Early Incorporation of Design for Manufacturing in the Engineering Curriculum

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Introduction

Design for manufacturing (DFM) and/or concurrent engineering has been a focus for engineering educators and industry partners for decades. The efforts throughout the engineering communities have resulted in improvements in methods, training, and software. Largely thanks to the performance of DFM ready engineers, there have been notable improvements in profitability and design cycle lead time[1,2]. However, the trend toward urbanization and reduction in secondary education shop classes has made DFM training at the post-secondary level more challenging. Specifically, engineering freshmen are less likely to have hand skills or familiarity with manufacturing equipment than previous generations[3-6].

This paper describes a mechanical engineering department curriculum developed to provide DFM and manufacturing training in the freshman year. Skills obtained in the freshman year are subsequently utilized in the sophomore year via a significant product design and development project. This curriculum provides underclassmen the opportunity to develop a fundamental understanding of DFM and to build upon this understanding through application later in the curriculum including senior capstone design. The goal is a more industry-ready graduate who has an understanding of the principle of "first time right" and who has the confidence to address the increasingly complex issues arising in engineering design in the global manufacturing arena. There are related efforts at other universities [8-9].

The approach described in this paper is a three course series. The first course in the freshmen year establishes fundamental mechanical engineering principles, including a focus on problem solving skills and specialized design tools (e.g., CAD/CAM). The second course in the freshman year develops manufacturing skills including work-place safety, lean manufacturing, and the philosophy of first-time-right while providing students with hands-on training in woodworking, light metalworking, manual milling, manual lathe work and Computer Numerical Control (CNC) machining. The intent is not to train engineering students to be machinists but rather to give them an understanding of fundamental manufacturing processes. Each student must complete an individual design project and be part of a design team on a CNC project. These projects require that the students complete fully dimensioned and toleranced engineering drawings and a work order including material selection and a planned build process.

The third course in the sophomore year is a product development course focused on sustainable energy. The lecture content includes renewable and sustainable fossil and nuclear energy. The students complete a supporting lab series including solar, wind, fuel cell and hydroelectric experiments. During the last half of the course the students design, build, and test an energy related product of their own invention receiving guidance and critique throughout the process. The design build section relies heavily on DFM skills developed in the freshman year.

The coherence of these three courses has yielded positive results. Material waste has dropped off significantly and the quality of the manufacturing (student builds) has increased significantly as a result of more complete and accurate prints and part build plans. The students have shown an increased understanding of the build process and more confidence with making design decisions. The project results have been impressive, including novel designs for sterling motors, counter rotating windmills, a solar charging cell phone case utilizing additive manufacturing, and others. The student presentations often highlight the value of material selection; build plans, complete drawings and proper tolerancing.

Future plans include facilitating increased student machine time in the DFM lab as well as the development of a junior level course including a more significant product development and larger scale laboratory work focused on sustainable energy. This is expected to build on the current series and feed directly into the senior capstone design course.

The curriculum changes outlined in this paper had multiple goals:

- Encourage innovation by challenging students with globally significant projects.
- Facilitate innovation through design rigor and an iterative review process.
- Develop design for manufacturing skills early in the students' academic career to be honed with subsequent academic design projects.
- Utilize project teaming as a standard part of the curriculum to facilitate group learning and personal growth.
- Produce a more industry-ready engineer with a first time right mentality.

The paper will discuss the progress made in achieving those goals. Additionally it will consider the instructional approaches developed over the last 2 years, project examples, and semester-by-semester assessment results.

Introduction to Mechanical Engineering, Freshman Year

The first course in the series during the freshmen year focuses on problem solving, engineering fundamentals, and SolidWorks for both 3-D model and engineering drawing development. From a mathematical perspective the treatment is basic; the only prerequisite for the course is college algebra, and some portion of the students will be concurrently enrolled in trigonometry. The treatment of engineering fundamentals is based on the textbook by Wickert and Lewis[7], with topics including free body diagrams and equilibrium, normal and shear stresses, hydrostatics and laminar pipe flow, and first and second laws of thermodynamics. Basic problem solving skills are emphasized in each of these areas, including dimensional consistency and order-of-magnitude estimates to check the validity of results. Rather than attempting to achieve student mastery of these topics, the goal is for students to be familiar with the basic concepts in each area. These basic takeaways include resultant forces, moments, and conditions under which equilibrium is valid; definitions of normal and shear stresses and failure criteria for yielding;

hydrostatic pressure, buoyancy, and the Reynolds number; and energy conservation via the first law and the second law's implications for efficiency. In addition to this focus on fundamentals, students are required to develop communication skills via memo writing on various topics.

A secondary aim of the course is to development basic SolidWorks proficiency, which provides the link between the two freshman courses. Students are provided with custom tutorials to learn the basics of 3-D modeling and drawing generation; these tutorials are built off of lectures on engineering drawing fundamentals. The geometry shown in Figure 1 is used to train both orthographic to isometric sketching skills and SolidWorks basics. Further projects require students to follow standard tutorials on assembly generation and creation of complex geometries. These self-guided exercises are augmented by interactive teaching assistant sessions and in-class question and answer periods.

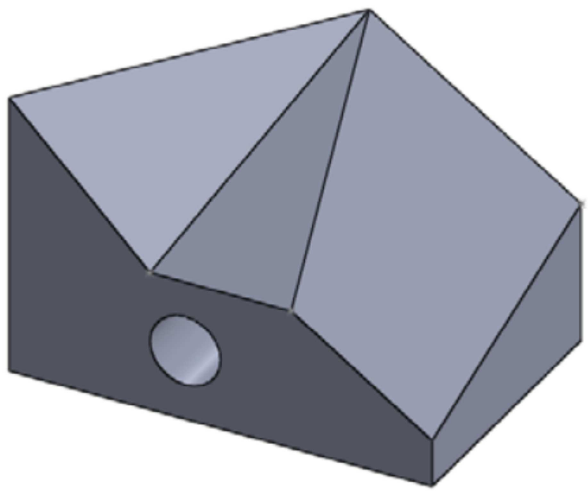

Figure 1: SolidWorks model from custom tutorial. Students sketch the isometric view of this part from orthographic views in an earlier portion of the course.

Design for Manufacturing, Freshman Year

The second course during the freshmen year introduces the students to basic manufacturing processes through hands on labs including woodworking, general machine shop equipment, manual lathe, manual mill and CNC machining. In these labs the students learn through instruction and hands on project builds. Each student builds a birdhouse, a simple frame member, a mill soft jaw and a two piece top. An example is shown in Figure 2. 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 frame member lab and the soft jaw labs focus on tolerance control and introduce geometric dimensioning and tolerance. The concept of developing dimensioning schemes to match manufacturing processes is well demonstrated. An example student drawing is shown in Figure 3. 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.

Figure 2: Each students completes 4 hands-on projects during the lab portion of the course.

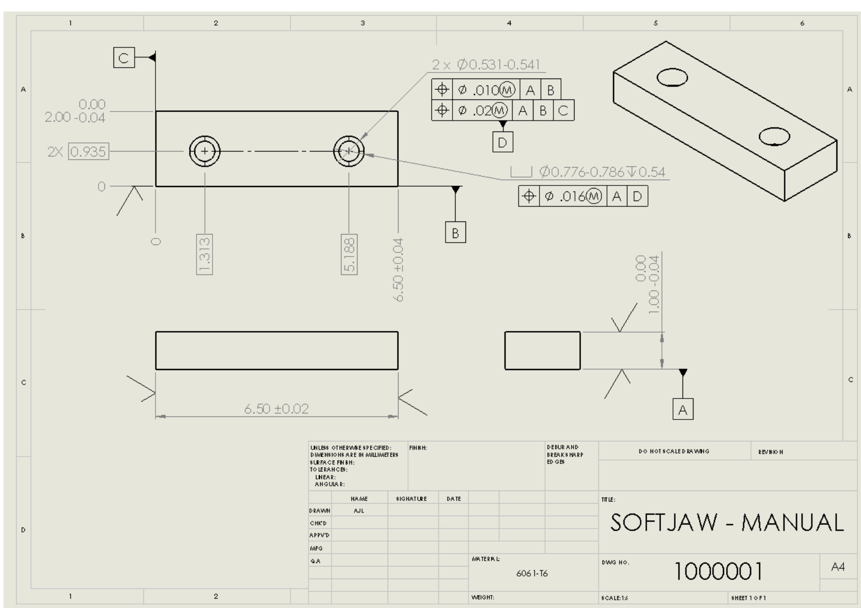

Figure 3: Soft-jaw print used during manual mill lab.

The lathe lab greatly reinforces the understanding of tolerances. The two piece assembly requires a press fit driving the tolerance requirements to the limits of the equipment. The flywheel hole is reamed with a 14 inch 3 jaw gear-head lathe and the spindle is produced with a 10 inch tool-room, belt drive collet lathe. 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.

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 practice. 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 manufacturing and CNC equipment.

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

- Fully dimensioned and toleranced drawing with a complete title block and document control.
- Work order with process plan, cost estimate and correlation to document control.
- Feed and speed calculations for all machining operations.

The subject of the student project is of their own invention. They are allowed to utilize any of the processes covered including additive manufacturing in a number of 3D printers, and CNC production in a vertical machining center or CNC lathe. An example of a student project is shown in Figure 4. With the group projects the students are required to increase the project challenge through part complexity, use of the CNC processes or design of an assembly. Additionally, the students are required to give a group presentation on their final design. The student project grades are based solely on the documentation they produce 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. The project builds are encouraged and supported but not required; two such completed projects are shown in Figure 5 and Figure 6. The grades are based on the design and documentation that the students produce but not on product they build which reinforces the priority of the design and documentation as an engineering responsibility.

Figure 4: 3D printed monolith completed as an individual project during the Design for Manufacturing course.

Figure 5: CNC connecting rod completed as a group project during the Design for Manufacturing course.

Figure 6: Snowmobile spindle assembly with CNC main structure completed as a group project during the Design for Manufacturing course.

Energy Systems Product Development and Design, Sophomore Year

The sophomore energy systems product development and design class includes four major components:

A lecture series considering sustainable conversion and use of energy; long term utilization of energy sources and the environment; fossil, nuclear, and selected renewable sources; conversion techniques and efficiency; sustainable energy for vehicles.

A supporting lab series that focused on evaluating efficiency of small scale energy conversion devices including:

- Solar energy transfer and constant
- Thermal radiation
- Fuel cell conversion of solar energy
- Wind energy
- Hydro-electric energy

Introduction of an innovation product design methodology focused on stimulating innovative thinking. Student teams conceptualize multiple ideas in each of the following areas:

- Energy conversion processes (fossil, renewable),
- Energy storage, conservation,
- Consumer product,
- Energy for vehicles,
- CO_2 capture, NO_x emission reduction,

- Completely different/unique idea (could be outside the energy focus)

Through iterative design reviews and a weighted evaluation in areas including safety, cost, lead time, manufacturability, ability to verify and innovative merit the team selects one project for further development.

Student team projects are developed and completed during the course for a multiday series of final design reviews. Attendance at the reviews includes the students from the freshman course, enhancing the freshman understanding of expectations in the sophomore year and reinforcing the value of the freshman training. Traditional design process tools are combined with the innovative approach for total design rigor that includes:

- Multiple concept evaluation
- Weighted decision making process
- Design reviews including faculty, peers and support resources
- Project packet including fully dimensioned prints and manufacturing plan
- Student manufactured product
- Product performance verification
- Final presentation of the product, process and results.
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Figures 7, 8 and 9 show some of student products.

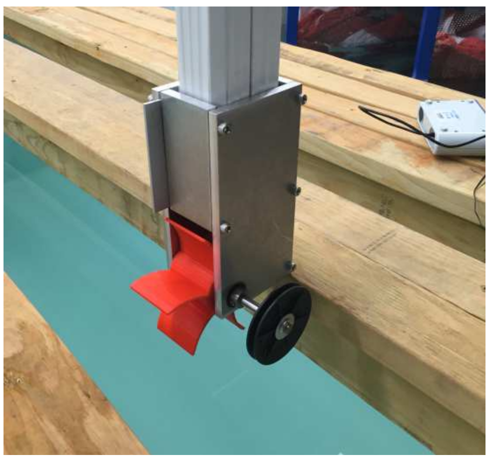

Figure 7: Rain gutter hydroelectric power generation assembly with 3D printed impeller, machined components and real time data collection completed as part of energy systems product design.

Figure 8: Solar powered radio controlled car completed as part of energy systems product design. Feasibility studies were completed for fully solar powered application and solar assist.

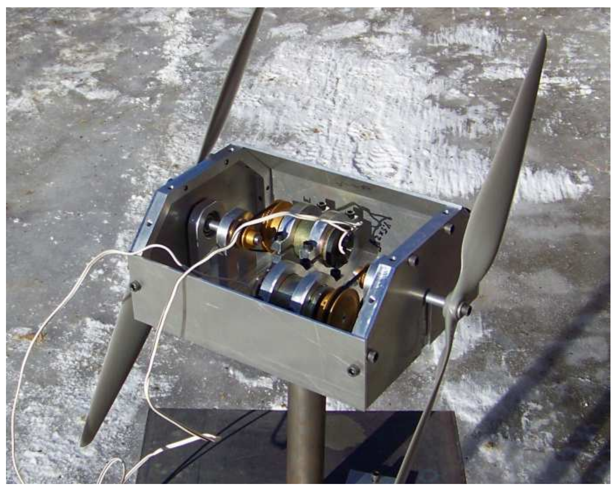

Figure 9: Counter rotating prop wind generator completed as part of energy systems product design. Various prop configurations were studied to maximize efficiency with varying wind conditions.

Results to Date

Results we have noted include:

- A culture of safety and acceptance of lab policies. There are a formal set of lab policies included in the design for manufacturing course zero tolerance lecture. Initial enforcement of these rules resulted in several students loosing lab access. Within the first year of implementation of zero tolerance, open violations were eliminated and the students now commonly will ask for assistance on any potentially hazardous activity. Additionally students now commonly will offer their opinions on safety to the instructors and fellow students.
- Reduced scrap due to a philosophy of first time right. The students understand that they must invest time up front in development of a complete set of prints and process plans before fabrication begins. The students are seeing the benefits and the department is realizing them. Prior to implementation of design for manufacturing an audit of student projects showed that almost 75% of all components built either had to be reworked or rebuilt. Primary sources of this scrap included lack of consideration for tolerance, stacked tolerance, loss of reference between setups and poor material selection. Currently rework and rebuild levels are less than 5%. Typically there is at least one considerable discussion on the build plan for each job. These discussions are a learning opportunity for the students as well as an opportunity to showcase the thoughts they have put into the planning.
- Improved student understanding of the manufacturing processes resulting in more confidence and fewer problems. The students have a better idea of what they are doing and why, and they are required to have a plan. As a result they are also making fewer mistakes. The net result is a less stressed atmosphere in the lab with fewer rushed projects and repairs.
- A student understanding of an innovative product development process that requires rigorous evaluation of multiple options before arriving at the design of record. Early exposure in their academic career allows the student to integrate the process in subsequent academic semesters. By repeating and iterating the process the graduates are better prepared for working in an innovative field.
- Students understand the value of product evaluation including tangible results against proposed gains. Grading in sophomore design is based in part on verification results. Often verification shows unexpected results, solidifying the value of verification to students.
- The understanding of the teamwork required to take a product through a design process including conception, evaluation, design, manufacturing, verification and presentation. In both design for manufacturing and sophomore product development students are required to present results and discuss the issues of the project. Students commonly highlight the issues and advantages of working with their team.

- Early engagement in teams and tasks involving complex engineering design projects increases the student's confidence and self-efficacy and encourages students to develop academic and social support networks while in school. Our expectation is that this will increase academic performance throughout their college career.
- Generally, a high level of student interest in this course series. There are a number of factors that may contribute to this interest:
  - Many students view energy sustainability as a globally significant and exciting focus.
  - Hands-on fabrication is appealing to many students.
  - The creative freedom encouraged provides positive reinforcement of student ability.
  - The innovative design process gives students a structure to be productive in a group that explores novel territory.

Future Plans

As with any significant undertaking the development of this curriculum has been iterative and will likely continue to be so. There is an immediate plan to include an alternate path within the freshman year including marketing and graphic design. The concept here is to enable the students less interest in hands-on manufacturing to develop an alternate skill set that complements the manufacturing skill set. For the second half of the course the freshman students from both training options would be integrated into project groups for better-rounded teams. Introduction of the innovative design process at the freshman level has been proposed, developing an innovative mindset earlier while allowing the students to repeat the process and improve their understanding at the sophomore level.

The long term plan includes formal evaluation of projects near the end the sophomore year for innovative merit. Projects meeting established criteria as innovative and with merit will continue on through the junior year as part of an innovation curriculum. There will be another evaluation at the end of the junior year and acceptable projects will be part of capstone design under the innovation curriculum. The innovation agenda will include continuous product improvement through regular design reviews by faculty, peers and industrial partners and increasing design rigor as student academic knowledge grows. This "innovation path" is depicted schematically in Figure 10.

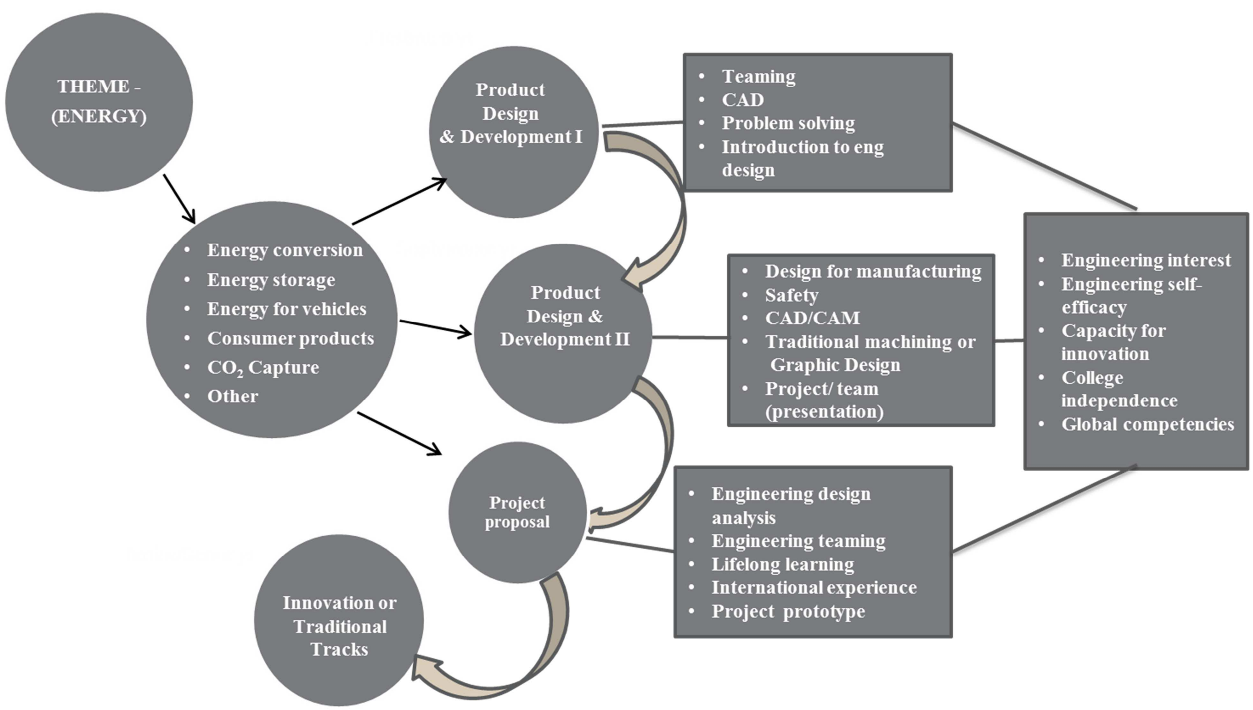

Figure 10: Proposed innovation path will build on elements in the current curriculum to develop a freshman through capstone product development sequence.

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