

Adapting a Freshman Manufacturing Course to Different Learning Styles

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Lisa Carlson is the Director for Women in Science and Engineering, at South Dakota School of Mines and Technology. Ms. Carlson earned her Bachelor of Science in Business Administration- Marketing, at Black Hills State University, and her Master of Business Administration at Chadron State College. Working mainly with women's issues at the university, Ms. Carlson established a women's mentoring program for first year students at the university, and just recently established a women's center at SD Mines - the first to exist on any South Dakota university campus.

Mr. Eric Jon Holmgren

Originally graduating with a BA in Studio Art from St. John's University in 2004, Eric Holmgren relocated to Minneapolis, MN and found work in the publishing industry. For several years he worked as a bindery and press operator until a junior software developer position opened. With his self-taught technical background, including Linux and networking, he excelled in this position and over time became the development manager at the company known as BookMobile.

Being a Rapid City, SD native, Eric was well aware of South Dakota School of Mines & Technology's reputation and had always regretted not attaining an engineering degree there. In fall of 2013, this became a reality when he returned to Rapid City to attend SDSM&T full time as an undergraduate mechanical engineering student. As of fall 2016, he will be a graduating senior with many years of active participation in the campus machine shop and as a member of the Baja SAE team.

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Introduction

Our mechanical engineering curriculum includes a freshman course in Design For Manufacturing (DFM). This course introduces project management skills via a curriculum employing project-based learning. These skills include product design, resource planning, process planning and cost analysis, but the primary focus is in producing a design that is manufacturable. The most recent offering of this course gives the student an option of lab series in which to develop the concepts of DFM. One series uses manual machining processes and the other uses Computer Numerical Control (CNC) manufacturing. Ideally each student can learn using the method they are most comfortable with and improve self-efficacy.

As part of the most recent semester we conducted a student self-efficacy survey in both the original and alternative DFM paths. The hope is that allowing the student to choose a lab path more suited to their learning style will create a higher level of self-awareness of design for manufacturing while building self-confidence.

History and motivation

Our department created our DFM course two years ago¹. The first eight weeks of the semester included hands on training in various manufacturing processes: woodworking, welding, manual turning and manual machining. During the second half of the semester the students completed design projects. The grading of the student projects was based on the print quality, resource planning, process plan, cost analysis, and consideration of manufacturing processes.

Based on assessments conducted at the conclusion of the first semester, it was evident that the students had gained a fundamental understanding of DFM. Additionally, the majority of the students showed a high level of interest in learning how to operate the manufacturing equipment, particularly the machining equipment (lathes, mills). However, based on anecdotal student feedback, it was also evident that a smaller but significant percentage of students were not interested in and were somewhat intimidated by the hands-on operation of machining equipment. Since the goal of the class is the understanding of manufacturing processes for engineering purposes and not the training of machinists, a curricular alternative was proposed.

In the DFM class, 3D printers were made available for prototyping component parts; however prototyping was not a course requirement. We observed that the majority of the students who utilized the 3D print option were the same students who were not interested in operating machining (machine shop) equipment. We decided, therefore, that 3D print applications would become the building block for the alternate DFM lab path series. Although the manufacturing concerns with 3D print are different from other manufacturing processes, the fact is every manufacturing method has unique concerns. 3D print offers students the opportunity to develop a cost analysis and process plan similar to the requirements of traditional manufacturing processes, for the 3D print projects, we require a set of fully dimensioned drawings.

In addition to a 3D print project, the DFM alternate path includes computer numerical control (CNC) machining, 2D graphic design and 3D graphic design. We added these curricular elements to the alternative path because CNC is similar to 3D print in that a solid model is used to generate machine control to fabricate a part, albeit a prototype with the 3D printer. Also, CNC uses a machine (a mill or lathe in our case), tooling and methods similar to the manual machining lab in the original DFM course. The graphic design labs were included because they build on the solid modeling skills required for 3D print and CNC machining and also provide training valuable to practicing engineers – that of presenting complex ideas based on solid models to managers and lay people. Graphic design skills also improve an engineer's ability to communicate and market design ideas via enhanced concept drawings. Marketing paired well with graphic design and we had received feedback from industrial partners that engineers could benefit from marketing training.

The current structure of the class includes two options for the lab series, the original manual machining series and the alternate more programming based machining series. Each lab series is completed in the first 8 weeks of the semester. During the second half of the semester students from all lab series options are combined for the project portion of the class. There is also a common lecture series. The students choose which lab series they would like to participate in.

Novel content

There are other engineering programs that include marketing. There are programs dedicated to engineering sales, notably Iowa State, Penn State and Florida State¹⁴. The content of our course is not intended to create marketing and presentation skills at the sales engineer level but rather to give an understanding that will improve the design engineer's ability to interface with marketing functions and support quality presentations through graphic design. Additionally there are engineering programs that use machine fabrication to train design for manufacturing^{15,16}. Our approach is unique in that the student chooses the lab series they are most comfortable with to get to the goal of an understanding as well as the project they would like to demonstrate and further develop their understanding. The hope is that the freedom to choose the approach that they are most comfortable with will boost student confidence and motivation.

Design for manufacturing, original path

The original lab series introduces the students to basic manufacturing processes through hands on labs including woodworking, general machine shop equipment, welding, manual lathe and manual mill. In these labs the students learn through instruction and hands-on project builds. Each student builds a birdhouse, a weldment door or book stop, a hammer head and a two piece top. Figure 1 shows student built examples. Because the intent of the labs is not to train technicians but rather to train engineering students in the connection between design and manufacturing, each lab has an engineering theme in addition to the hands-on training. The birdhouse project focuses on standard print structure with a six page print package including an assembly drawing, bill of materials, component level drawings, and standard material controlled dimensions and tolerances. The example is given for rapid product development through standard parts and drawing revisions. The stop focuses on weld dimensioning. The hammer head focuses on geometric dimensioning and tolerance (GD&T). The concept of developing dimensioning schemes to match manufacturing processes is well demonstrated. Figure 2 shows an example of a student drawing. Because the students are using mills equipped with digital readouts, the use of ordinate dimensioning and properly defining a zero location greatly reduces the potential for error in the build process. The two piece top assembly requires a press fit driving the tolerance requirements to the limits of the equipment. The project demonstrates the advantage of precision equipment, the challenge of critical tolerances, and deflection of the material during the turning operation as well the impact of the operator on the process.



Figure 1: Each student completes 4 hands-on projects during the lab portion of the course



Figure 2: Hammer head print used during manual mill lab.

Common content

A lecture series accompanies the labs to further develop engineering skills. The primary focus of these lectures is to introduce the student to common industrial practices. Topics included are:

- Safety and zero tolerance
- Lean manufacturing
- General dimension and tolerance
- Geometric dimension and tolerance
- Process planning
- The design process
- Document control
- Additive manufacturing
- Computer aided design
- Computer aided manufacturing and CNC equipment.

The course concludes with two projects, one individual and one group project. These student projects require:

- Fully dimensioned drawings including tolerances with a complete title block and document control.
- A work order with process plan, cost estimate and correlation to document control.
- Feed and speed calculations for all machining operations.
- A presentation of results.
- Participation in the design fair with demonstrations and marketing.

Students choose on the subject of their projects. For the group projects the students are required to increase the project challenge through part complexity or design of an assembly. The student project grades are based on the documentation they produce, the design fair content and their presentations. This is in accordance with industry where an engineer's job performance is based upon the documentation they produce and their understanding of the processes, but not their ability to perform those processes. Two completed projects are shown in Figure 3.



Figure 3: Battleship game and snowmobile uprights completed as group projects

Design for manufacturing, alternate path

When developing the alternate lab series, the intent was to create the same learning experience in terms of demonstrating the connection between manufacturing and design and the value of concurrent design as with the original path but with a lab series that allowed student to work with tools that they felt comfortable with. As discussed above, CNC programming with machine tools and 3D printers were an obvious choice. But what we did not anticipate was in developing the alternate path we came upon curriculum elements that would also enhance the original path, For example, graphic design content was included in the alternate path because the software tools are very similar to the software tools used for computer aided design and computer aided manufacturing. Graphic design skills are useful to the working engineer in conveying ideas and marketing concepts^{2, 3}. Additionally, once the decision was made to include graphic design,

marketing seemed like a logical extension and one that would be valuable to all mechanical engineering students upon graduation. Graphic design and marketing content was included in the alternate path. Because of the positive feedback we received and student request we are now including marketing and graphic design in both paths.

3D print lab

Students in the alternate path are trained in 3D printing and how to use it to produce models. The class includes a historical review and a discussion of the different additive manufacturing processes in use today including Stereo lithography, Fused Filament Fabrication (FFF), Powder bed and inkjet head printing and laser additive manufacturing. The students use the FFF process depicted in Figure 5.



Figure 4: FFF Process -- http://reprap.org/wiki/Fused_filament_fabrication

With the FFF process, a solid model is created and then placed into a slicing program. Within the slicing program, the build orientation is determined and the model is sliced into a number of layers. The layers are then used to create the tool paths which allow the FFF machine to build the model from the bottom to the top.

Design consideration for the FFF process includes the strength of the material, build layer orientation, support, layer thickness, warping and any internal shapes and cavities. Students quickly learn that the process is not as simple as it appears. One of the most crucial design considerations is the build orientation of the part. This orientation has an effect on the overall strength and durability of the part being produced. The transverse direction of the build layers is up to 20% weaker than the longitudinal direction and this could be significant depending on the functional requirement of the part. The orientation of the part also affects the footprint of the part on the build bed and how stable the build is. The students are required to model and print a project of their choosing. Project ownership increases student motivation. Figure 6 includes a sample of student project.



Figure 5: 3D printed and machined desk fan modeled after a windmill.

CNC machining

In the CNC lab students are given the experience of manufacturing parts with a Vertical Milling Machine (VMC). Figure 7 shows the HAAS VMC available for student use.



Figure 6: HAAS Mini Mill

The lab includes MasterCam^{©4} training, the industry standard for computer aided manufacturing (CAM) program. The MasterCam[©] program allows the student to take a computer generated 3D model and create the tool path operations necessary to produce the part in the VMC. The students are given a copy of MasterCam[©] home edition which allows them to work at their own pace on their personal computer. Critical topics include:

- Logical part origin for manufacturing and coordinating with the design process.
- Proper tool selection
- Optimal process parameter control
- Process planning optimization for dimensional performance and efficiency

Students are given an example part on which to experiment. They quickly learn that there are many possible solutions for process planning and the challenge lies in choosing the best option.

Students are given an assignment to design and build a part of their choosing. Just like for the 3D printing, this ownership motivates students to apply their education by allowing them to build something that interests them. Figure 9 includes examples of student project parts completed with the training in the CNC portion of the alternate path.



Figure 9: student CNC machining projects.

2D and 3D graphic design

The intent of the 2D/3D graphic design portion of ME-125L is not to give students the same experience they would have in a standard arts program. Instead, it is aimed at providing a solid foundation for the creation and manipulation of media for use in engineering reports and presentations. In the 2D section, students are exposed to GIMP° ⁵ and Inkscape° , open source software packages for raster and vector image editing. In the 3D section, SolidWorks $^{\circ}$ ⁷ motion and PhotoView 360 $^{\circ}$ ⁸ are used for creating animations and rendering photorealistic images.

GIMP© is a raster image editing suite (similar to Adobe Photoshop©⁹) which allows the user to retouch photographs and perform basic photo manipulation. This is often useful for optimizing photographs that were not taken in ideal conditions so that they convey the information in the best possible manner. Figures 10 and 11, show how a cluttered background can be removed to enhance the clarity of the main focus.



Figure 10: Original image



Figure 11: Background removed

Whereas GIMP© is concerned with editing images made up of pixels, Inkscape© creates images based on vectors (similar to Adobe Illustrator©¹⁰). This allows the images to be scaled without bounds and still retain their crispness at any size. Vector-based image editing programs excel at the creation of many engineering diagrams, such as the free-body diagram seen in Figure 12 and the moment-torque diagram in Figure 13.



z M T M *Figure 13: Moment-torque diagram created with Inkscape*©

While being competent in the use of Inkscape[©] is helpful in creating diagrams for reports and presentations, it is also very useful in the creation of banners and promotional material such as t-shirts for collegiate competition teams.

While 2D images will suffice for communication in some situations, there are many times when the production of 3D content helps convey the concept in an even clearer manner. SolidWorks© provides a vast materials library which makes it very easy to assign realistic materials to an assembly. Then, PhotoView 360© can be used to create a realistic looking rendering via ray

tracing which can mimic what a design will look like in real life. A PhotoView 360[©] rendering is shown in Figure 15.



Figure 15: PhotoView 360© rendering from SolidWorks©

It is also often useful to show how a complex design operates or is assembled. Students are shown how to create animations with SolidWorks[©] motion when they are able to model the motion of a design and create exploded animations which can then be rendered to video. The end result of an exploded animation is shown in Figure 16.



Figure 16: Frame from assembly explode video generated by SolidWorks©

Ultimately, the 2D and 3D graphic design sections of DFM give the students powerful communication tools that they are able to use in engineering reports and presentations as they progress through school and finally enter the workforce. They are able to:

- Perform basic photo manipulation
- Create crisp looking diagrams
- Create photorealistic renderings of their 3D designs
- Produce animations of their designs that bring further clarity to their audience.

Marketing

Marketing has become an integral part of many engineering positions and pairs well with graphic design and 3D printing. The engineering field is evolving and employers desire, now more than ever, to hire a well-rounded engineer that possesses a good balance of technical ability and interpersonal and communication skills. Engineers need to be able to communicate with marketers, budget personnel, company executives, and potentially even stakeholders and customers. The value of a basic understanding of marketing principles is two-fold: to be able to validate product-market fit, and also to hone one's communication skills for a non-engineer audience.

The marketing lectures were delivered by two marketing professionals. Originally, the lectures were limited to section sizes of about 20 students in the alternate path. Due to positive feedback and at the request of the students, the lectures were moved to the common lecture for all students.

The lectures cover basic marketing topics including marketing strategy, market positioning, emotional versus rational marketing, personal branding and social marketing, and marketing to a non-technical audience. The lecturers used several case studies that students could easily relate to, such as failed video game console marketing strategies, Mac vs PC, and automobile marketing examples. Figure 17 is a rendering developed for marketing material of a student product design.



Figure 17: Rendered image of student design developed for marketing material.

Assessment of the course

The assessment of this course involved a demographic questionnaire and a survey adapted from three instruments. The survey included 6-points Likert scale questions adapted from Science Motivation Questionnaire II¹¹ and LAESE survey¹², and rating questions (0 to 100) from the Engineering Design Self-Efficacy Instrument¹³. We assessed students' engineering self-efficacy, intrinsic motivation, coping, and feeling of inclusion as well as their degrees of confidence, motivation, expectation of success, and degree of anxiety in performing engineering design tasks.

A total of 104 students who enrolled in ME 125L in fall 2015 were involved in this study. Fifteen (15) students selected the alternate path while 89 were in the traditional path. As shown in Figure 1 below, the alternate path was more attractive to female students. The ratio of female students was higher in the alternate path (40.0%) than that in the traditional path (7.9%). Moreover, more students in the alternate path (33.3%) had at least one parent/guardian as a scientist/engineer compared with those in the traditional path (14.6%). There was no statistically significant difference between the two paths in terms of attracting minority students. The minorities in this study included American Indians, African American, and Latino students.



Figure 18: Comparison of demographics of students with different path

Significant differences were found between students who selected the alternate and traditional paths. As shown in Table 1, the pre-survey data indicated the students in the traditional path had higher self-efficacy, design confidence, and expectation of success than those in the alternate path.

Pre-survey	Scale	Alternate path	Traditional path	t_{102}	Sig.
		Mean	Mean		(2-tailed)
		(SD)	(SD)		
Engr. Self-Efficacy	0-6	4.43	5.00	3.16	.002
Design confidence	0-100	56.38	72.69	2.19	.044
Expect. of success	0-100	60.03	75.30	2.12	.049

Table 1: students' differences reflected in pre-survey

The post-survey was conducted at the end of the semester. Datasets from 49 students were involved in the pre- and post-surveys analyses and 89.4% of them were males. There were no significant differences between the students who finished the post-survey and those did not,

except the average grade. Among the students in the traditional path, the average grade of those who finished the post-survey ($M_1 = 0.884$, $SD_1 = 0.077$) was higher than the others' ($M_0 = 0.817$, $SD_0 = 0.179$; $t_{87} = 2.31$, p < .05).

Considering only four students in the alternate path finished the post-survey, all datasets were combined for the pre- and post- surveys analyses. As shown in Figures 2 and 3, students in ME 125L had significantly higher (p < .05) average intrinsic motivation ($t_{47} = 2.46$, p < .05; Cohen's d = 0.30), average feeling of inclusion ($t_{47} = 2.00$, p < .05; Cohen's d = 0.35), and average expectation of success ($t_{47} = 2.54$, p < .05; Cohen's d = 0.50) by the end of the course. The values of Cohen's d indicated the course had a small effect on students' intrinsic values, and medium effects on students' feeling of inclusion and expectation of success in engineering design. However, it is worth mentioning that the pre-survey was conducted during the middle of the semester. If measured for a whole semester, the data may have shown relatively larger effect sizes on students' engineering motivation and design self-efficacy. Longitudinal data will be collected to investigate the influence of the course on students' attitudes toward and learning of engineering.



Figure 19: Comparison of student engineering motivations



Figure 20: Comparison of student design self -efficacy

Conclusion

Feedback from industrial partners indicates that the course and the alternate path are serving the students well in terms of developing skills valuable to the working engineer. Observations and feedback from the students and course include:

- Design for manufacturability skills are developed regardless of which path the students follow. With the student designs, the most limiting processes are generally machining and turning. The bulk of these limitations are the same with manual and CNC control. Because the students work in mixed teams of traditional and alternate path they are also able to understand as a team the differences in applicability of CNC control vs manual control and include those decision in their project plan development.
- During the group project phase it is common for students to receive training in the lab series that they did not choose as they work as team to complete their project.
- Students are allowed and encouraged to divide responsibilities during the project phase to match student interests and abilities with tasks. This seems to drive engagement.
- Potentially linked to student engagement, often project scope well exceeds course requirements.
- The increase in project scope has resulted in increased demand for student knowledge of design software and design standards.
- Internal conflict within the groups is not uncommon. Because this course is taught at the freshman level, it is often the first opportunity students have to work on a group design project. Faculty and staff actively observe, correct and improve group interaction. Additionally, one of the industrial partners will deliver a presentation on effective teaming.

Review of survey results with consideration of the informal feedback suggests that the alternate path is providing a favorable option to a varied population. Evaluation of the pre and post results suggests that there is opportunity for improvement in terms of self-efficacy and motivation. The student evaluation will continue to be an integral part of the course and will be used as a tool to evaluate and direct course improvement.

Course changes planned for next semester include increased training with design tools, specifically solid works. It is hoped that increasing student confidence with this tool will improve the overall student confidence and allow students to better understand the broader topic of design for manufacturing. Training in effective teaming will be included in hopes to improve the overall student experience and maintain and increase student motivation towards design projects. There will be an increased focus on the design fair and project presentations with the intent of demonstrating a broader interest in student accomplishments.

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