

## **Metal Cutting and Manufacturing Economics Project for Freshmen**

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## **Metal Cutting and Manufacturing Economics Project for Freshmen**

### **Abstract**

This paper describes a practical student experience consisting of a manufacturing laboratory experiment and a team project designed to teach manufacturing concepts to freshmen engineering and engineering technology students at the Old Dominion University. Students learn engineering concepts and skills they will need later. First, students organize into randomly assigned teams with specialized responsibilities for the purpose of calculating the total production time and cost of manufactured parts using turning, drilling, and milling operations. Then, students learn or improve their spreadsheet skills while performing data entry and necessary machining calculations. While these first-year students do not perform any metal cutting themselves, they observe a machine shop technician who performs the operations. Students collect data and take pictures of the operations as they are exposed to rather messy realities of metal cutting. Then, they calculate manufacturing cost of the part. Each team wrote a technical team report to document the manufacturing experience they had. The experiment and the team project are described in sufficient detail to allow easy adoption. Students reflections and informal interviews show that the students are satisfied with the experience and that they highly value gained insights and skills.

### **Introduction**

Experiential learning<sup>1-3</sup> is a well recognized part of Kolb's experiential learning cycle/spiral<sup>4-6</sup> that is used as a powerful pedagogical strategy in many engineering programs. Creating products is the essence of manufacturing, thus the product realization-based learning seems a natural model for learning manufacturing engineering<sup>7</sup>. Project-based learning (PBL) pedagogy is well accepted in education<sup>8, 9</sup>. It is also emphasized as one of the high priority education methods/pedagogies required in manufacturing engineering education<sup>10</sup>. PBL pedagogy is successfully implemented in a manufacturing processes course<sup>11</sup>. The practical experience described in this paper is product realization centered. Also, it uses PBL pedagogy and teamwork.

### **Curricular Context**

ENGN 110 is an introduction to engineering and technology course designed to "introduce a variety of engineering and technology disciplines" through a series of engineering projects. The course emphasizes team work, design, manufacturing, testing, communication and presentation skills, as well as discovery, creativity, and innovation<sup>12</sup>. The course is a one-semester, 2 credit course required for all engineering and engineering technology programs. The described practical manufacturing-related engineering experience presents one of the major learning modules in this course. The practical experience encompasses all four pillars of manufacturing engineering: "1) Materials and manufacturing processes; 2) Product, tooling, and assembly engineering; 3) Manufacturing systems and operations; and 4) Manufacturing competitiveness<sup>13</sup>." Student work in teams of three to four with about 100 students per semester.

### **Educational Goals, Activities, and Outcomes**

Educational goals of this project include increased excitement for engineering resulting in increased retention, motivational preparation for further studies in engineering, and gaining an insight into what engineers do. The practical experience consists of several activities: observation

of real metal cutting operations, realizing overhead costs, calculating realistic manufacturing costs, applications of learning curves, and development of spreadsheet skills. There are several project learning outcomes that stem from project educational goals that are reinforced/implemented through project activities. They include 1) development of teamwork skills, 2) increased appreciation for future coursework in physics, statics, dynamics, and thermodynamics, 3) an early understanding of the role of experimental and analytical approaches to engineering problem solving, 4) development of written communication skills through writing technical team reports, 5) increased appreciation for engineering by experiencing a “real life” like hands-on engineering project from start to finish, and 6) learning about manufacturing in general. These outcomes are closely related to ABET-EAC Criterion 3, a-k student learning outcomes<sup>14</sup>, specifically outcome a - an ability to apply knowledge of mathematics, science and engineering, outcome b - an ability ... to analyze and interpret data, outcome g - an ability to communicate effectively, and outcome k - an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

## **Practical Experience**

### *Manufacturing Task*

A steel coupler is machined. The intended use of the coupler is to connect two other metal parts. A 1018 mild steel with a diameter of 3” and a length of 10” is turned down to a diameter of 2.25” in three passes for a length of 7” on a manual engine lathe. Then, a 2” deep and 1.75” diameter hole is drilled on the uncut side of the part on the same lathe. The part is then moved to a HASS CNC mill that removes, 3” from the end lengthwise, top 0.84” section of the turned 7” long cylindrical section and drills a 1.5” diameter hole in the middle of milled area. Finally, a 3/8” diameter pin hole is drilled on the side with 2” deep blind hole at the end. Figure 1 shows 3-D view of the finished part. Each student team was also required to envision a potential application and sketch it freehand. Appendix B shows some sample sketches that depict potential uses for the coupler.

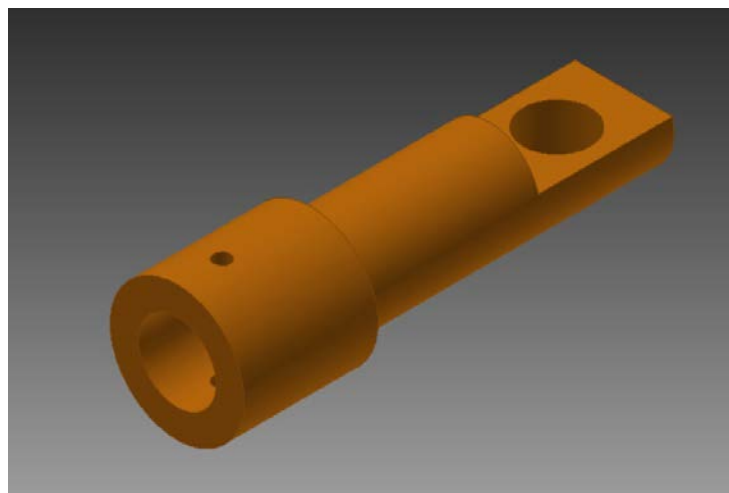


Figure 1. 3-D Rendition of the Finished Product (Coupler)

Figure 2 shows the side view engineering drawing of the coupler. The dimensions and the tolerances were adhered to.

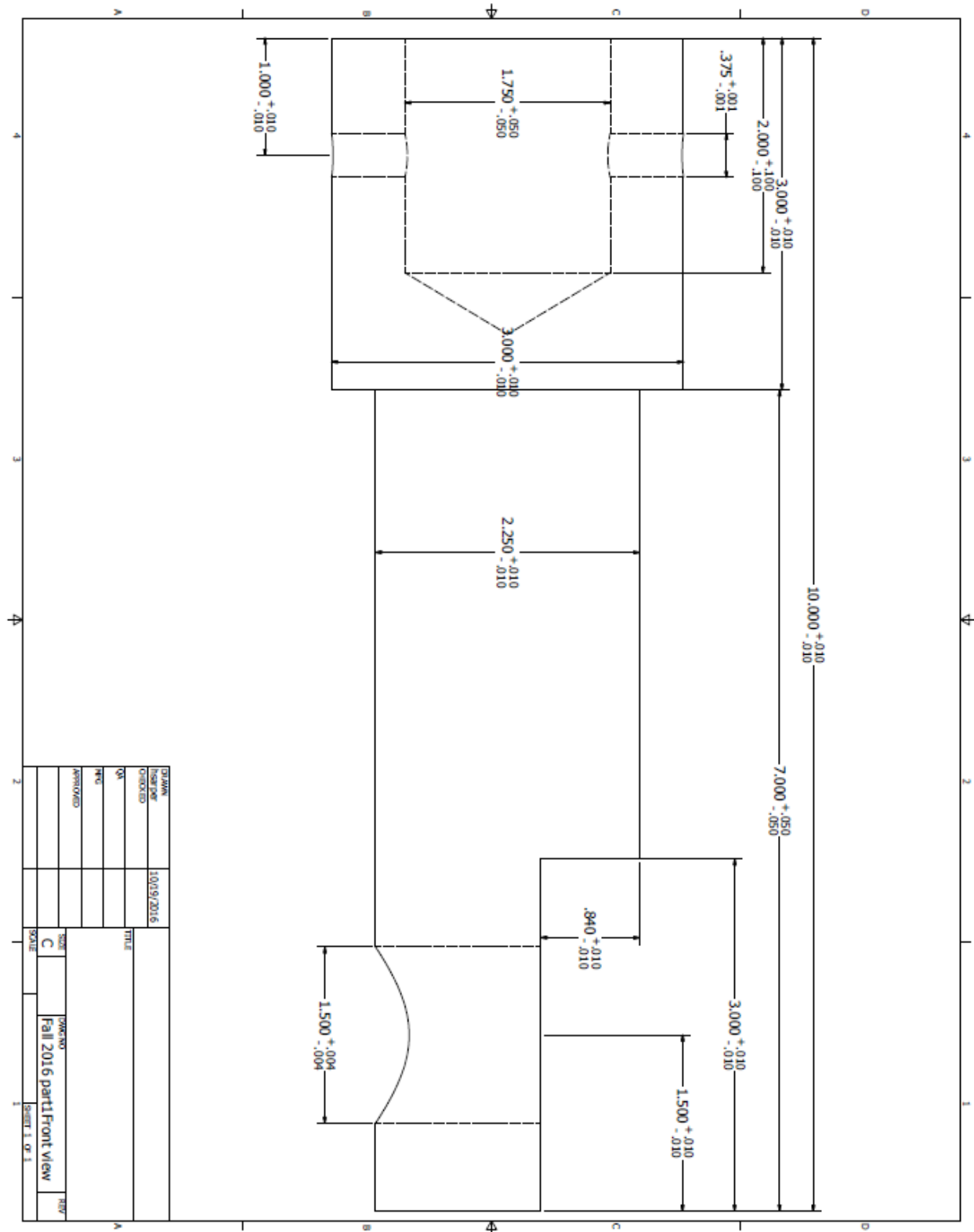


Figure 2. Engineering Drawing of the Coupler Showing Basic Dimensions and Tolerances

Each cut is timed and the part is weighed before and after each cut to calculate experimental metal removal rate (in<sup>3</sup>/min.) for each cut. All experimental observations are compared against analytical results for each machining parameter set (spindle speed, feed, and depth of cut). Calculated energy for each cut is compared against the maximum power the motor can deliver at the cutting point with an assumed machine efficiency of 80%. Necessary set up times and other unavoidable time losses are also noted and used in final calculation of total production time per part. Actual tool, energy, raw material, and hypothetical labor and overhead costs are used in calculation of total production cost per part under various cost and annual demand scenarios. Learning curve effect is included for non-machining activities such as handling and minor setup times. It is also assumed that raw material cost decreases as the quantities increase.

This is a complex project with multiple educational goals. One of the goals is to educate students on the circle of manufacturing in which the final product of one company becomes the input of another company. In this case, raw material shown in Figure 3 was used to manufacture the coupler shown in Figures 1 and 4. Figure 4 shows painted finished couplers as well as the raw material to illustrate how manufacturing, by applying energy to raw material, has transformed it into a finished product. Students were able to witness how value was added to raw material through series of machining operations. Appendix C contains pictures of these operations.



Figure 3. Incoming Raw Material (1018 Cold Rolled Steel) at \$22.25/piece



Figure 4. Finished and Raw Coupler Parts.

Another objective of this project was to expose the first year students to the process of using collected data to write a report from an engineering perspective. Manufacturing is the process of fabricating a raw material into a predetermined functioning final product. During this project the students were able to see the manufacturing process firsthand and experience it albeit without actually making the cuts.

#### *Discussion of Project Calculations*

Each team calculated coupler cost under the assumption that learning curve applies in two ways:

- 1) Raw material cost per coupler decreases as quantities purchased double. A 95% learning curve was applied. This means a reduction of 5% will be realized in raw material cost. This assumption is supported by literature and the quotes obtained from the supplier for

increased order quantities. According to a textbook on cost estimation<sup>15</sup> the learning curve is 93% – 96% for raw materials, 85% – 88% for purchased parts, and 85% for operations that are half hand assembly and half machining.

- 2) Indirect labor time will decrease with a learning curve of 85% as the quantities double. Initially, it was assumed that the indirect time per part (handling, positioning, measuring, etc.) is equal to 100% of the direct time. This seemed reasonable as each part took about twice as long as the sum of all operations of the direct times. The total direct cutting time of about 31 minutes is a constant, but the indirect times improve with repetition.
- 3) No cost reduction is assumed for tool, energy, and paint usage with increasing quantities. Some cutting tool costs (drills and milling cutters) were assumed to be a part of the overhead cost charge as a percent of the labor cost shown in Table 1. In case of turning operations, disposable carbide insert cost was available (\$10.25 for a 3 pack with a total of 9 cutting edges). This cost is distributed to each coupler as a direct cost.

Table 1 shows six likely cost scenarios the company may face in manufacturing of couplers. It is assumed that the maximum of 5000 parts/year can be manufactured.

Table 1. Scenarios Considered in Manufacturing Cost Calculations

Overhead Rate	Direct Labor: \$18.25/hr	Direct Labor: \$25.00/hr	Direct Labor: \$34/hr.
60%	Scenario 1	Scenario 2	Scenario 3
40%	Scenario 4	Scenario 5	Scenario 6

It is also assumed that the overhead rate fully covers all indirect costs of the company. In scenario 2 for example, direct labor rate of \$25/hr is inflated to  $25 \times (1 + 0.6) = \$40/\text{hr}$ . and then converted to \$ 0.67/min. as the loaded applicable labor rate. As an aid in performing student calculations pertinent equations are provided to students, as described in Appendix D.

Table 2 and Figure 5 show the cost reduction (learning) effect for doubled quantities of raw material. Forty-eight pieces of 20-lb cold rolled steel were purchased at the cost of \$22.25 each from a supplier that later refused to provide quotes for increased hypothetical purchase quantities for this project. Another supplier was willing to provide realistic quotes for increased hypothetical quantities to assist in manufacturing education. Power curves with decrease coefficients of 6.3% and 11.3% were fit to represent raw material cost at increasing quantities as shown in Figure 5. Then, a conservative value of 5% reduction for doubled quantities (95% learning or improvement effect) assumed in project calculations was justified with the real quote shown in Table 2. This information was another good manufacturing-related lesson for the students. Raw material cost consists of unit cost of steel and the labor cost of the supplier to cut 20 foot long steel bars into 10” sections. It was emphasized that 20 foot long steel bars were an input for local supplier who received them from a mill that produced these 20 foot long bars.

Table 2. Raw Material Quote to Illustrate the Reduction in Cost with Doubling Quantities

QTY	HR 1018				CD 1018			
	2016 Price/lb	Jan 2015 \$/lb	Labor/pc 2016 Total		Price/lb	Jan 2015 \$/lb	Labor/pc 2016 Total	
1	\$1.08	\$1.32	\$40.00	\$61.63	\$1.35	\$1.88	\$40.00	\$67.04
6	\$0.99	\$1.28	\$13.30	\$198.78	\$1.27	\$1.82	\$13.30	\$232.43
12	\$0.95	\$1.26	\$10.00	\$348.34	\$1.24	\$1.78	\$10.00	\$418.05
24	\$0.93	\$1.25	\$6.66	\$606.91	\$1.22	\$1.75	\$7.08	\$756.40
48	\$0.93	\$1.25	\$5.83	\$1,173.98	\$1.21	\$1.73	\$6.83	\$1,491.18
96	\$0.79	\$1.23	\$5.00	\$1,999.08	\$1.17	\$1.66	\$6.35	\$2,859.37
192	\$0.77	\$1.19	\$5.00	\$3,921.24	\$1.17	\$1.65	\$6.00	\$5,651.54
384	\$0.75	\$1.16	\$5.00	\$7,688.64	\$1.17	\$1.65	\$6.00	\$11,303.08
768	\$0.70	\$1.10	\$5.00	\$14,608.13	\$1.14	\$1.55	\$6.00	\$22,144.67
1536	\$0.58	\$0.72	\$5.00	\$25,524.33	\$0.91	\$1.28	\$6.00	\$37,213.13

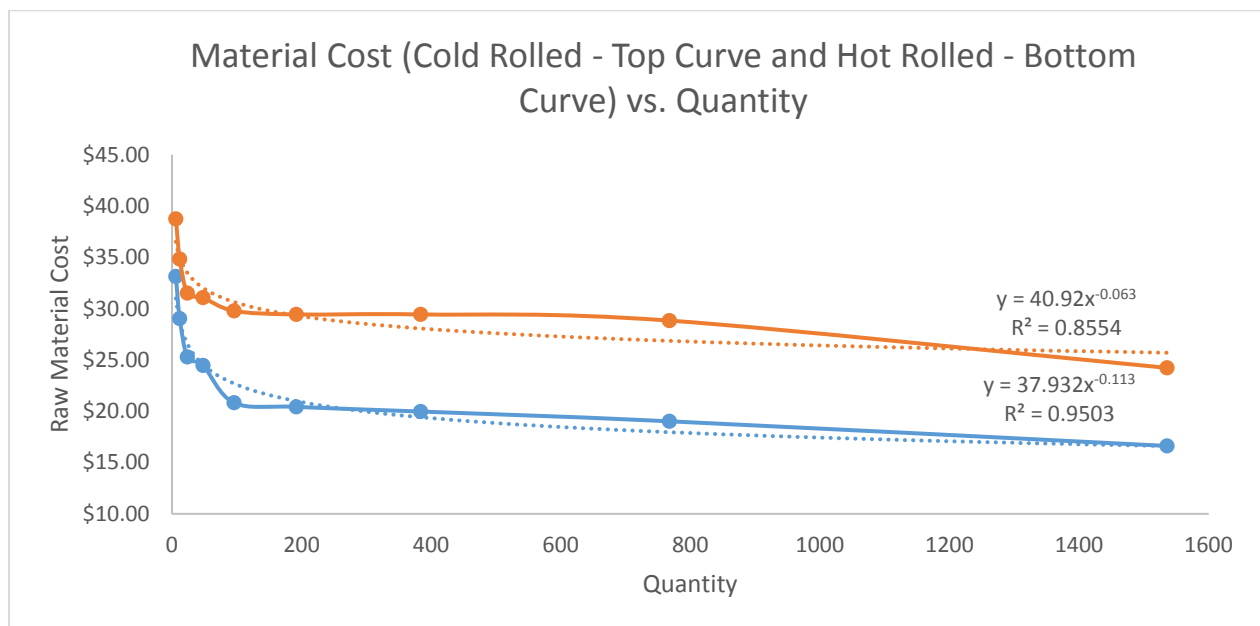


Figure 5. Reduction in Raw Material Unit Cost for Increasing Quantities

### Project Results

Using an assumed maximum annual plant capacity of 5000 couplers per year, manufacturing cost for increasing quantities were calculated using an Excel code shown in Appendix E. Student teams wrote this code with guidance from the instructor and the graduate assistant. Table 3 shows the individual and average costs for various quantities using cost scenarios 2 and 6. For example, the 10<sup>th</sup> unit will cost \$55.17 in scenario 2, but charging \$551.70 for 10 couplers would not be accurate. Instead, a moving average cost is used to provide more accurate and financially viable cost value of \$61.28 for the first 10 couplers for a total of \$612.80.



Table 3. Sample Item and Average Costs Using Cost Scenarios 2 and 6

Quantity Manufactured (X)	Cost of the X <sup>th</sup> Unit Scenario 2	Average Cost of X Units Scenario 2	Cost of the X <sup>th</sup> Unit Scenario 6	Average Cost of X Units Scenario 6
1	\$67.38	\$67.38	\$75.33	\$75.33
10	\$55.17	\$61.28	\$61.46	\$68.40
60	\$48.66	\$51.92	\$54.16	\$57.81
100	\$47.15	\$47.91	\$52.47	\$53.32
200	\$45.29	\$46.22	\$50.81	\$51.44
400	\$43.63	\$44.46	\$48.58	\$49.50
800	\$42.15	\$42.89	\$46.95	\$47.77
1200	\$41.35	\$41.75	\$46.08	\$46.52
1600	\$40.82	\$41.09	\$45.49	\$45.79
3000	\$39.72	\$40.27	\$44.30	\$44.90
4000	\$39.26	\$39.49	\$43.80	\$44.05
5000	\$38.91	\$39.09	\$43.42	\$44.05

The average cost could be calculated more accurately by using the individual costs of couplers 1 through 10, but this was deemed unnecessary. Figures 6 and 7 show decreasing average costs for increasing quantities for all six cost scenarios in Table 1. All average cost curves have high R<sup>2</sup> values indicating good statistical fits.

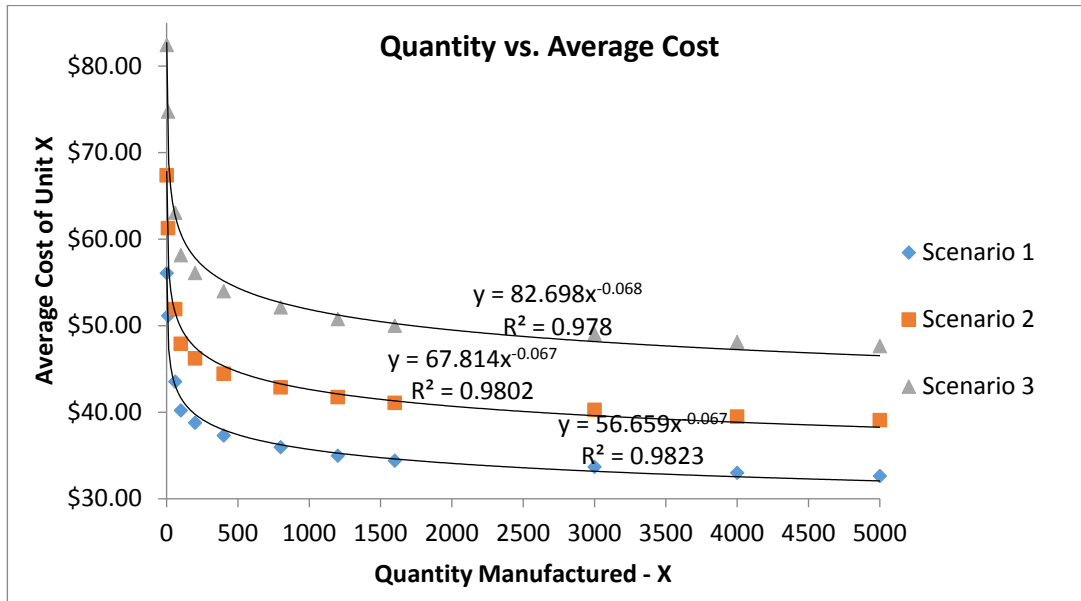


Figure 6. Average Cost Curves Under Learning Curve Effect for Scenarios 1, 2, and 3.

If, for example, scenario 2 applies to company's cost structure and a customer requests a quote for 550 couplers, the sales person could calculate the total estimated manufacturing using the middle equation in Figure 6 above. Using  $X = 550$ , the total estimated cost:  $550 * 67.814 * 550^{-0.067} = \$24,439$ . There is no reason for the sales person to have access to detailed cost and manufacturing process information presented in Excel spreadsheets in Appendix E. Such information is often a company trade secret that should be guarded. The sales person would now add an applicable profit margin and a commission before presenting a quote to an interested customer. For example, the quote with an overall profit and commission factor of 32% is  $1.32 * 24,439 = \$32,260$ . Customer's cost per unit is  $\$32,260 / 550 = \$58.66$  excluding tax and the shipping cost if it is not included in the overhead cost. This amount reflects a direct cost item in the final product of the customer who may use the coupler in assembling and/or constructing another product.

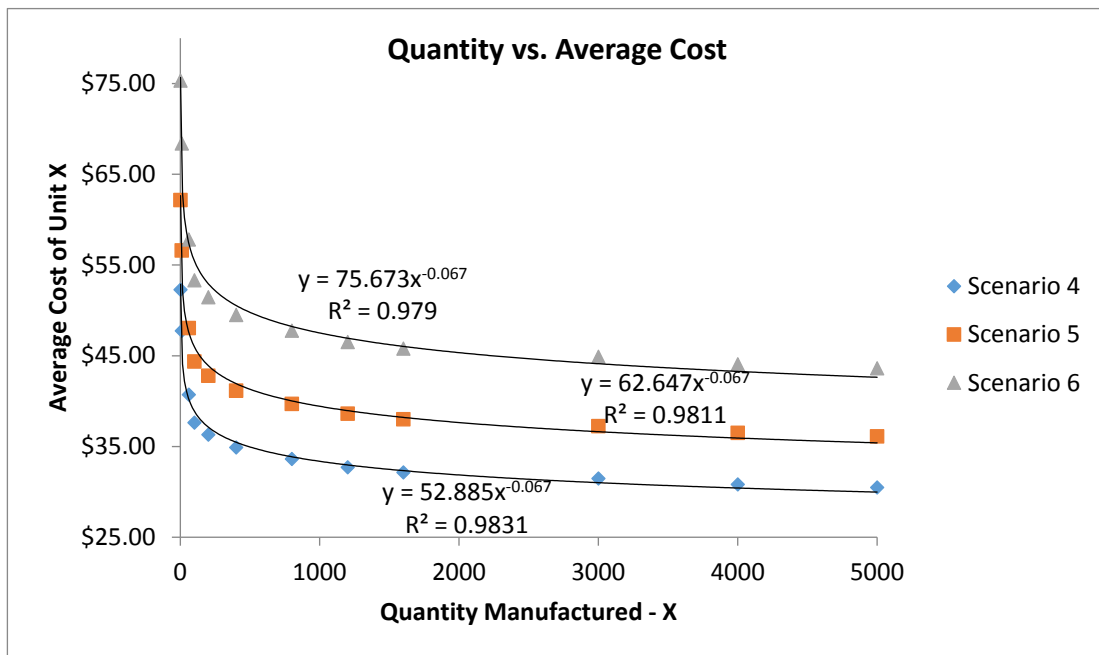


Figure 7. Average Cost Curves Under Learning Curve Effect for Scenarios 4, 5, and 6

### Lessons Learned and Educational Impact

The learning outcomes of this project include an understanding of how the physical experiments and analytical calculations can yield almost the same values in manufacturing. Other learning outcomes include gaining a firm belief that engineering data is often resource intensive, facility dependent, and it must be carefully recorded and saved for future use. Documentation of lessons learned is a major learning outcome also. Students received a practical introduction to many engineering concepts they will encounter later on.

As mentioned earlier, there were several educational goals expected of this project: 1) develop team work skills, 2) gain appreciation for future coursework in physics, statics, dynamics, and thermodynamics, 3) get an early understanding of the role of experimental and analytical approaches to solve engineering problems, 4) gain practice in writing technical team reports, 5) experience a “real life” like hands-on engineering project from start to finish, 6) learn about manufacturing in general, 7) excite students about engineering and manufacturing and improve overall retention rate of this cohort. These educational goals above were either accomplished or it is too soon to tell as in the case of goal 7 that seeks to improve retention. Team reports show that goals 1, 3, 4, and 5 were accomplished at various levels that ranged from fair to excellent. Teams were required to meet with the instructor and/or the graduate assistant to go over draft versions. Anonymous exit survey taken on the last day of classes indicate that a majority (70%) of the students felt this project was a very good learning experience for all the goals above.

In addition, substantial qualitative evidence suggests that this project had a positive impact on student learning and retention. Positive student comments about the project were not just limited to student exit survey and course evaluations. The instructor kept receiving positive feedback from those who somehow heard about this project. Some of the 215 students enrolled in spring and fall 2016 lab sections chose to enroll selectively so that they can participate in this project. Here are some of student testimonials.

*“In the end the experience I garnered from this will be invaluable moving forward in my MET career. Having 20 years of manufacturing experience with 10 of those years spent as a machinist, I can absolutely see the value in this project. I will be holding on to these formulas and experiences for future use as I hope one day to run my own machine shop. This exercise gave me a glimpse of the large amount of work that goes into the manufacturing and pricing of parts before a sale has even been made.”*

*“This project gave us an incredible opportunity to see what it is like to manufacture a product and the style of which engineers do business. It was predominantly related to the field of manufacturing engineering, and it was a tremendous experience to be given to us.”*

*"This project introduced challenging concepts for all students, from the massive amount of calculations to the direct and indirect costs of manufacturing. We know the factors that directly affect cost such as material and labor; however, we were exposed to the indirect costs as well, things that do not directly correlate with machining the part, which we would have never thought of if not for this project."*

*“This project was a perfect project for first semester engineering students like ourselves. To give us experience that is based off of real life situations is a great thing to do. We all know there is a lot of math that comes with engineering but this project showed that engineering can be just as much business than it is math and problem solving. Making us*

*take in every encounter that effect cost such as overhead. This project required us to actually go to the machine shop and actually watch what goes into making the actual products for costumers. We did not have any hands on experience with creating but we still had more experience than other people just now starting engineering. This semester is ending soon but the knowledge and experience that was taught this semester will last forever”.*

## **Conclusions and Recommendations**

During the course of this project students observed machining operations, collected data in the machine shop, and performed machining cost calculations using Microsoft Excel. Students were able to get a very good understanding of manufacturing-related engineering problems and cost accounting concepts including applications of learning curves. Students’ self-reflections indicated excitement when working on “real life” engineering projects suggesting increased motivation resulting in increased retention rates. Due to long cutting times caused by mechanical properties of steel, aluminum should be used as raw material instead. In addition, when using steel, certain feed and speed combinations could not be used due to high cutting forces that result. Lower material toughness of aluminum should alleviate this problem.

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## APPENDIX A. MANUFACTURING PROCESSES & OPERATION TIME DATA

This appendix shows operations' times for each of four parts produced. Although identical speeds and feeds were used, finished dimensions were not identical as one would expect. The average starting weight of the raw material was 19.995 lbs. The average finished (pre-paint) part had a weight of 10.738 lbs. Students were able to observe and visualize how subtractive or traditional manufacturing works: value was added as material was removed.

### FALL 2016 - LABORATORY DATA FOR ENGN 110 PROJECT 3 - MANUFACTURING & COST ANALYSIS OF A STEEL COUPLER

MATERIAL: Cold Rolled 1018 Mild Steel Stock.

Part 1) Starting  $W_0$  : 20.10 lbs;  $D_0$  : 3.0000 inches;  $L_0$  = 10.000 inches  
 Part 2) Starting  $W_0$  : 19.93 lbs;  $D_0$  : 2.9999 inches;  $L_0$  = 10.000 inches  
 Part 3) Starting  $W_0$  : 19.93 lbs;  $D_0$  : 3.0000 inches;  $L_0$  = 10.003 inches  
 Part 4) Starting  $W_0$  : 20.02 lbs;  $D_0$  : 2.9950 inches;  $L_0$  = 10.065 inches

**A) Center Drill Operation (0.5 min) and Turning Operation** to reduce diameter to 2.25" for a 7" long section PART 1

Machine Tool: *Engine Lathe* Power: 7.5 hp Tool : *Carbide insert – three edges*

<b>Inputs (1,2,3) and Outputs (4, 5, 6, 7)</b>	<b>Pass 1</b>	<b>Pass 2</b>	<b>Pass 3</b>
1) Spindle speed (N) rev/min or rpm	260	350	470
2) Feed Rate (f) in/rev or ipr	0.008	0.012	0.016
3) Depth of cut (c) in inches	0.200	0.125	0.0435
4) <i>Observed time to cut in min:sec</i>	3:27	1:46	0:50
5) <i>Diameter after the cut (<math>D_i</math>) in inches</i>	2.595	2.337	2.255
6) <i>Length of the cut in inches</i>	7	7	7
7) <i>Weight after the cut (<math>W_i</math>) in pounds</i>	16.60	14.61	14.05

**B) Drilling Operation** 2" deep 1.75" diameter hole on the side of the stock that remains as 3" dia.

Machine Tool: *Engine Lathe* Power: 7.5 hp

Step 1: Center Hole Tool : *Center drill* Time: *0.5 min.*

Step 2: Pilot Hole Tool: *0.75" drill* f = hand N = 260 rpm Time : 1:28 Weight After 13.78 lbs

Step 3: Final Hole Tool: *1.75" drill* f = hand N = 108 rpm Time 1:49 Weight After 12.74 lbs.

**A) Center Drill Operation (0.5 min) and Turning Operation** to reduce diameter to 2.25” for a 7” long section PART 2

Machine Tool: *Engine Lathe* Power: 7.5 hp Tool : *Carbide insert – three edges*

<b>Inputs (1,2,3) and Outputs (4, 5, 6, 7)</b>	<b>Pass 1</b>	<b>Pass 2</b>	<b>Pass 3</b>
1) Spindle speed (N) rev/min or rpm	260	350	470
2) Feed Rate (f) in/rev or ipr	0.008	0.012	0.016
3) Depth of cut (c) in inches	0.200	0.125	0.033
4) <i>Observed time to cut in min:sec</i>	3:22	1:45	0:48
5) <i>Diameter after the cut (Di) in inches</i>	2.585	2.315	2.254
6) <i>Length of the cut in inches</i>	7	7	7
7) <i>Weight after the cut (Wi) in pounds</i>	16.63	14.36	13.95

**B) Drilling Operation** 2” deep 1.75” diameter hole on the side of the stock that remains as 3” dia.

Machine Tool: *Engine Lathe* Power: 7.5 hp

Step 1: Center Hole Tool : *Center drill* Time: *0.5 min.*

Step 2: Pilot Hole Tool: *0.75” drill* f = hand N = 260 rpm Time 1:24 Weight After 13.68 lbs

Step 3: Final Hole Tool: *1.75” drill* f = hand N = 108 rpm Time 1:56 Weight After 12.60 lbs.

**A) Center Drill Operation (0.5 min) and Turning Operation** to reduce diameter to 2.25” for a 7” long section PART 3

Machine Tool: *Engine Lathe* Power: 7.5 hp Tool : *Carbide insert – three edges*

<b>Inputs (1,2,3) and Outputs (4, 5, 6, 7)</b>	<b>Pass 1</b>	<b>Pass 2</b>	<b>Pass 3</b>
1) Spindle speed (N) rev/min or rpm	260	350	470
2) Feed Rate (f) in/rev or ipr	0.008	0.012	0.016
3) Depth of cut (c) in inches	0.200	0.125	0.0425
4) <i>Observed time to cut in min:sec</i>	3:18	1:45	0:52
5) <i>Diameter after the cut (Di) in inches</i>	2.595	2.335	2.255
6) <i>Length of the cut (Li) in inches</i>	6.990	6.990	6.990
7) <i>Weight after the cut (Wi) in pounds</i>	16.37	14.55	13.86

**B) Drilling Operation** 2” deep 1.75” diameter hole on the side of the stock that remains as 3” dia.

Machine Tool: *Engine Lathe* Power: 7.5 hp

Step 1: Center Hole Tool : *Center drill* Time: *0.5 min.*

Step 2: Pilot Hole Tool: *0.75” drill* f = hand N = 260 rpm Time 1:22 Weight After 13.59 lbs

Step 3: Final Hole Tool: 1.75" drill f = hand N = 108 rpm Time 1:42 Weight After 12.54 lbs.

A) **Center Drill Operation** (0.5 min) **and Turning Operation** to reduce diameter to 2.25" for a 7" long section PART 4

Machine Tool: *Engine Lathe* Power: 7.5 hp Tool : *Carbide insert – three edges*

<b>Inputs (1,2,3) and Outputs (4, 5, 6, 7)</b>	<b>Pass 1</b>	<b>Pass 2</b>	<b>Pass 3</b>
1) Spindle speed (N) rev/min or rpm	260	350	470
2) Feed Rate (f) in/rev or ipr	0.008	0.012	0.016
3) Depth of cut (c) in inches	0.200	0.125	0.0527
4) <i>Observed time to cut in min:sec</i>	3:28	2:10	0:50
5) <i>Diameter after the cut (Di) in inches</i>	2.609	2.350	2.248
6) <i>Length of the cut (Li) in inches</i>	6.980	6.980	6.980
7) <i>Weight after the cut (Wi) in pounds</i>	16.64	14.65	13.93

B) **Drilling Operation** 2" deep 1.75" diameter hole on the side of the stock that remains as 3" dia.

Machine Tool: *Engine Lathe* Power: 7.5 hp

Step 1: Center Hole Tool : *Center drill* Time: *0.5 min.*

Step 2: Pilot Hole Tool: *0.75" drill* f = hand N = 260 rpm Time 1:20 Weight After 13.67 lbs

Step 3: Final Hole Tool: *1.75" drill* f = hand N = 108 rpm Time 1:25 Weight After 12.61 lbs.

All four parts had identical times on the HASS machine.

C) **Milling Operation** 0.84" deep 3" long slot on the 2.25" diameter end of the part.

Machine Tool: *HASS Mini Mill 2* Power: 7.5 hp Tool : *4-tooth 1.5" diameter face mill*

Making profile cuts using face milling

<b>Input/Output</b>	<b>Pass 1</b>	<b>Pass 2</b>	<b>Pass 3</b>	<b>Pass 4</b>
Speed (N) rpm	1100			
Depth of cut - in	0.21			
Active Feed (ipm)	8.8			
Chip load (ipt)	0.004			

**Total Observed Milling Time :** 9:00 min for 4 passes **Max Observed Power Use :** 2.2 kW



**D) Drilling Operation** on the milled surface - 1.5" dia through hole centered 1.5" from the tip

Machine Tool: *HASS Mini Mill 2* Power: 7.5 hp

Step 1: Pilot Hole Tool : 0.75" drill

Using a 0.75" diameter drill bit in 15 pecks. Chip Load: Active feed:

Step 2: Final Hole Tool: 0.5" end mill N = 2673 rpm :

The end mill spirals to enlarge the hole to 1.5" diameter. Chip load (ipt) : 0.0028 feed rate: 14.97.

**Total Observed Drilling Time: 4:00 Max Observed Power Use : 3.4 kW**

**E) Drilling Set Screw Hole** on the 3" diameter end of the part, two 0.375" diameter holes centered 1" from the end are drilled.

Machine Tool: *HASS Mini Mill 2* Power: 7.5 hp

Step 1 : Center Hole Tool: 0.375" Center drill to center hole due to sloped surface.

Step 2: Final Hole Tool: 0.375" drill  $f = 2.88$  N = 791 rpm

**Total Observed Drilling Time: 2:00**

**Total Observed Time on the HASS Milling Machine: 15:00 minutes for 3 operations.**

Final Weight : 10.86 lbs (part 1), 10.74 lbs (part 2), 10.65 lbs (part 3), 10.75 lbs (part 3)

**Deburr /Sanding Operation: 2 minutes**

**Paint Operation - Primer + Final paint using spray can: 3 minutes.**

Painted shipping weight: 10.89, 10.77, 10.67, and 10.77 lbs for parts 1, 2, 3, and 4.

## APPENDIX B. SAMPLE PROJECTED USE DEPICTIONS

Each team was required to come up with a proposed use for this steel product called “Coupler”. The goal was to come up with a meaningful hand drawn depiction of a potential use for this product. This appendix shows some proposed sample uses.

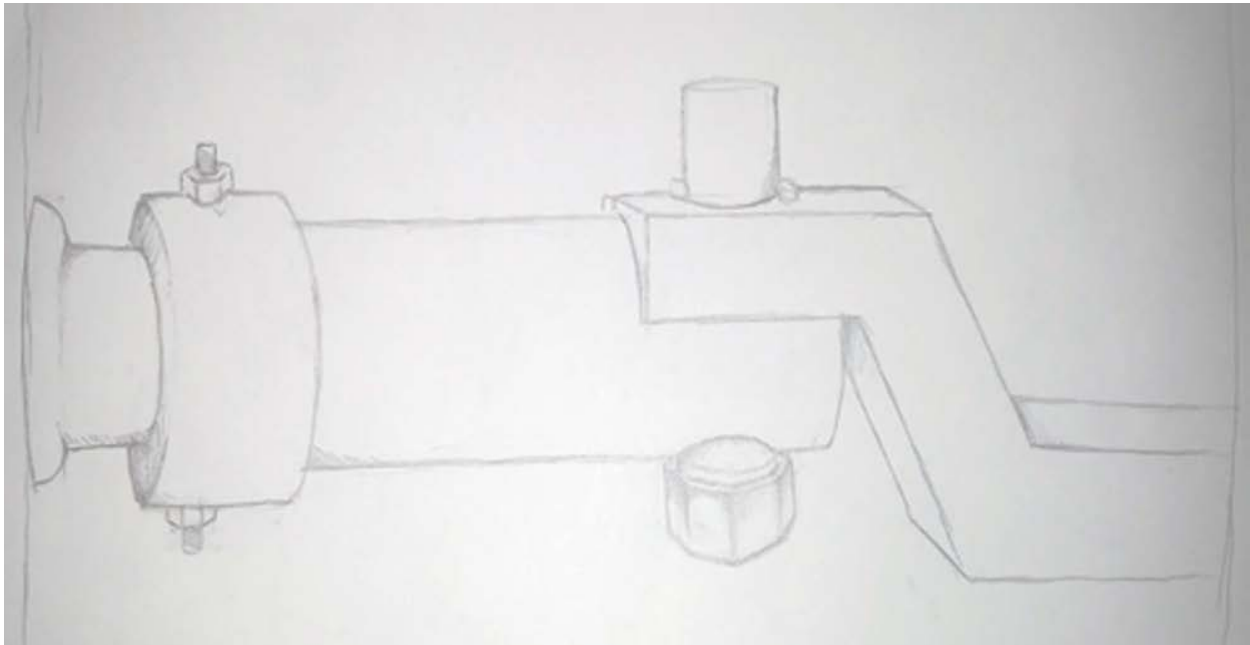


Figure A.1. Sample Use of the Coupler: Truck-Trailer Connection (close up)

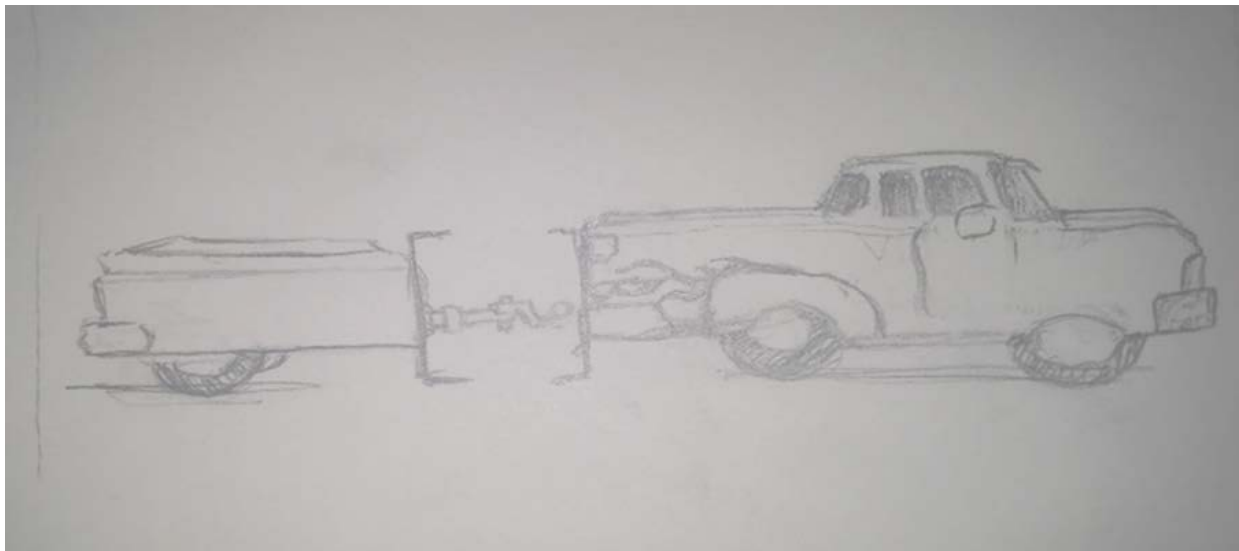


Figure A.2. Sample Use of the Coupler: Truck-Trailer Connection

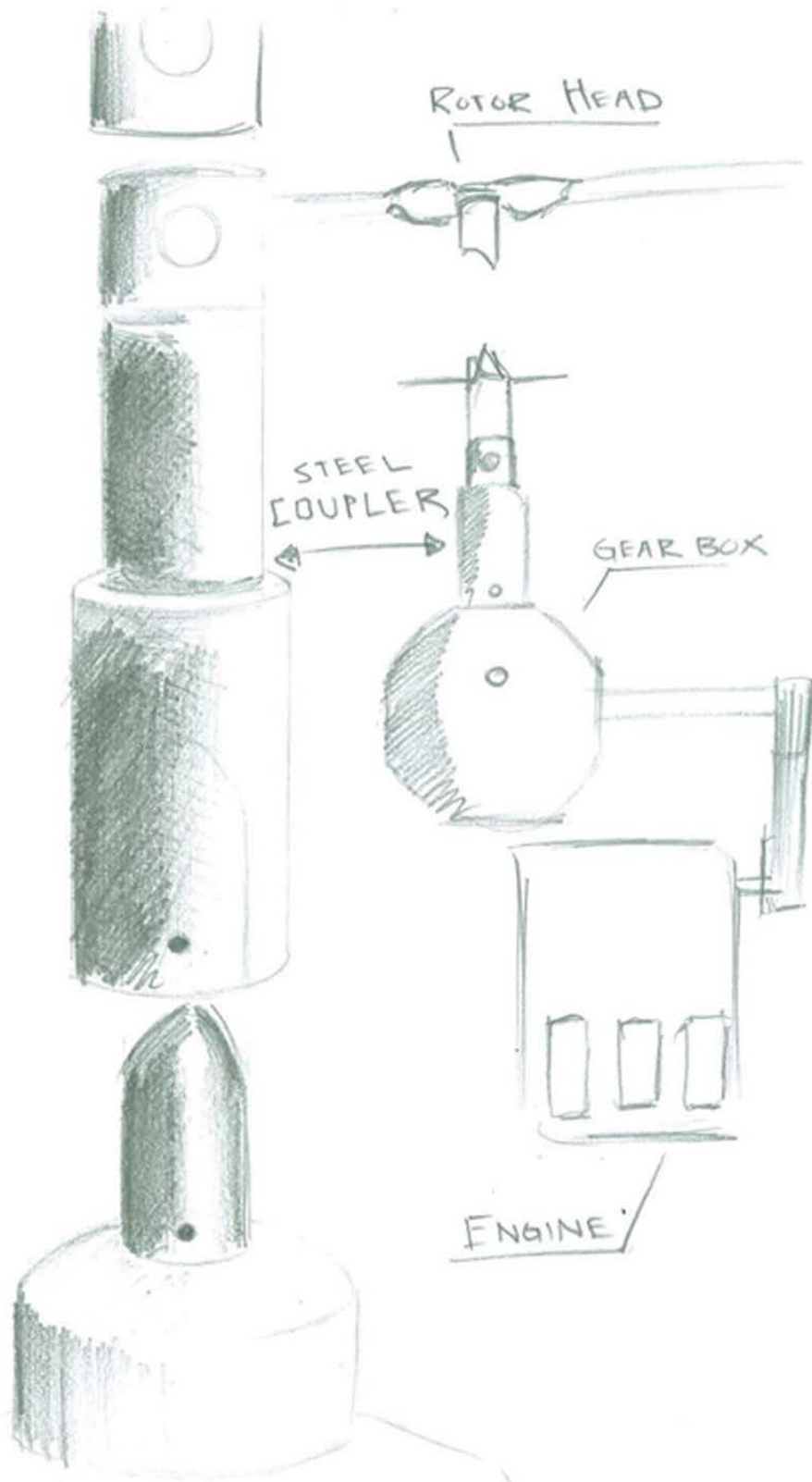


Figure A.3. Sample Use of the Coupler: Gear Box – Rotor Head Connection

## APPENDIX C. SAMPLE MACHINING OPERATIONS PICTURES

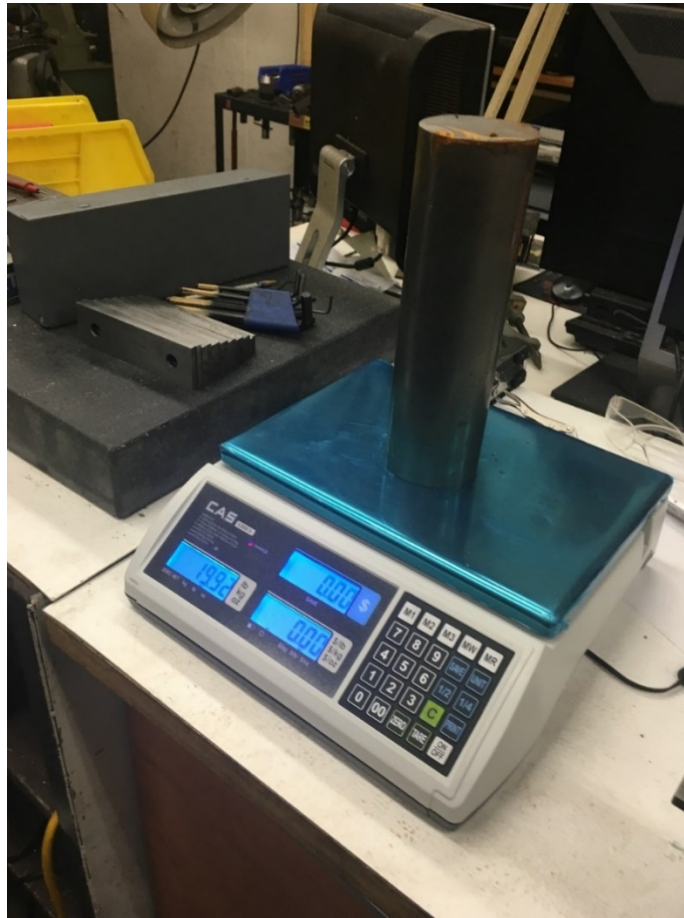


Figure A.4. A Random Part is Weighed

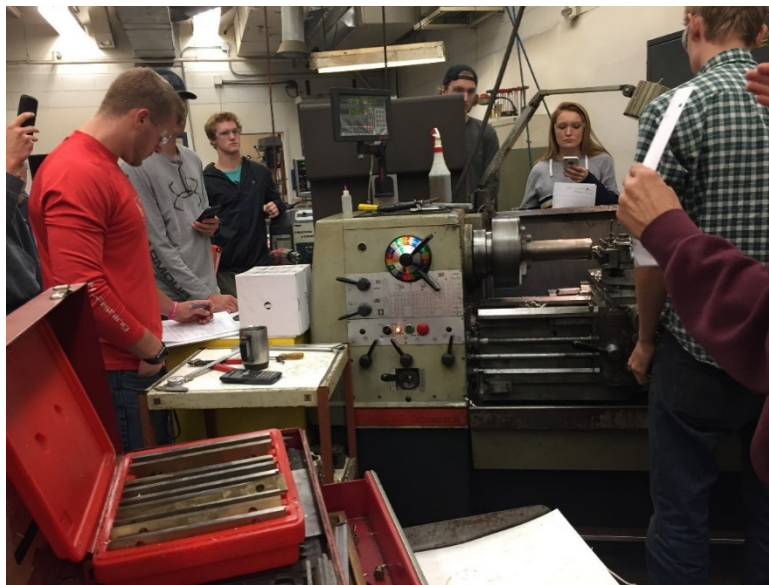


Figure A.5. Students Gather around the Operator

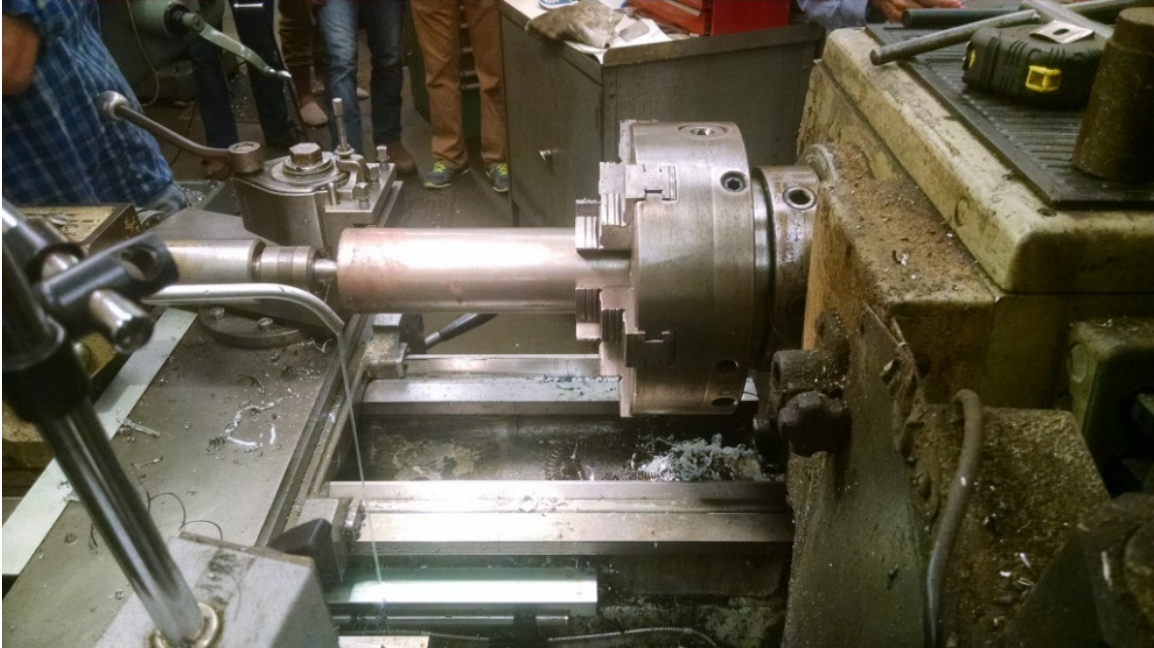


Figure A.6. Turning Operation on a Lathe

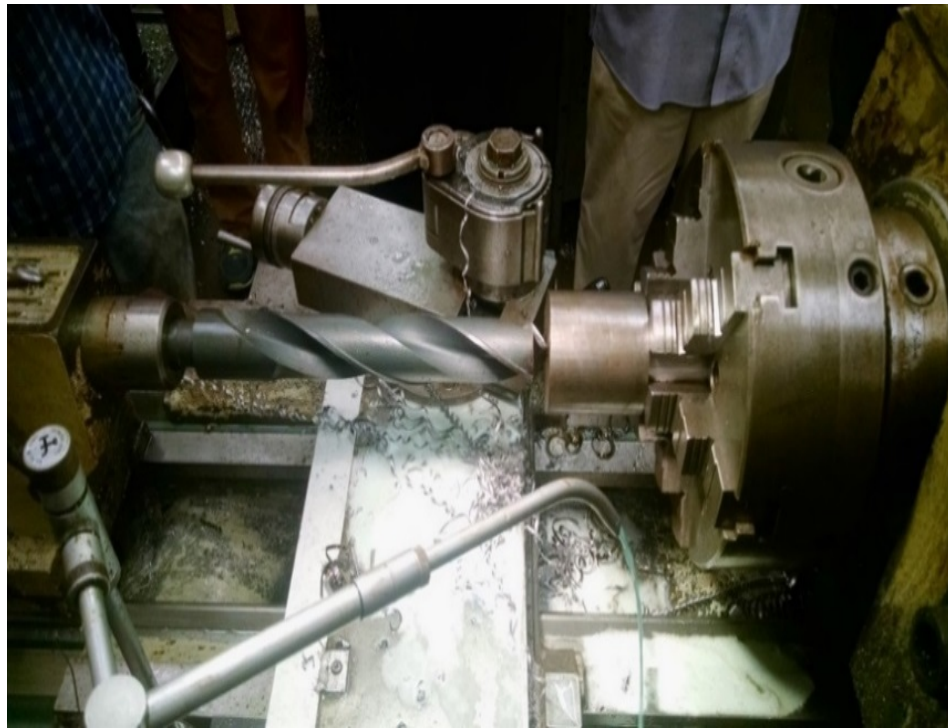


Figure A.7. Drilling on the Same Lathe

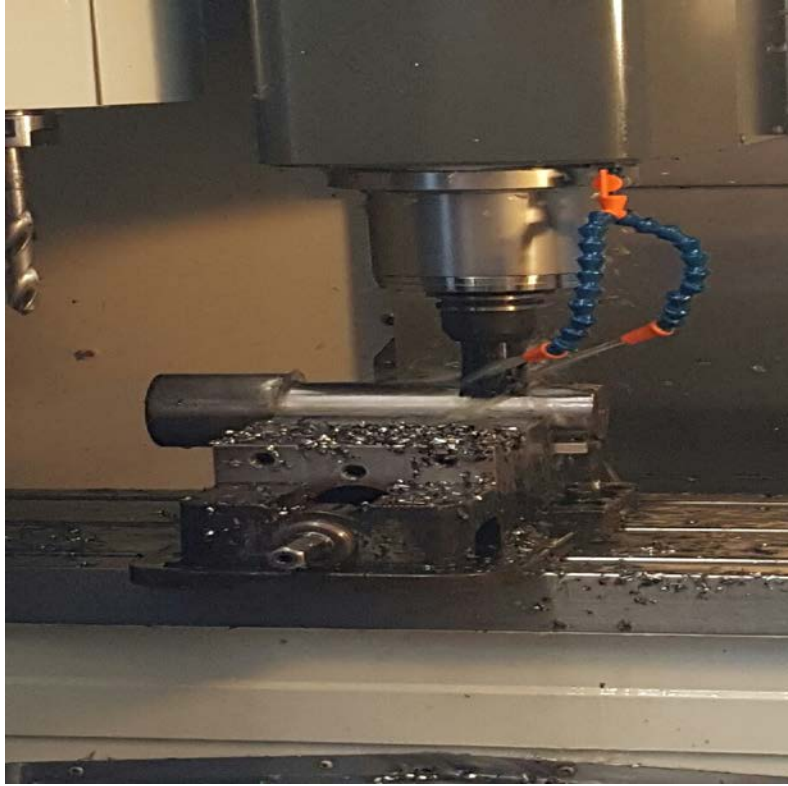


Figure A.8. Milling and Drilling Operations on the HASS CNC Machine.

## APPENDIX D. EQUATION LIST FOR PROJECT COST CALCULATIONS

### Definition of Variables:

N: Spindle speed in revolutions/minute (RPM)  
f : Feed rate for turning and drilling in inches per revolution (ipr)  
c : Depth of cut in turning (inches)  
k = 12 in/ft  
V<sub>c</sub>: cutting speed in feet/min  
D: diameter (inches)  
D<sub>b</sub> : Diameter before the cut in turning (inches)  
CT: cutting time per pass in turning (minutes)  
L: length of cut or depth of hole (inches)  
A: allowance or starting offset (1/8")  
Q: Material Removal Rate (MRR) in cubic inches/min  
F<sub>c</sub>: Cutting force in turning (pounds)  
T : Thrust in drilling (pounds)  
M : Torque in drilling (in-lbs)  
C<sub>f</sub>: A constant of 120,000  
a : constant of 0.8  
b: constant of 0.9  
P<sub>c</sub>: Power to cut (hp)  
P<sub>u</sub>: unit power (1.5 for 1018 Steel)  
E: Machine efficiency (0.8)  
F = Feed for milling in inches/min  
K = A constant of 24000  
Density = 0.2814 lbs/in<sup>3</sup> (1018 steel)

### Equations Used:

1.  $V_c = \frac{N * \pi * D_b}{k}$
2.  $CT = \frac{(L+A)}{f * N}$
3. MRR for Turning:  $Q \approx k * V_c * f * c$
4.  $F_c = C_f * f^a * c^b$
5.  $P_c = P_u * Q$
6.  $P_c = \frac{F_c * V_c}{33,000}$  (Turning)
7. Final  $P_c = \text{Avg. \#5 \& \#6}$
8.  $P_{\text{motor}} = \frac{P_c}{E}$
9.  $P_{\text{kw}} = P_{\text{motor}} * 0.746$
10. Energy (kWh) = cutting time (hr) \*  $P_{\text{kw}}$



11. Time to drill =  $\frac{L+(A)+(A)}{f*N}$
12. MRR for Drilling:  $Q = \pi \left(\frac{D^2}{4}\right) * f * N$
13.  $T = 2 * K * f^{0.8} * D^{0.8} + 625 * D^2$
14.  $M = K * f^{0.8} * D^{1.8}$
15. Power in Drilling :  $P_c = \frac{M*N}{63,025}$  (hp)      For Milling:  $P_c = MRR*Specific\ HP$
16. MRR for Milling :  $Q = Depth * Width * Feed$  (milling)
17. Actual Depth of cut = (Difference in successive diameters)/2
18. Actual MRR = ((Difference in successive weights)/Density)/ Actual Cutting Time

### COST CALCULATIONS

19.  $C_m$  (Material Cost) = (Initial Cost) \* [ ( Quantity<sup>ln(phi-m)/ln(2)</sup> ) ]  
 95% discount curve (phi-m = 0.95) is applied for doubled quantities  
 $Y = A X^B$  where A is the initial raw material cost, X is the quantity count, and  $B = \ln 0.95/\ln 2$

**PART HANDLING FACTOR:** A percent of the direct labor time to account for the indirect times in processing each part. This factor is assumed to be 100% for the first part based on anecdotal evidence. This factor improves as more parts are manufacturing according to an 85% learning curve.

20. Part Handling Factor = (Initial Handling Factor) \* [ ( Quantity<sup>ln(phi-p)/ln(2)</sup> ) ]  
 85% learning curve (phi-p = 0.85) is applied for doubled quantities  
 $Y = A X^B$  where A is the initial handling factor, X is the quantity count, and  $B = \ln 0.85/\ln 2$

21. Part Handling Factor is subject to 85% learning curve for doubled quantities
22. Total Labor Time = Total Direct Labor Time \* (1 + Part Handling Factor)

**OVERHEAD FACTOR:** A percent of the direct labor cost charged to cover general overhead expenses as explained in Table 1 above.

23.  $C_l$  (Labor Cost ) = Direct Labor Rate (1 + Overhead Factor) \* Total Labor Time
24.  $C_t$  (Tool Cost) = { (Cost of a three insert pack)/ [ (edges/pack)\*(Parts Turned/Edge)] }  
 + Paint Cost.

Note: Drill and milling cutter costs are assumed to be in overhead cost.

25.  $C_m$  (Energy Cost) = Total Energy in kWh \* Unit Energy Cost in \$/kWh
26.  $C_i$  (Total Part or Item Cost) =  $C_m + C_l + C_m + C_t$
27. Sales Price =  $C_i * (1 + Markup\ Fraction)$

## APPENDIX E. EXCEL CODE USED IN CALCULATIONS

U.S. STANDARD UNITS  
 ARE USED  
 ENGN 110 COST CALCULATION OF A MANUFACTURED PART UNDER LEARNING CURVE EFFECT TEAM PROJECT  
 OLD DOMINION UNIVERSITY - NORFOLK, VA

		PART is						
		1018 Steel-Cold Rolled		Allowance(A): 0.125				
		10" Long 3" Dia						
		at start (nominal)						
		Fall 2016						
		Sample 1						
		Input						
OPERATION	Pass Name or Number	Spindle Speed [N-Rev/Min or RPM]	Tool Feed (f-in/rev or ipr)	Depth of Cut (c-inches)	Ending Diameter (D- inches)	Ending Weight (W-pounds)	Ending Length (L-inches)	Observed Time (minutes)
Turning (Step A)	0-start	n/a	n/a	n/a	2.995	19.93	10.00	n/a
	1	470	0.006	0.1250	2.755	17.73	7.00	2.27
	2	260	0.010	0.1880	2.363	14.64	7.00	2.80
	3	350	0.014	0.0565	2.253	13.86	7.00	1.37
Drilling (Step B)	0-start	n/a	n/a	n/a	n/a	13.86	n/a	n/a
	Center hole	n/a	n/a	n/a	n/a	13.86	n/a	0.50
	Pilot hole	350	0.005	n/a	0.5	13.74	2.00	1.20
	Final hole	108	0.010 (manual feed)	n/a	1.75	12.69	2.00	2.00
Milling (Step C)								
Drilling (Step D)								
Drilling (Step E)								
Deburr/Sand/Center Drill								
Painting (prime + final)								
				Final Weight		lbs		
				Number of Passes:		4		Total time: 9.00
				Total Depth of Cut:		0.840		in (for milling)
								4.00
								2.00
								3.00
								3.00

ENGN 110 COST CALCULATION OF A MANUFACTURED PART UNDER LEARNING CURVE EFFECT TEAM PROJECT  
 OLD DOMINION UNIVERSITY - NORFOLK, VA

U.S. STANDARD UNITS  
 ARE USED

Density (lb/inch cube) : **0.2814**  
 Specific HP : **1.5**      Motor Efficiency: **0.8**

OPERATION	Cutting Speed (Eq.1) (Vc-feed/min or fpm)	Calculated Cutting Time (Eq. 2) (minutes)	Average Cutting Time (minutes)	Actual Depth of Cut - c - Eq. 17 (inches)	Calculated Material (Q) Removal Rate (Eq. 3) (cubic inches/min)	Actual MRR (Calculated via Weight Difference) Eq. 18 (cubic inches/min)
Turning (Step A)	n/a	n/a	n/a	n/a	n/a	n/a
	368.5	2.53	2.40	0.120	3.18	3.444
	187.5	2.74	2.77	0.196	4.41	3.922
	216.5	1.45	1.41	0.055	2.00	2.023

use actual c

Total Turning Time: **6.58**

Use Eq. 11  
 0.5 for center hole

Drilling (Step B)	n/a	n/a	n/a	n/a	Eq.12 n/a	n/a
	n/a	0.50	0.50	n/a	n/a	n/a
	n/a	1.29	1.24	n/a	0.34	0.36
	n/a	2.08	2.04	n/a	2.25	1.87

Total Drilling Times : **3.78**  
 (deduct the pilot hole Q from the final Q)

Eq. 16

Milling (Step C)	min (observed)	n/a	<b>9.00</b>	n/a	(width*feed*depth per cut) (not equal to total depth, they look the same)	Excludes stops in milling. Do not use
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**4.00**

**2.00**

min (observed)

min (assumed)

Deburr/Sand/Center Dri

Painting (prime + final)

ENGN 110 COST CALCULATION OF A MANUFACTURED PART UNDER LEARNING CURVE EFFECT TEAM PROJECT  
 OLD DOMINION UNIVERSITY - NORFOLK, VA

U.S. STANDARD UNITS  
 ARE USED

OPERATION	Average MRR (cubic inches/min)	Cutting Force (Pounds) via Eq. 4	Torque (inch-pounds)	Power 1 (Eq.5) (hp)	Power 2 (Eq.6) (hp)	Average Power (Eq.7) (hp)	Power at Motor (Eq.8) avg. power/ motor efficiency (hp)	Energy/ Cut (Eqs. 9, 10) (kwh)
<b>Turning (Step A)</b>	n/a	n/a	n/a	Use Average Q				
	3.31	297.14	n/a	4.97	3.32	4.14	5.18	0.15
	4.17	695.36	n/a	6.25	3.95	5.10	6.38	0.22
	2.01	290.01	n/a	3.02	1.90	2.46	3.08	0.05
		use actual c		use avg MRR				Use avg time 0.43 kwh
<b>Drilling (Step B)</b>								
	n/a	n/a	Eq.14	Eq.15			Eq.8	
	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	0.35	554	99	0.55	n/a	0.55	0.69	0.01
	2.06	3801	1651	2.83	n/a	2.83	3.54	0.09
<b>Milling (Step C)</b>	Q	n/a	n/a	Eq. 5	blank	1.80 (already in kW)	Eq. 8	0.10 kwh
	use the calculated MRR				blank		2.25	0.3375 kwh
							Total Energy = for all cuts	(per pass or cut) 1.35 kwh
<b>Drilling (Step D)</b>						3.4 (already in kW)	4.25	0.28 kwh
<b>Drilling (Step E)</b>						1.1 (Assumed and in kW)	1.375	0.05 kwh
<b>Deburr/Sand/Center Drill</b>								
<b>Painting (prime + final)</b>								

Convert  
 hp to kW: 0.746

Energy=  
 Power(kW)\*time(hours)

