Strengthening Knowledge Structures Using Psychomotor Learning in a Manufacturing Processes Course

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ABSTRACT

A Manufacturing Processes laboratory can assist students in developing a deeper understanding for the traditional topics covered as part of a manufacturing processes course. These include topics such as chip deformation, material or tool speed and feed rates. By carefully designing the student implement-operate project, multi-impact learning experiences can also be realized. These multi-impact learning experiences can help build knowledge structures that extend beyond manufacturing processes to include topics such as material selection, design for manufacturing, communication through engineering drawings, and other engineering topics. Beyond the development of the Cognitive domain, however, further learning opportunities exist by exploring the Psychomotor domain. An immediate extension to the Psychomotor involves application of forces and moments to either the tool or workpiece during a manufacturing process. These Psychomotor experiences can help enlighten students to processes such as surface finish or time of operation. This paper describes the 5-year evolution of a Manufacturing Processes laboratory that has been designed to activate both the Cognitive and Psychomotor learning domains. It is believed that this is resulting in an ability to strengthen student knowledge structures in areas that are far removed from Manufacturing Processes.

KEYWORDS

Manufacturing Processes, Dual-Impact Learning Experience, Design-Build Exercises, CDIO Standards 5, 6, and 7

INTRODUCTION

Manufacturing Processes is a core course in most Mechanical Engineering programs that provides an important bridge between Design (Materials Selection) and Implementation (Materials Transformation) in the lifecycle of an engineering project (C**DI**O). A typical Manufacturing Processes course will include topics such as the mechanical behaviour of materials, properties of metals, polymers, and ceramics, casting, forming, machining, and joining. Given that course topics in a typical Manufacturing Processes course overlap with other core courses in the Mechanical Engineering curriculum (Mechanical Behaviour and Materials Selection), students can sometimes become overwhelmed by the diverse range of course topics. This is further complicated by the fact that current students entering into Engineering programs have little prior experience with many of the materials transformation processes covered in a Manufacturing Processes course.

The University of Calgary has offered a course in Manufacturing and Production Processes for over forty years, and the course was originally lecture based at three hours per week.

During the 1980's it was decided to augment the lecture component of the course with laboratory demonstrations (adding two hours per week), involving students watching machinists and technicians from within the Engineering Faculty Shop complete material transformation processes.

During the same time period, a change process was also underway within the K-12 educational system in the province of Alberta, a change that is in general reflective of similar changes in K-12 schools throughout North America. In the 1970's the Province of Alberta offered, through Alberta Education, courses in Industrial Arts that were taken *only* by male students and Home Economics that were taken *only* by female students. Both programs involved approximately 30 weeks of 3 hours of contact per week, for a total of 90 hours of hands-on laboratory instruction per grade level. Grade 8 Industrial Arts included ceramics (potter's wheel, slipcasting, hand building), woodworking (wood lathe, cutting, drilling), metals (forging, casting, cold metal forming, drilling and fastening), and plastics (injection molding, vacuum forming, rotational molding). Grade 9 Industrial Arts included printing, steam and gas power cycles, metalwork including turning, milling and shaping, computer technology, electronics, and photography.

Starting in the 1980's these courses, referred to as Knowledge and Employability Occupational courses, were modified. One extremely positive change was the removal of gender segregation, enabling both male and female students to take content across the Knowledge and Employability Occupational stream. In this revised delivery model, schools have been allowed some degree of freedom in the design of their own programs based on available facilities and equipment [Alberta Education, 2015]. Areas of study can include art/design and communication, auto mechanics, business services, construction, fabrics, foods, horticulture, human care, and workplace readiness. An example program could include approximately 40 hours of Industrial Arts for the first half of the year, and another 40 hours of Home Economics during the second half of the year. Although these changes have undoubtedly resulted in the education of more well-rounded students, the changes have unfortunately also diminished student exposure to areas that are of importance to both Mechanical and Electrical Engineering programs. The ability to perform engineering design requires an understanding of the constraints, and a firm knowledge of these constraints is critically important as one progresses from conceptual design to detailed design to design realization.

In light of the importance of Manufacturing Processes to the lifecycle of an engineering project, and specifically the relationship between Design and Implementation, in 2010 the University of Calgary started a process of redesigning its Manufacturing and Production Processes course. This paper will provide the pedagogical reasoning behind this change, it will describe the change process, and it will provide examples of the current project-based learning experience that now forms the backbone of the course.

BACKGROUND

Knowledge, Skills and Attitudes

The design of any CDIO program begins with the central question "What is the full set of knowledge, skills, and attitudes that a student should possess as they graduate from a university?" Within CDIO the knowledge, skills, and attitudes reside within the CDIO Syllabus (Crawley et al., 2007) and consist of the following four core areas: CDIO 1. technical knowledge and reasoning; CDIO 2. personal and professional skills and attributes;

CDIO 3. interpersonal skills – teamwork and communication; and CDIO 4. the lifecycle of an engineering design process set within the enterprise and societal context. It has been pointed out that the four areas of the CDIO Syllabus map directly to UNESCO's Four Pillars of Education (Delors, 1996), which include (1) Learning to Know, (2) Learning to Be, (3) Learning to Live Together, and (4) Learning to Do.

Bloom's Taxonomy also provides a classification of knowledge, skills and attitudes that are addressed through the learning process. The **Cognitive Domain** covers mental processes that ascend through *Remember, Comprehend, Apply, Analyze, Evaluate,* to *Create* (Bloom et al., 1956; Krathwohl, 2002). The **Affective Domain** covers human emotions and ascends through *Receive, Respond, Value, Conceptualize Values,* to *Internalize Values* (Krathwohl, 1956). And finally, the **Psychomotor Domain** covers physical skills and abilities and ascends through *Imitate, Execute, Perform, Adaption,* to *Naturalize* (Simpson, 1972).

Goldberg and Sommerville (2014) refer to what can be viewed as a holistic mix of all three of Bloom's domains as manifested in their "six minds of the Whole New Engineer," covering the *analytical* mind (CDIO 1 and 2), the *design* mind (CDIO 4), the *linguistic* mind (CDIO 3), the *people* mind (CDIO 3), the *body* mind (CDIO 3 and 4), and the *mindful* mind (CDIO 3 and 4). The authors are careful to point out that these six capacities extend beyond cognition and that they are not fixed but rather grow and develop as a student / engineer progresses.

Given that all of these models describe the knowledge, skills and attitudes that are constructed within a student during the educational transformation process, it should not be overly surprising to see similarities in all three models. It is interesting to note that this type of model was also contemplated by Aristotle over two thousand years ago , and he referred to it as the five virtues of thought which included *epistêmê*, *sophia*, *nous, technê*, and *phronêsis*. *Epistêmê* is often referred to as knowledge or scientific knowledge, *sophia* is wisdom or "knowledge with its head on," *nous* is the highest form of knowledge - intellect gained through experience, *technê* is craft or art that is an application of knowledge that leads to a tangible realization, and *phronêsis* is practical judgement that leads to living well (Reeve, 2013; Parry, 2014).

A Deficiency of Skills and Attitudes

A recent ASME Vision 2030 project solicited feedback from academia, early career engineers and industry (Kirkpatrick et al., 2012). A total of 80 Mechanical Engineering (ME) department heads, over 1500 industry engineering managers, and 635 early career mechanical engineers were surveyed as part of this project. The ASME Vision 2030 project identified areas of perceived weakness as reported by Industry Supervisors, with i) Practical Experience, ii) Communication, iii) Engineering Codes and Standards, iv) Overall Systems Perspective, and v) Problem Solving and Critical Thinking reported as areas of greatest weakness (Kirkpatrick et al., 2012).

All five of the areas of weakness identified by the ASME Vision 2030 survey relate to four of Aristotle's five virtues, excluding only *epistêmê*. It is speculated that given that *epistêmê* is the one Aristotelian virtue most easily taught by lecture and assessed by traditional exam, it is the one virtue that is most focused upon within higher education. A review conducted by the Quality Assurance Agency for Higher Education (QAA, 2003), as described in Boud and Falchikov (2006), commented that *the main deficiencies identified in university courses were not related to teaching and learning, but to assessment practices*. They continue to write *reviewers had found a very narrow range of assessment methods in use and over-reliance* *on traditional examinations.* This would suggest that within engineering education (and higher education in general), assessment is primarily focused on scientific knowledge (*epistêmê*), and in so doing skills and attitudes important for professional practice are often neglected, as evidenced by the weaknesses identified by the ASME Vision 2030 project.

The knowledge, skills, and attitudes gained through the Manufacturing Processes course include traditional knowledge acquisition and reinforcement (CDIO 1, UNESCO's Learning to Know, Bloom's **Cognitive** domain, Goldberg's *analytical* and *design* mind, and Aristotle's *Epistêmê*) and extend to cover skills and attitudes not commonly covered in engineering education programs (CDIO 4, UNESCO's Learning to Do, Bloom's **Psychomotor** domain, Goldberg's *body* mind, and Aristotle's *technê*). These latter skills and attitudes help assist in developing what Goldberg and Sommerville (2014) refer to as the *Whole Engineer*, they help to address different learning styles, and they help to motivate students.

Learning Styles and Student Motivation

The Manufacturing Processes laboratory takes place outside of traditional lecture-based instruction, and given the active role that students play in the laboratory, it could also be argued that it also takes place outside of traditional laboratory-based experiences. According to the Felder-Silverman learning style model (Felder et al., 2005), the range of learning styles include:

1. **Sensing-intuitive** – concrete, hands-on, practical learning versus more conceptual and theoretical learning style.
2. **Visual-verbal** – visual learners prefer visual representations (flowcharts, diagrams, etc) while verbal learners prefer written and spoken explanation.
3. **Active-reflective** – active learners prefer to learn by trying and doing things (often together) while reflective learners prefer to think things through (often alone).
4. **Sequential-global** – sequential learners like to go step-by-step through a process, whereas global learners like to see the "big picture" all at once.

The laboratory component of the Manufacturing Processes course would appeal to the Sensing-Visual-Active-Sequential learning styles. Traditional lecturing may not capture all of these learning styles, and consequently the laboratory helps to improve student learning by appealing to a more diverse group of students.

Student motivation can also be impacted. The process of creating an object out of raw materials helps provide the students with intrinsic motivation, and this can extend to improve student learning in the other more theoretical components of the course (Ambrose et al., 2010). Providing students with authentic real-world tasks also assists helping with developing student understanding (Ambrose et al., 2010).

TRADITIONAL LECTURE-BASED METHODS

A common issue reported by students, referring to the Manufacturing Processes course at the University of Calgary, is a lack of tangible experiences. While the course material may be interesting or even entertaining, there is a fundamental disconnect by the students preventing the development of firmly engrained knowledge structures. From its most pessimistic view, the course represents an exercise in memorization that students promptly forget following final examinations. In order to combat this we introduce the concept of scaffolding (Hsi & Agogino, 1995) which postulates that new knowledge is best assimilated when linked to previous experiences. In addition, it's proposed that linking these experiences within the Psychomotor Domain will further deepen the connections and knowledge structures of the students. In an attempt to conceptualize these ideas into exercises and activities suitable for students of many different backgrounds and prior skillsets, the manufacturing projects were developed. The projects within the manufacturing lab provide the students with the vehicle from which knowledge formation can be enhanced.

EVOLUTION OF THE STUDENT PROJECTS

Since the manufacturing lab was introduced as a compulsory component for all Mechanical Engineering undergraduate students, the projects have evolved in an attempt to further engage and excite the highly diverse student population. These changes have come about through both instructor observations and periodic polling of students, as will be seen in the following sections.

Previous Lab Projects

During the Fall 2011 and Fall 2012 semesters, material removal and machining were the primary activities performed by students during the projects. The course material was produced and taught by the machine shop technicians at the University of Calgary and consisted of projects on the milling machine and lathe. CAD models of the first project sets can be seen in Figure 1.

Figure 1: Student Projects 2011-2013

The projects consisted of a six sided die with centre-drilled holes to mark the numbers, a nut hand tapped from a piece of hexagonal stock, and a shaft with a diameter and mating thread cut on the lathe. These parts were all manufactured from brass as it is highly machineable, does not require coolants or lubricants, and forms highly segmented chips that do not present a possible safety concern. In this setting, the students were able to learn various machining processes such as turning, facing, drilling, tapping, grooving and threading. The feedback from students was generally positive with students saying that the projects helped to improve their grasp of the course material.

The labs were conducted in this format for four semesters before the Mechanical Engineering Department decided to modify the lab. The machine tools used during this period were not of superior quality and had been well used by the previous students. Questions as to the longevity of these machines and their ability to cope with any further expansion to the projects were asked. It was then decided to invest in higher quality machines with more size and power to permit more freedom in the design and creation of future projects. It was also decided to increase the allotted time for students to participate in the labs. This opened an opportunity for increased experiential learning and more complex projects. Finally, it was decided to hire a recent engineering graduate to develop the course content. While the prevailing factor in this decision was based on conflicts between the job descriptions of the technicians (instruction) and the duties of lab instructors (instruction and assessment), this did present an opportunity to address the problem of experiential student learning from an alternative point of view as the engineering graduate had significant manufacturing experience and a trade certificate in machining.

The new iteration of the lab content (Figure 2) included a number of new components. The lathe project was extended to include three components: a shaft, bushing and a nut. These additions allowed for the inclusion of a new material (steel) and the addition of new manufacturing processes such as boring, knurling, taper turning, countersinking and reaming. The additional parts also permitted a discussion about assemblies, engineering blueprints, and concepts such as fits and tolerances.

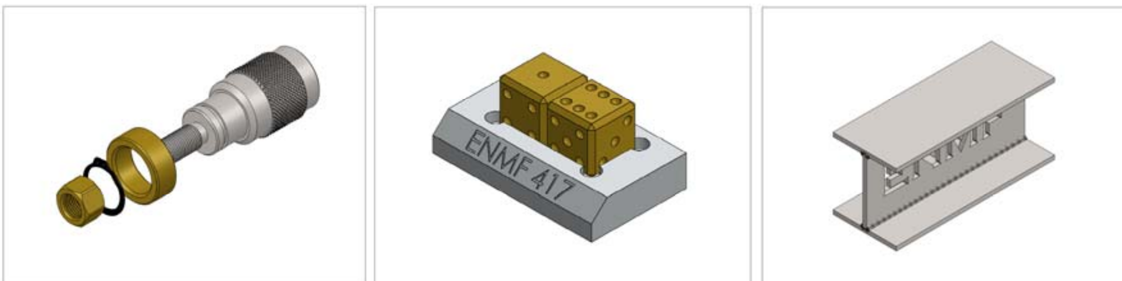

Figure 2: Student Projects 2013-2014

The milling project was similarly expanded to include three components. The single six-sided die was increased to two dice and revamped to include ball end milling of the numbers, and an option of two types of edge treatment (both using different milling form cutters). To complement the dice an aluminium stand was added to both diversify the materials and introduce students to additional important concepts such as pocketing and cutter radius compensation. The milling project as a whole also provided a good introduction to surface finishes. As both brass and aluminium are highly lustrous, it was very straight forward for students to learn the effects of different tools on surface finish from rough saw-cut surfaces through to machined, filed, sanded and highly polished surfaces. As many of these operations were completed by hand, it provided students a great appreciation for the additional time and cost associated with specifying progressively smoother surface finishes and evaluating which finish is the most robust for the intended application of the part.

In addition to the reworked milling and lathe projects, a welding project was also added to introduce students to joining processes. This section of the labs was broken down into two stages. The first stage involved demonstrations of all the available welding and thermal cutting processes available in the Engineering Faculty Shop at the University of Calgary. Once the students were introduced first hand to the myriad of processes, they were given a project to weld a structural I-beam using multiple welding processes (GMAW and SMAW). A degree of personalization was also included as students were able to design custom webs for their I-beam that were then cut out using an abrasive water-jet machining process.

The overall response to these new labs was far superior to the original ones. This can be attributed to the upgraded machine tools, the new projects and the overall quality of instruction.

Reflective Transformation

While the previous iteration of projects (Figure 1 to Figure 2) was a great improvement, there was a common criticism from students concerning the lathe project. While the project was interesting and engaging during the manufacturing process, the finished components lacked an overall function. It was designed only to be a learning aid to students and embody the desired goals of introducing students to different materials and processes. While the machining of the parts was useful, the finished part was contrary to the mindset of an engineer – to produce something with function.

These comments prompted a re-evaluation of the lathe project. It was determined that an overall paradigm shift was required, moving from the traditional process-based learning taught at trade schools where a student's primary objective is to become proficient in using the machine tools, to a function-based approach that matches the learning process taught in engineering programs. In this functional approach, the projects were viewed from the perspective of a design engineer. This allows students to learn in an integrated manner by continually linking features of each project back to the initial design consideration. This was in contrast to the previously used method by which the purpose of each part was somewhat arbitrary. Through this process the learning extends beyond the Psychomotor to include the Cognitive. Given that functional parts need to be made to certain specifications, it also engages students and encourages them to have a higher attention to detail.

Current Lab Projects

The current lab projects are shown in Figure 3. The welding and milling projects have remained essentially the same with exception of the material choices for the milling project. It was found that the rolling characteristics of the lighter weight aluminum dice were superior to the previous brass dice. The major novelty to the project lies in the lathe project. The project is now a yoyo which consists of four pieces that the students turn on the lathe along with components that exploit two new manufacturing processes: laser cutting/engraving and polymer casting. The new yoyo project helps to address many of the criticisms initially posed by the students.

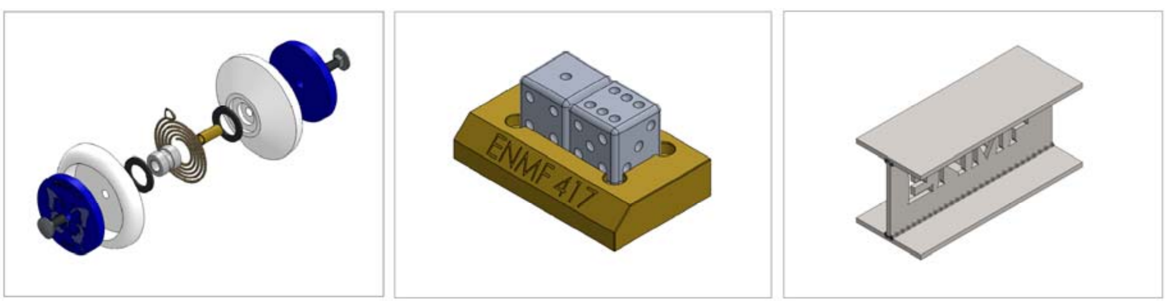

Figure 3: Student Projects 2014-2015

The project is slightly easier than the previous lathe project which provides slower paced students the opportunity to keep up and has enough detail and complexity for the faster students to remain engaged. The project also consists of many engineering materials (7 different materials in one assembly), leading to discussions on the importance of material selection as well as process selection during the design process.

STUDENT FEEDBACK AND EVALUATIONS

In order to evaluate the effects of change and evaluate the relative success of the labs, a number of qualitative and quantitative indices are extracted from survey results taken from students each semester. The results and discussion of these indices are discussed in the following sections.

Quantifiable Results

The primary quantitative index looked at has been overall student satisfaction with the labs. This index is made up of a number of indicators relating to quality of instruction, relative part difficulty, and satisfaction with various components in the lab, among other things. The results of these surveys are shown below in Figure 4.

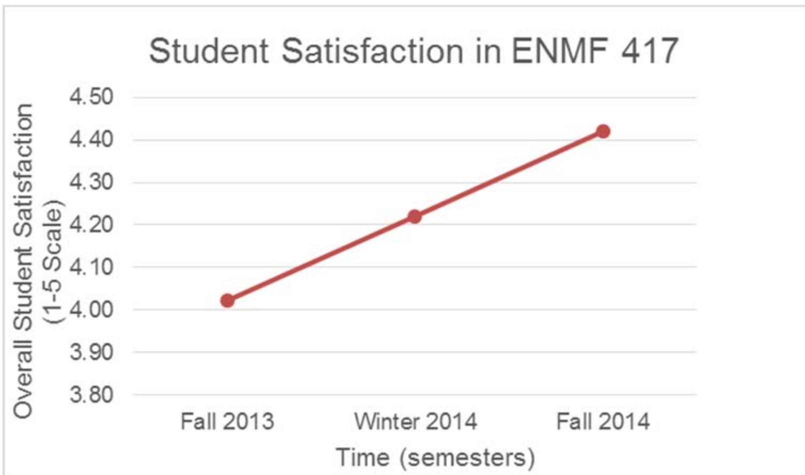

Figure 4: Trend of Student Satisfaction from 2013-2014

It should be noted that the data for this analysis is collected from roughly fifty percent of the students who have taken the course. In addition, it is taken on the last day of lectures so as to ensure that students have experienced the entire lab program before completing the questionnaire.

Anecdotal Evidence

The four main types of comments received from the students include:

1. Learning the different techniques required to complete a feature allows us to know what is and is not possible to manufacture.
2. The hands on experience of actually operating equipment and making parts. This thought process developed is not present in any other course.
3. Applications of theoretical knowledge with meaningful and tangible results.
4. Learning that we can use later in our careers as engineers.

These comments appear very promising as they reflect the objectives of the lab.

CASE STUDIES

A good indication of the success of a shift in educational pedagogy is in the application of acquired knowledge structures to other courses and activities. This section details the observed changes in student behaviour towards both capstone design projects and student competition teams.

Capstone Design Projects

The engineering capstone course is a full-year course that involves both paper-based design and a physical build of each student team's design. Student team size ranges from 4 to 6 students per team, and projects are initiated from three main sources – external sponsors, professors, and students themselves. Through the introduction of the Manufacturing Processes project-based laboratory, technicians within the Engineering Faculty Shop, who assist student teams during the fabrication phase of their design projects, were able to make observations about how students changed. The most notable changes included:

1. A greater appreciation for the amount of time required to complete a process, and therefore improved ability to set more realistic project management milestones.
2. A much greater anticipation for which process should be used to fabricate each component.

Both of these observations provide indication that the students were not developing mastery while being given a combination of lecture-based instruction and a laboratory that only involved observation. According to Ambrose et al. (2010):

> *To develop mastery, students must acquire component skills, practice integrating them, and know when to apply what they have learned.*

As part of the course, the students are required to compute the amount of time required to complete a machining process. Despite being taught this, they were either not able to connect this estimation process to their design projects or they were not able to comprehend what it was they were calculating (remaining in either the *Unconscious Incompetence* or the *Conscious Incompetence* stages in the Development of Mastery – Ambrose et al. (2010)).

The second point noted by the technicians within the Engineering Faculty Shop is also notable as it demonstrates that the students were not able to *know when to apply what they have learned.* The fact that the Manufacturing Processes course taught them a wide range of processes but yet they were not able to determine which process to apply indicates that they had not developed mastery over the material.

Both of the above observations provide support for the notion that the introduction of the Psychomotor Domain through the active project-based learning laboratory helped strengthen knowledge structures within the Cognitive Domain.

Student Teams

One area where a clear correlation can be made with regards to the effect of hands-on manufacturing experience is within student design teams. These teams within the mechanical engineering department share the common goal of designing and building some sort of vehicle that can transport a certain payload, whether human or otherwise. The teams include the Baja SAE team who are tasked with the manufacture of an off-road vehicle that can compete in many harsh environments such as dirt tracks and rocky hill climbs, the Formula SAE team who compete in a class of flat track open wheeled race cars, and other teams including a solar car and an electric motor bike. A case study is presented from the Baja SAE design team, investigating their experiences with the addition of new experiential learning in manufacturing processes.

Improved Project Quality: Baja SAE

One major observation made over the last few years is the dramatic improvement in part quality within the student teams, both from a design and manufacturing standpoint. When asked about the differences between the team dynamics from 4-5 years ago to present, the Baja SAE team cites a fundamental shift in the way they approach their design problems. “We really try to focus on design for manufacturing at an early stage of the process” say members of the team. “This mostly includes finding manufacturing firms that are willing to help us out and then tailor our designs to leverage their resources effectively and not overburden them. We really try not to burn any bridges with companies by asking too much of them.”

This idea of identifying available manufacturing resources and exploiting them in the detailed design phase has allowed the Baja SAE team to improve the overall performance of their car. One specific example is in their transmission gear box. As part of the competition rules all Baja teams must use a common engine supplied by the Briggs and Stratton motor company. This engine uses a continuously variable transmission (CVT) to control engine output speed and torque. Using this stock setup it is common for teams to have issues with power loss at high torque due to belt slippage. A common design solution used by many teams is to incorporate an additional low range gearbox to boost output torque and help maintain traction during the more difficult stages of the competition.

The first attempt by the Baja team to address this issue culminated in the artefact shown in Figure 5. This assembly entails two solid aluminum plates with machined surfaces, bearing housings, threaded holes for fastening and grooves to accommodate sealing materials. The transmission gears within were stock components and many of the other components were manufactured by the faculty machine shop. While this gearbox did function and worked sufficiently well during the competition, there were some inherent design flaws that were not addressed. The two critical flaws were the lack of any surface hardness treatments to the gears resulting in accelerated wear and the lack of design optimization for weight and strength requirements in the gearbox casing itself. Both of these issues are representative of an incomplete understanding of the manufacturing processes used. This project was designed and manufactured the year prior to implementing the new manufacturing curriculum.

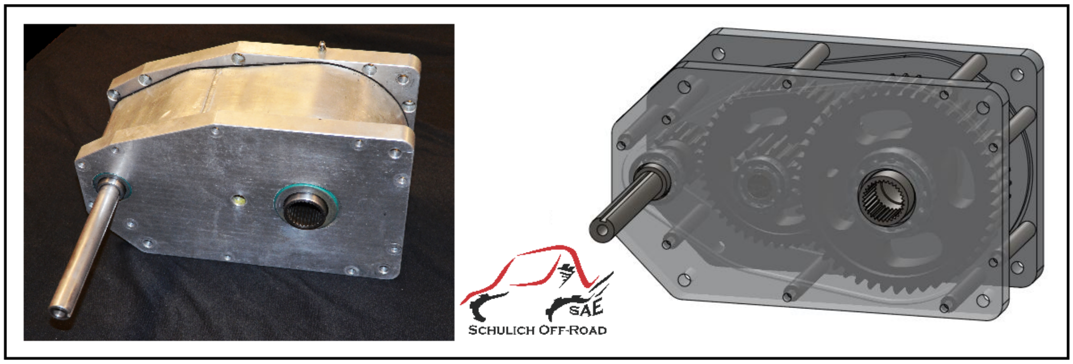

Figure 5: Baja SAE Artefact prior to Manufacturing Labs

Looking at team operations four years later reveal a significant improvement in the design and manufacturing methods used by the Baja SAE team. Their newest gearbox design (Figure 6) is greatly improved over its predecessors, with the weight of the entire assembly reduced by over 7 kg and custom manufactured gears with the correct heat treatments and surface finishes being used. The biggest improvement, however, lies in the casing design itself. Members of the Baja team explain, “The biggest issue we had with the previous designs of the gearbox was the lack of understanding of the machining processes involved. We would purposely design components to be overly simple in order to ensure manufacturability. It was very difficult for us to know what additional processes could be done to improve performance without adding significant complexity to the part.”

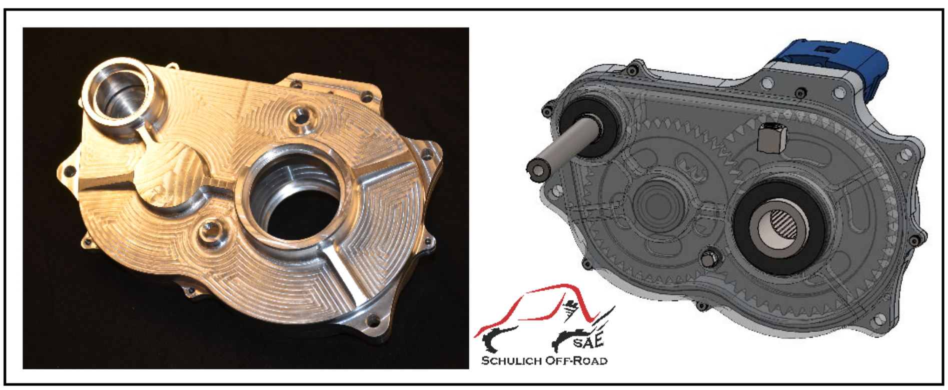

Figure 6: Baja SAE Artefact after 4 Years of Manufacturing Labs

When asked what changes had occurred in order to improve their understanding, they cited the addition of hands-on manufacturing experience, but not for the expected reasons. “We felt that having experience manufacturing parts allowed us as engineers to communicate more effectively with the technical staff and allow us to work together to find solutions to problems. We made sure to solicit the advice of the machinists from the very beginning to ensure our designs were manufactureable using their machines and tooling.”

While this case study illuminates the indirect benefits of hands-on machining experience by fostering enhanced communication between engineers and technical staff. It is also interesting to note a specific trend related to the success of the Baja SAE team. Over the 5 years prior to the implementation of the revised lab curriculum, the team finished highest in 47th place in five international SAE sanctioned competitions. In the years since the implementation of the revised lab content the team has jumped to the mid-twenties with a top thirteen finish in the last three years.

CONCLUSIONS

This paper has demonstrated that through the introduction of a project-based learning component to a Manufacturing Processes course, knowledge structures gained through traditional lecture-based instruction are enhanced. Evidence is presented to substantiate the improvement in student learning. It is believed that learning enhancement results as skills and attitudes not commonly covered in engineering education programs are targeted through the laboratory, including CDIO 4, UNESCO's Learning to Do, Bloom's **Psychomotor** domain, Goldberg's *body* mind, and Aristotle's *technê*.

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BIOGRAPHICAL INFORMATION

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