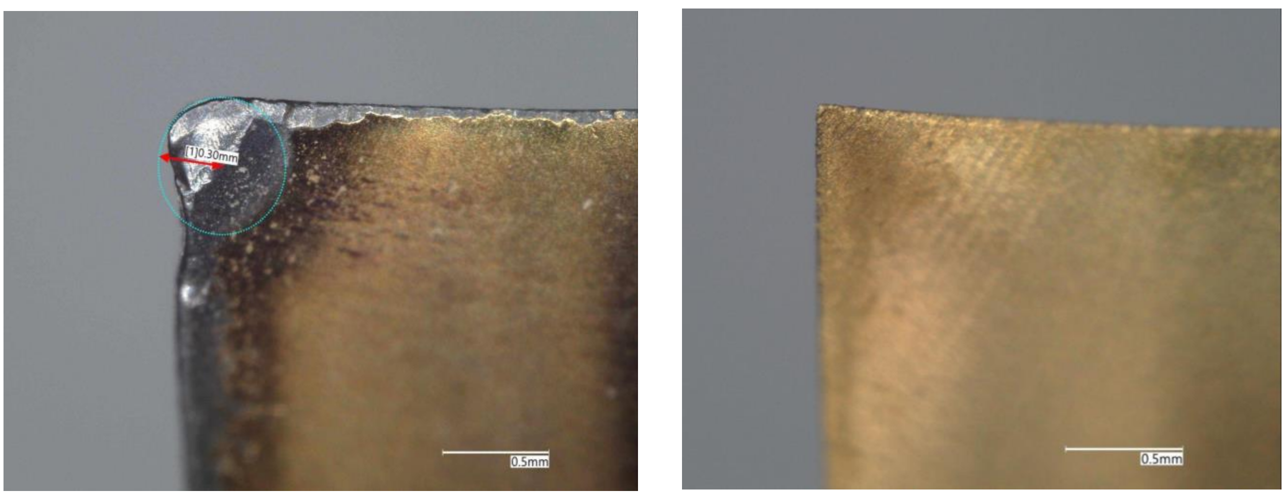

Figure 19: Comparison of tool tip between new and used tools

definitive removal of carbide. Due to the smooth nature of the wear, this is likely only abrasive wear with very little fracturing occurring. The coating has been 100% removed from this section and interestingly there is a significantly sized divot that makes up part of this section. This could have formed for a few reasons. One reason could have been a fracture early in the cutting process that got smoothed over due to consistent abrasive wear, or focused abrasive wear that occurred due to either the laminate layer or more likely interaction with the MDF spoil board on the machine. Finally, the last section shows almost exclusively fracturing of the carbide grains.

Some abrasive wear can be seen, but the majority is likely due to catastrophic failure resulting in the removal of large groups of carbide grains which creates a domino effect. In short, once a small section of carbide is removed the support of the surrounding grains is reduced causing even more fracturing which results in large regions of wear that are seen in figure 19. What does this mean for the test as a whole? When it comes to the number of resharpens, the larger the amount of wear, the large depth of cut is going to be required to bring the edge back to its original geometry.

When comparing the HPL and TFL tools used to 100% of the specified distance, quantitatively, there are large differences. Most notably, distance wise the HPL tool was only able to reach 130m compared to the 500m that achieved with the TFL tool. As mentioned earlier this is due to the makeup of the wood, and how it wears the tools differently. We see this in the measurement of the edge roundness. Figure 20 shows the roundness of both tools at their maximum distance.

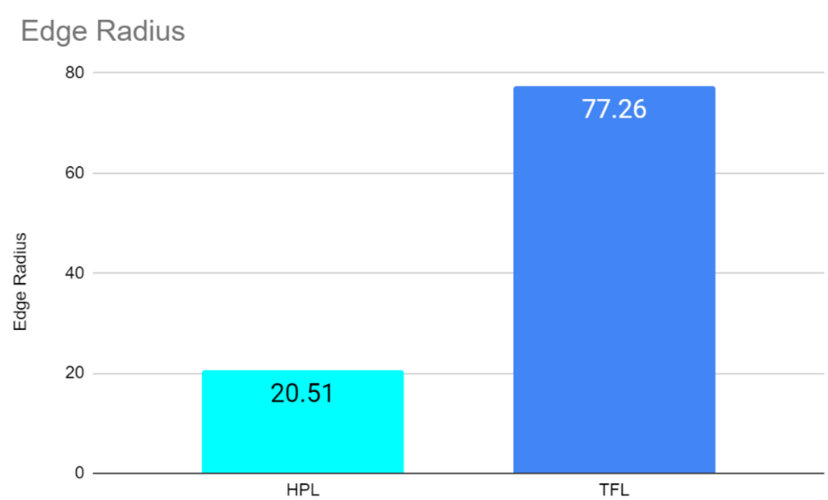

Figure 20: Edge radius comparison chart when tools are run to 100% capacity.

These measurements were taken in the middle of tool, which explains the large difference. As seen in the sensitivity analysis most of the wear for the HPL tools happens where the tool interacts with the top sheet layer whereas the TFL tools wear consistently along the edge. On the other hand, looking at the depth of the divot at the top sheet layer, on the HPL tool at 130m we found a divot .00524 micron in depth compared to TFL which was immeasurably small. This further reinforces the fact that the tool wood types wear the endmills differently and should be treated differently. This also influences the regrind, which can be seen in the comparison of regrind OD in figure 21. This measurement, which was done by the regrind contractor, tells us the depth of cut from new OD (.5in) that is required to bring the tool back to original geometry. Provided both tools started at .5in, the HPL tool required .0023in deeper of a grind to be acceptable. This is another example of how the two different types of wear affect the tools. Both tools were able to reach 3 resharpens which is the AIS's goal, which we found in our resharpened tool lifespan test.

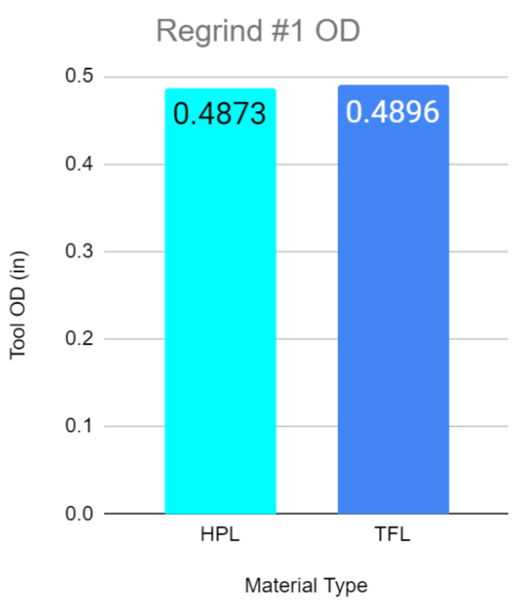

Figure 21: Comparison of OD of post grind endmills.

Resharpened Tool Lifespan Test

In the resharpened tools test, some interesting things happened. As a reminder we tested the lifespan of 3 stages of resharpening, to establish a baseline for the current conditions that AIS uses. As mentioned in the background, the end mills are resharpened using a CNC grinder that re-establishes the full geometry of the edge except for the inner flute. The grinder measures

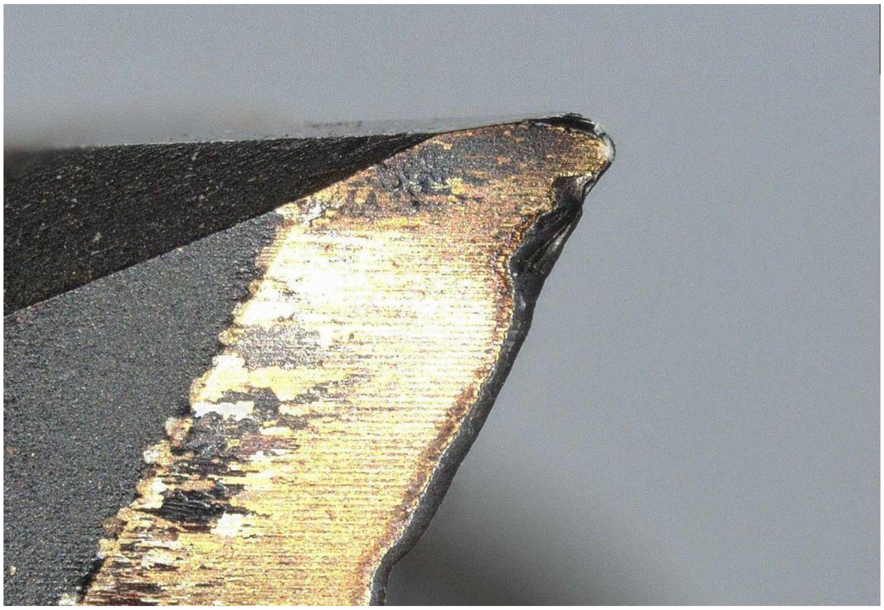

Figure 22: Firs Test Tool (Cut 500m TFL)

the tool before in order to decide the depth of cut as well as after to give the operators a diameter that can be used when establishing wear offsets in the router's controller

For the first resharpen we used the tool that cut 500m of TFL as well as the tool that cut 130.4m of TFL in the first test. These tools were chosen because they represented 100% of the lifespan of each respective wood type. The resulting footage can be seen in figure 23. There are a few things to note regarding the footage. The TFL footage was stopped at 298m due to chipping occurring on the cut edges. Fortunately, this chipping would likely be removed at downstream processes, but this was an indicator that signaled a changeover of an endmill. This was a surprise, due to our predictions based upon employee interviews being around the 320m range. This suspicion was reaffirmed when looking at the wear on the edge of the tool. Comparing the radius of the used reground tool to the first used end mill we found that the 500m tool was worn further without chipping

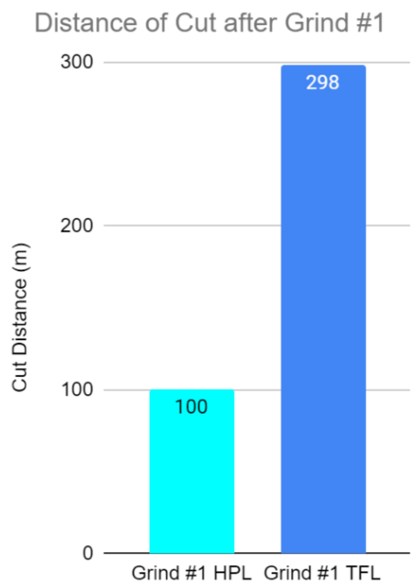

Figure 23: Comparison of distance of cut after first regrind.

the cut material. The difference was roughly 33.76 microns. The chipping on the workpiece was likely due to considerable chipping throughout the endmill that was not consistent with pre-resharpen wear. This can be seen in figure 24 below. The root cause of these inconsistencies was the regrinding process. According to the tooling supplier who also owns the regrinding process, pitting and inconsistent edge quality is likely due to the depth of cut that the machine is programmed to take. The decision was made to allow certain inconsistencies in the finished product to increase the number of resharpens available in each tool. The tooling supplier said: “If we were to grind out all of those chips and divots, we would only get one grind out of each tool.”[12]

To summarize the first resharpen, looking into the quality of the resharpening process may yield better results in terms of footage especially for the TFL. When it comes to the current state, the footage as stated above is a good reference for the first resharpen, but as mentioned, looking into the resharpening process could yield better results.

Looking at the second resharpen, we found some interesting occurrences. Our predictions based upon employee interviews indicated that as the OD of the tool decreases, the number of boards cut also decreases. Based upon the grind process we agreed that this would be the case, but as seen in the interview breakdown, they stated 45% of the unsharpened capacity as the

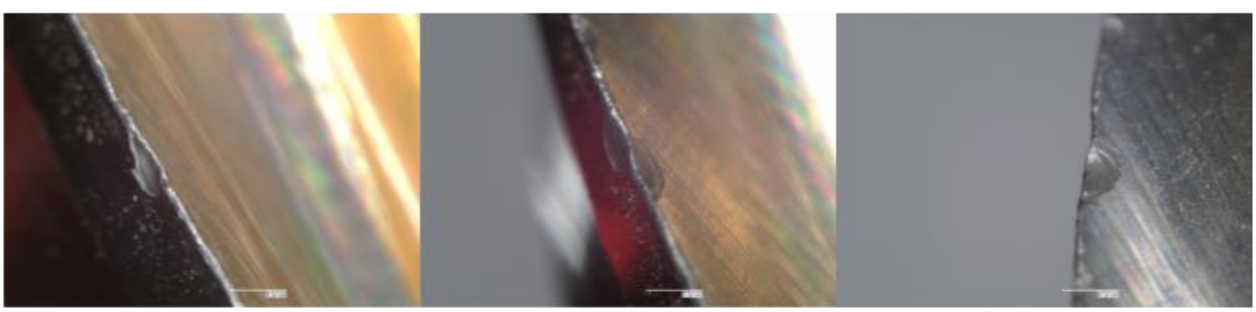

Figure 24: Examples of inconsistent chipping on endmill.

[12] (Nick, Patalano)

second resharpen for both HPL and TFL. To understand if we have reached full usage of the endmill we used a few indicators.

Recommendations/Deliverables

Predictive Changeover tool

To give AIS, the ability to verify that their operators are following the footage metrics that we have defined, we created a calculator that predicts the number of tools required to cut a certain number of boards. In order to calculate this, the calculator uses the data from the full-length distance test as well as the resharpened tools test. The calculator also considers the distribution of each type of endmill. The tool can also tell you the number of tools based upon a single tool type as well. The input and output can be seen in figure 27 below.

Cost Benefit Analysis

As mentioned in the interview methods and results section, a large part of this project was to understand what is currently occurring on the shop floor and compare it to our test data. The goal of the interviews was to understand what the operators perceived the status quo to be. To understand what exactly was going, we pulled production data that kept track of each tool changeover and its associated router and diameter. The results of this analysis are as follows in figure 25.

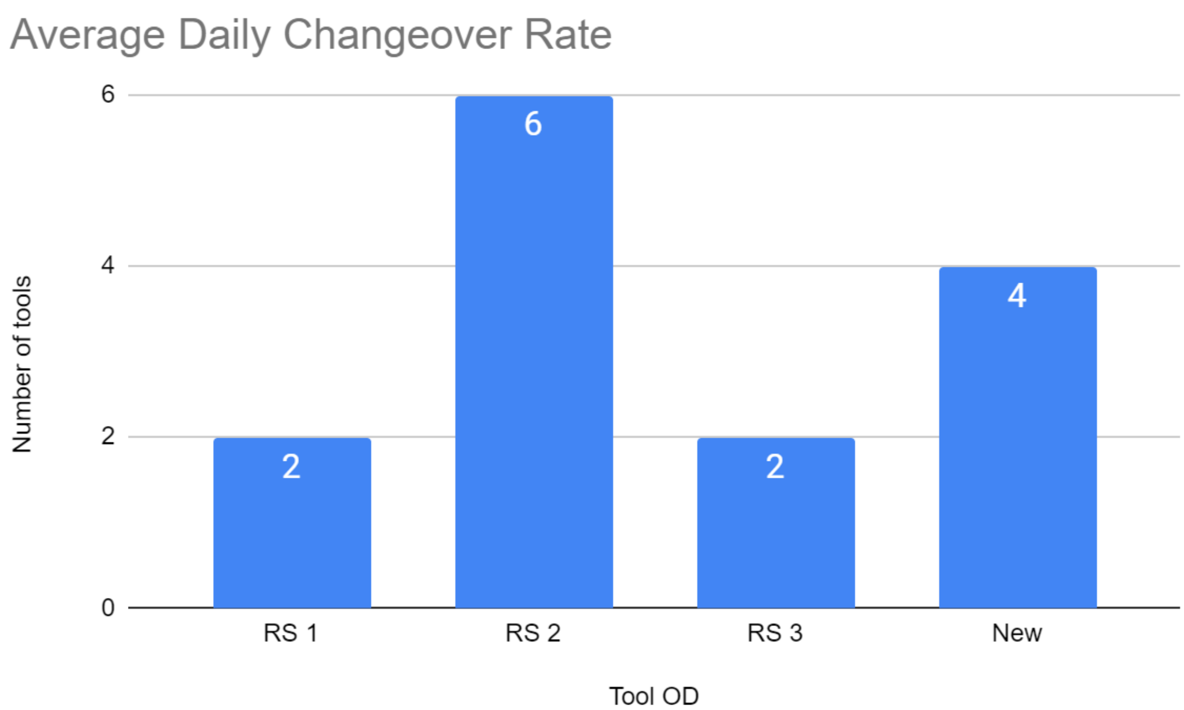

Figure 25: Daily changeover rate from a sample of 111 days.

In order to understand what is currently happening on the floor in regards to tool changeovers, we analyzed historic data the AIS has on the tool changeovers over 111 days. Operators are required to report when an endmill is changed, with reference to the time, date, and machine number. We used pivot tables as well as countif excel functions to average number of tool changes over first and second shift. We also recorded the distribution of size of tool to help refine our predictive changeover calculator. The results from this analysis are shown in figure 26 below. We also averaged the changeovers over 2 shifts across 4 machines.

Tool OD (in)	# of tools used over 111 days
.470-.479	185
.480-.489	637
.490-.499	196
0.5	372
Sum	1390

Router Number	Changeovers per day
R2	4.8
R3	4.5
R4	4.8
R9	4.2
Average	4.6

Figure 26: Changeover report analysis results

To calculate our predicted tool changeover rate, we used our predictive tool changeover calculator that was introduced earlier. In terms of the material input, the distribution of HPL vs TFL based upon estimations from production staff of 90% TFL and 10% HPL was used. The percentages of each tool type and wood type are shown below in figure 27. The footage numbers are for 1 CNC machine during 2 shifts since our interviews and testing only covered 1st and 2nd shift. The data input into the calculator as well as the results are shown below in figure 27.

Tool Usage Calc	
M of HPL	97.5
M of TFL	877.5
Single Tool Type	
Tool Type	New
Number of Tools Used	2.505
Distribution of Tool Type	
New %	26.76%
RS 1	14.10%
RS 2	45.83%
RS 3	13.31%
Number of Tools	**4.4**

Test Data for Comparison Analysis	
% tfl	90%
% hpl	10%
Boards per shift	50
Meters per board	9.75
# of shifts	2
M of TFL	877.5
M of HPL	97.5

Figure 27: Predictive tool changeover calculator with input data for comparison.

Looking at the results, they are not too dissimilar to our interviews. In our interviews, we had operators running tools for 150m while our calculations propose 200m. We also heard that about 90% of the shop floor was using resharpened tools compared to the calculated ~73%.

To get a current state figure for the process we used the same changeover data that was used for the tool distribution to calculate the changeover rate that is currently occurring. Using regex functions to sort through the data as well as pivot tables we were able to find the tool usage distribution stated earlier as well as average tool changeover rate for worksurface machines which came out to roughly 4.6 tools over tool shifts. The resulting averages for each machine are shown below in figure 28. The results from the predictive calculator as well as the data analysis were handed off to our partnered process team in order to support their time value of money analysis.

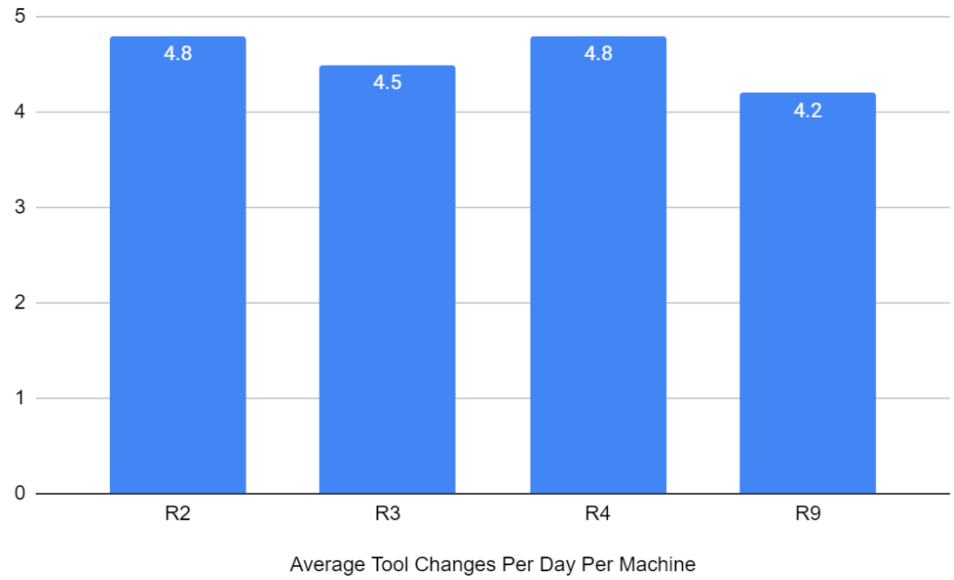

Figure 28: Average tool changes over 1st and 2nd shift.

To quantify the financial benefits that AIS could achieve from implementing our recommendations. Focusing specifically on the tool changeover rate standardization, as mentioned earlier if AIS implements that footage limits as defined earlier, there will be a 4.3% decrease in changeovers over 2 shifts per machine daily. To quantify this in conjunction with our partnered process team, we wanted to do a time value of money analysis of this improvements. Our analysis only looked a the cost of a tool due to the amount of variability in the cost of machine time due to the variability in AIS' process. Using FV calculations and the 41$ cost per use of a tool we got a yearly return of roughly $12,000. This is all based upon calculations shown in the analysis done by our partner team in their paper titled "Tool Change Process Improvement at AIS". The takeaway from this are that the cost of the distance measurement system on the machines are worth it, and with no other improvements, the software will pay for itself within the first year. A composite graph showing the FV and different depreciation rates of the savings resulting from our improvements is shown below in figure 29. [13]

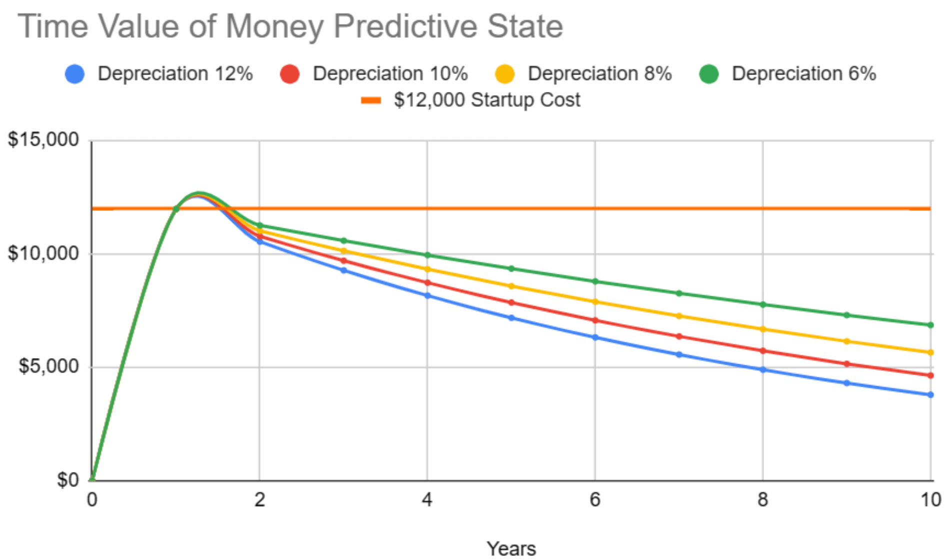

Figure 29: Time Value of Money with distance trackers installed in 4 CNC routing machines.

Operator Tool Use Standardization

Throughout our tests and interviews we have found that training and experience trumps all when it comes to understanding the indicators of a worn tool. AIS's current training protocol includes a shadowing process where new operators are paired with an experienced operator for around a month. We recommend adding a focus on key indicators of tool wear. Currently, operators change tools almost regularly at 2.5 hours, despite there potentially being mixtures of material used on the same tool. We recommend that the majority of routers be designated to TFL orders, but also having a couple routers solely devoted to HPL. Therefore, people working on those machines know to be switching the tool out for 10-11 boards, while the other operators working on TFL continue changing every 2.5 hours.

[13] (Byrum)

Equipment Modifications

When it comes to the machines, we recommend that spindle load monitoring is a must for all the CNC machines. This is for a few reasons. Firstly, the variability of the wear due to the variability of the material and tool paths means that to predict a tool removal would require an advanced model that would be time prohibitive to create. The reason that we recommend spindle load is because it, alongside the temperature of the end mill, gives the operator the best insight as to the sharpness and efficiency of the end mill. For our tests a current sensor was installed in parallel with the power lines leading into the spindle. A widget in the machine controller would help with limits set as to the power consumed for each tool type. As mentioned in our background, acoustic emissions have proven to be a good source of information as to what is happening at the end mill, but the issue with applying that to this scenario is that the base sound floor of the machine shop will make it difficult to differentiate between the sounds coming from the machine with the sensor installed and the surrounding equipment. To set the power consumption limits further testing would be needed, but this would not need to be as detailed as the tests that we have run. We would recommend running multiple tools to the specified minimum OD as stated by the resharpening specs. Averaging the power consumption at said minimum tool conditions and using that to define at a minimum a notification on the CNC controller that the power usage indicates wear.

On top of the addition of various sensors we also recommend the implementation of footage tracking software on all worksurface routers. As we’ve shown in our estimates, implementing more standardization when it comes to the rate of changeovers can have a positive effect on the overall tool usage with no effect quality. This would be at a cost, but as shown in our time value of money calculations, the benefit over time outweighs the cost over time.

Future Work

Future work either for another student group or AIS can go one of two ways. Firstly, more testing could be done to get a better idea as to the footages for each individual wood type and color. This can add more sensitivity to the predictive tool changeover calculator. On the other hand, focusing on adding more sensors to the machines and doing testing to understand the limits of those new parameters. If done in conjunction, doing both things would allow for AIS to have a better idea as to what is happening with the machines and have the ability to make the changeover of a tool more defined and remove the variability that comes from operator input. Improvements also could be found with higher sensitivity regarding predictive changeovers as well as including more sensors and limiting parameters. In general, both things do need to be done, but the order is arbitrary.

Going into next year, the following group will have to do a few things early in the school year before testing to ensure a good project. First, they must gain a clear understanding of their project before mobilizing. This can be done by doing multiple walkthroughs at AIS and observing worksurface pieces go through the different steps of manufacturing. Before testing, it would also be ideal for this group to have interviews with operators and directors on the floor. These people are carrying out the operations at AIS and can help their group with opinions on what is working, and they feel can be improved upon. While interviewing, it will be helpful to keep in mind that the scope of the project may change so you will more than likely have to interview people more than once for information. Also, that AIS has multiple shifts, therefore people on 1st shift may have completely different opinions or input compared to people working second shift.

Conclusion

Throughout our work at AIS, our group learned how high functioning of an organization AIS is, and that their leadership has probably tested many ways to reduce tooling prices and changeover, as well as create the most efficient operations. Based on the resources we had, our goal was to deliver the AIS team tooling data that they had never seen before and prompt future experiments for them regarding the best practices for tool changeover. Our group achieved this by conducting interviews and doing tests based on the information provided to us by employees and machine operators.

Our first test was a tool sensitivity analysis where we measured the performance of the heat shrink versus the hydraulic holder. It was evident that there was slightly more damage done to the hydraulic holder, but none significant enough to show correlation. The second test we did was running each tool to its maximum distance. By doing this we were able to learn, the more wear the tool undergoes, the larger the cut will be when it is reground. This means the new tool may not get three resharpens out of it or its resharpened performance may be worse than anticipated. Our last test was a resharpened tool test where we looked at each tool's performance when resharpened 3 times. This test backed up our interview's data and confirmed that the resharpened tools cannot run nearly as long as the new tools while keeping high quality.

Our group concludes that to continue work on this project or implement changes, there are a couple routes that can be taken. Our first plan of action would be equipping routers with current sensors. This would be able to show operators the tool's spindle load and when the tool is working harder than normal to change it out. This would somewhat reduce damage to the tool and potentially enhance the performance of reground tools. Next, we recommend sorting orders to where routers are only cutting either TFL or HPL materials. With this in place there is more standardization and less chance of an operator ruining a tool because they ran it to a full TFL distance while mixing in some HPL boards.

On top of this we found that with our standardization recommendations, there is a monetary gain that could be had, which came from our comprehensive time value of money analysis in conjunction with our process improvement team.

Reflections

As a group overall, we feel as though our project with AIS provided us with real world applications, as well as an opportunity to showcase skills we have developed through courses in the business school and mechanical engineering department. Looking back on the project, it was not always smooth sailing, as changes within the scope of our project occurred, but we proudly believe that we adapted and overcame obstacles by creating good baseline data for AIS to take away from us. In terms of workload, Ryan took more of a forefront in gathering background information from interviews and seeing what information applied to us and could affect our project. Phil on the other hand, managed more of the mechanical aspect of the project and did well gathering data in the lab looking at the worn tools. When it comes to the tooling analysis, we started with a very big group of tests that we wanted to run, but as we got closer and closer to the process, we realized that the number needed to be cut down. This is where the predictive tool changeover calculator came from. In talks with our advisors, we realized that this tool would be of great use to AIS as well as ourselves and our partnered group. The reduction in the number of tests compared to our original plan meant that the results were far better and less rushed. Partnering with the WPI LEAP lab was also a successful partnership as we were able to get all the information and more from the equipment available as well as support and guidance from the staff. Overall, this project went quite well, with some major and minor changes throughout we were able to fully apply our degrees while also providing AIS with invaluable information on top of lining up word for future technical work at a project site that historically was only accessed by business school majors.

Works Cited

"The Correct Way to Setup a Compression End Mill." *Stepcraft, Inc.*, 21 Mar. 2022, www.stepcraft.us/blog/stepcraft-blog-6/the-correct-way-to-setup-a-compression-end-mill-8#:~:text=A%20compression%20end%20mill%20has,finish%20on%20your%20work%20piece.

Tool, Triumph. "How Using a Hydraulic Tool Holder Will Save You Money." *Triumph Tool*, 13 Jan. 2020, www.triumphtool.com/metal-working-tools-blog/hydraulic-tool-holders-will-save-you-money/#:~:text=A%20hydraulic%20tool%20holder%20uses,to%20grip%20the%20tool%20shank.

"Benefits of the Heat Shrink Tool Holder." *GDP Tooling*, 27 Jan. 2021, gdptooling.com/heat-shrink-toolholder/#:~:text=The%20receiving%20end%20of%20the,an%20electric%20heating%20induction%20machine.&text=This%20causes%20the%20steel%20body,the%20shank%20of%20the%20tool.

"Thermally Fused Laminates." *Composite Panel Association*, 25 Jan. 2022, www.compositepanel.org/products/decorative-surfaces/thermally-fused-laminates/.

GISIP, JUDITH. Improvement of Wood-Based Machining Operations on a CNC Router through Extending Tool Life. (Under the direction of Dr. Richard L. Lemaster and Dr. Daniel E. Saloni.)

Brown, Christopher. "An Introduction to Axiomatic Design." *YouTube*, YouTube, 16 Apr. 2013,

www.youtube.com/watch?v=WiimzxRJhWs.

Byrum , K. (n.d.). *Tool Change Process Improvement at AIS*.

AP-42 CH 10.6.2 particleboard manufacturing. (n.d. https://www3.epa.gov/ttnchie1/ap42/ch10/final/c10s06-2.pdf

Goodwin, P. (n.d.-a). *Decision Analysis for Management Judgment* (Vol. 5). Wiley.