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Adopting a Common Product Design Process across the Undergraduate Mechanical Engineering Curriculum

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Introduction

Although most mechanical engineering undergraduate programs in the US include a capstone senior design experience, the level of training that the students receive in the product design and development process can vary considerably between programs. In some cases, students learn the product design process in parallel with their capstone senior design project. In others, there are one or more previous courses that focus on teaching different phases of the product design and development process. Also, there are other factors that impact student learning such as variations in the design process favored by each faculty member supervising a capstone senior design project, the specific design process presented and the terminology used in different product design textbooks, and the product design textbook selected for each course of a product design course sequence.

To provide students a comprehensive education in product design and development, the Mechanical Engineering Department at the South Dakota School of Mines & Technology implemented a holistic multi-pronged strategy. First, it adopted a specific product design process as the standard reference that faculty, students, and product design related courses would consistently use. Then, it identified a design spine sequence of project courses throughout the curriculum in which the students would be exposed to different aspects related to that product design and development process. This information was codified in the department's website and brochures where current and prospective students could find general information about the product development process and the product design topics that students would learn in each course in the sequence.

The product design process selected is based on existing references [1,2] and is well-suited for products of low to moderate complexity that are engineered, discrete, and physical. The course sequence includes courses at the freshman, sophomore, and junior levels, and culminates with a comprehensive capstone senior design project that is conducted over two semesters. In some of the courses in the sequence students are introduced to basic systems thinking and systems engineering concepts to help them pursue a holistic approach while conducting design tasks. To further complement their product design education, interested students can also take a senior elective course that places a strong emphasis on design thinking.

Commented [MKKH1]: Include the reference

This paper describes in detail the multi-pronged approach used at South Dakota Mines' mechanical engineering undergraduate program to provide students a comprehensive education in product design and development. The product design process selected as the common reference is presented, the product design and development topics covered in each course of the sequence are given, and examples of key learning activities that take place in each course are provided. Reflections from faculty teaching the courses are also shared.

Faculty members from other educational institutions may find the information useful to develop strategies to increase the training that their students receive in product design and development.

Product Development is a Means to Make Better Future Engineers

Product design and development is core to the educational mission of Mechanical Engineering at the South Dakota School of Mines & Technology. The Mechanical Engineering Department has a culture of product development promoted throughout the undergraduate curriculum by way of a project-based learning product design spine, and supporting resources, to make better future engineers.

Our undergraduate curriculum injects product development across the curriculum completely, establishing learning experiences from first to senior year. Many courses throughout the curriculum have aspects of an applied nature, making connections for students to the local and global context of mechanical engineering. Faculty incorporate product development in a project spine of courses at each level. The traditional engineering shop functions for students as a makerspace and innovation commons, giving space and time for appropriate work and collaborations outside of class. We seek to have a holistic understanding of balancing mechanical engineering's engineering science and its application to innovation, and to connect theory and application/context for students through product development.

Context and ABET

ABET criteria includes the following definition [3]:
"Engineering design is the process of devising a system, component, or process to meet desired needs and specifications within constraints. It is an iterative, creative, decision-making process in which the basic sciences, mathematics, and engineering sciences are applied to convert resources into solutions. The process involves identifying opportunities, performing analysis and synthesis, generating multiple solutions, evaluating those solutions against requirements, considering risks, and making trade-offs to identify a high-quality solution under the given circumstances. For illustrative purposes only, examples of possible constraints include accessibility, aesthetics, constructability, cost, ergonomics, functionality, interoperability, legal considerations, maintainability, manufacturability, policy, regulations, schedule, sustainability, or usability."

The ABET student outcomes (General Criterion 3) include:

- An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.
- An ability to apply the engineering design process to produce solutions that meet specified needs with consideration for public health and safety, and global, cultural, social, environmental, economic, and other factors as appropriate to the discipline.
- An ability to function effectively as a member or leader of a team that establishes goals, plans tasks, meets deadlines, and creates a collaborative and inclusive environment.

Methods

Documentation analysis

To identify common and distinguishing elements across courses with respect to product design and development, documentation analysis (course syllabi, course descriptions in academic course catalog, textbook) [4, 5] was undertaken. A cross-case comparison [6] is undertaken to be able to compare and contrast these learning experiences more specifically.

Qualitative interviews of teaching faculty

This qualitative set of descriptions are augmented by interviewing faculty of these courses. A series of qualitative, semi-structured, reflective and critical incident interviews [7] were performed. The interview protocol used is listed below in Table 1.

Table 1 Faculty interview protocol

1. Can you tell me about the Product Development classes at Mines? What are your views on the program?
2. Can you tell me how this approach differs from other institutions? Ones you've taught? Where you went to school?
3. Can you speak on some of the goals you have when teaching *insert class number*? Do your goals differ from the goals of the PDP Program? In what ways?
4. Can you give a brief summary of your *insert class number* class?
5. Can you walk me through your syllabus for *insert class number*? What activities do you do in there that teach students about PDP? Could you give me examples?
6. What are your thoughts on senior design? In what ways does your class touch on preparing the students for future classes in the PDP?
7. What do you like about ME PDP? What would you change?
8. What made you want to develop this program?

Personal reflection

The first author also added her own reflection and autoethnography as an undergraduate student in the Mechanical Engineering program, along with specific project examples to illustrate course content.

Positionality

The first author is an undergraduate Mechanical Engineering major in the fifth year of study. She mentors first-year students in a first-year introduction to manufacturing course and serves as a grader for the introduction to mechanical engineering course. Like many students enrolled in this degree, she knew she wanted to be an engineer because of the toys she grew up with. Successive internships made real the importance of a structured engineering design process. The value of a mindful design process is a newly discovered curiosity.

The second author is a faculty member in the Mines Mechanical Engineering department with a background in user-centered design and an interest in better understanding the learning of students as they navigate design courses and activities. He and the third author have a personal and professional stake in the propagation of design throughout the curriculum.

Overview and Context: Learning By Product Development Project Spine

A formal product development set of project-based learning courses have been developed and infused throughout the four years of the curriculum. Throughout their studies, students are assigned team projects to conceptualize, design, prototype, and demonstrate a new product concept that solves a real-world problem and satiates a social need. A product development process is a sequence of steps or activities that are followed in order to conceive, design, and commercialize a product. Our focus is on market-pull product opportunities. Market opportunities are identified and then engineering and science are employed to satisfy that market need. A visualization of these courses is given below in Figure 1 and described in the following section.

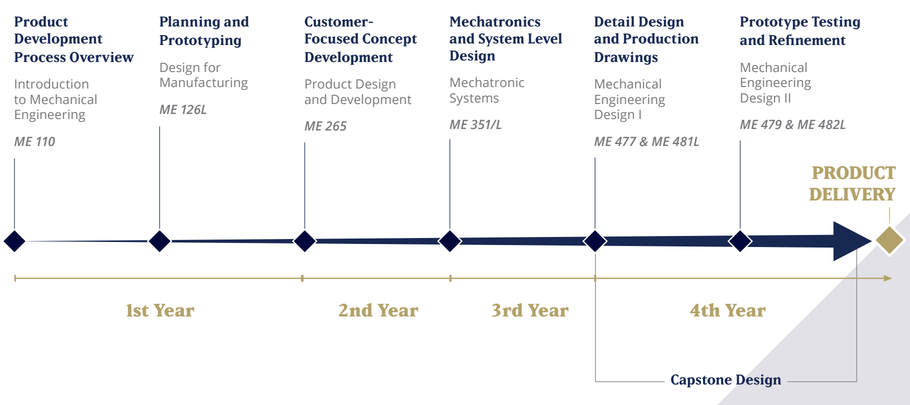


Figure 1: Mapping of Product Development via Project-Based Learning courses

Product Development Course Overview: Descriptive

First Year

ME 110 Introduction to Mechanical Engineering: This course provides a general overview of the product development process adopted by the Mechanical Engineering Department, so that the students become familiar with its phases and terminology during the first year. Emphasis within the course is placed on fundamental engineering analysis that is needed within the product development process along with hands-on experimental lab/project team activities to better understand the engineering fundamental principles along with the benefits of working in a team. [8,9]

ME 126L Design for Manufacturing: This course focuses on concept development, detail design, and testing and refinement steps in the product development process. This course will teach students the use of CAD software, geometric dimensioning and tolerancing, and considerations for the manufacturability of a product. The class includes hands-on training and the use of machining, welding, 3D printing, woodworking, and plasma cutting equipment. Students gain experience with hands-on, manual equipment, as well as programming of computer numerically controlled (CNC) equipment. With the final team project, the students get to learn through a student-driven design build project. [10]

Second Year

ME 265 Product Design and Development: The course presents a typical development process for products of low to moderate complexity and introduces basic systems thinking and systems engineering concepts. Emphasis is placed on presenting structured methodologies to conduct each of the main activities of the conceptual design phase. Students work in teams on a semester-long project that allows them to apply what they learn in class to develop a concept for a simple product. At the end of the semester, the teams use a physical prototype to illustrate how their proposed product would look and work. [11]

Third Year

ME 351/L Mechatronic Systems: The course presents the design process for complex products whose operation requires the synergistic combination of multiple disciplines of engineering including mechanical, electrical, computer, and control systems engineering. During the semester students learn the basic concepts for each of the main components involved in the design of a mechatronic system including sensors, actuators, input/output signal conditioning and interfacing, digital control systems, and user communication. The final project includes student teams integrating their learning from the classroom and laboratory experiments and applying them toward the design and implementation of a mechatronic product. [12]

Fourth Year

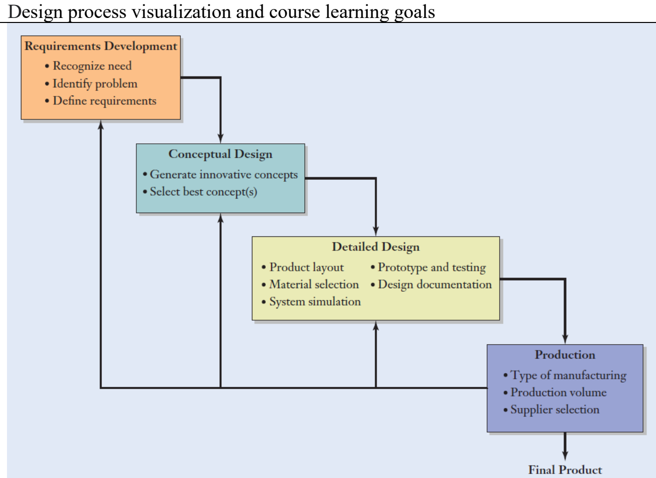
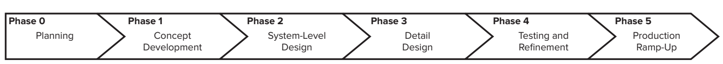
ME 477 & 481L Mechanical Engineering Design & ME 479 & 482L Advanced Product Development: This is a two-semester sequence focuses on the entirety of the product development process up to prototype development and testing. During the first semester, teams focus on project definition, customer needs, and product requirements before diving into the preliminary design process where multiple alternatives are considered, and a final conceptual design is created. Initial prototypes and proof of concept experiments can be conducted to support the preliminary design. During the second semester, detailed design and analysis is completed to ensure the product will meet functional requirements and customer needs. Manufacturing drawings and plans are developed in order to complete a functioning prototype that is tested and evaluated by the team. These results are showcased in a senior design fair at the end of the semester.

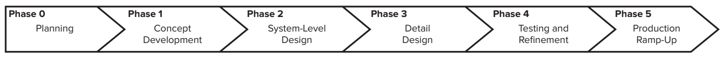
Results

Design Process Maps

The range of courses identified have visualizations of the engineering design process appropriate for the course level and course content. It ranges from a prescriptive introduction of a process to specific skills and tools to apply to the design challenge at hand. Figure 2 captures examples from course textbooks.

Figure 2 Design process maps

Setting	Design process visualization and course learning goals
First year intro to ME course	 from [2]
2nd year, Product Design and Development course	 from [1]
3rd year, Mechatronics course	Below is a set of basic guidelines you should follow when using breadboards to prototype circuits involving integrated circuits. Generally, if you carefully follow this protocol, you will save a lot of time and avoid a lot of frustration: a. Start with a clearly drawn schematic illustrating all components, inputs, outputs, and connections. b. Draw a detailed wiring diagram, using the information from datasheets regarding device pin-outs. Label and number each pin used on each IC and fully specify each component. This will be your wiring guide. c. Double-check the functions you want to perform with each device and test them individually. d. Insert the ICs into your breadboard. e. Wire all connections carefully… f. Be very gentle with the breadboards…

Capstone design course	 from [1]

Specific Course Reflections and Example Projects

The Introduction to Mechanical Engineering, or ME 110, course introduces many concepts that freshman will use throughout their entire curriculum. These topics include units, basic statics, and one of the most important, brainstorming. Concept generation is an important aspect of any Product Development Process (PDP). Design projects are specific pedagogical moves in the course to get students excited about their Mechanical Engineering major. One design challenge is having student groups explore fluids engineering and buoyancy by designing and 3D printing small boats to optimize the amount of mass to be held [8,9].

The goal of the Design for Manufacturing (ME 126) course has remained the same for as long as the first author has been at the South Dakota Mines. According to course coordinator, the goal is simple "to have the ability to design a part that can be built and machined." This is important because understanding the limits of machining is a critical when a student designs a component. There may be a stigma with machinist and engineers because so often engineers do not understand the limitations of how things can be made. "The 126L class goes a long way when helping students understand that process." This class was designed to force people to collaborate and come up with new innovative ideas. The resources, mentorship, and equipment have greatly improved since the first author did her project. When the first author was a freshman taking this class, her team took their common love for the outdoors and made a product to represent that. They called the product that they made a "Porta-grill." A small grill you could take with you anywhere in the outdoors (see Figure 3). This class provides specific experience for many students who had never been in a machine shop, and strokes a passion for the hands-on design and build process. There is a support structure of near-peer student mentors to help with the ideation and fabrication. A goal for some mentors is to help freshman take their wildest ideas and turn them into a buildable prototype.

Figure 3: The Porta-grill prototype

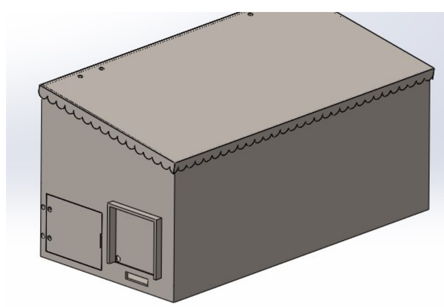


Figure 4: Mailbox Hide-a-key Prototype Design

The main priorities of Sophomore Design (ME 265) are focusing on the customer when it comes to product design. Students are first given a task for their projects to be built off. For example, when the first author took the class students were given the task of “creating a security system.” By giving students a topic to start it narrows down the product space. The attention of the student teams is centered on the concept development phase. Although prototype development is not the main focus of this class, the project requires the use of an Arduino to show students the power in prototyping with simple electronics. According to one of the course instructors,

> *“265 is the front end of the spine. Are we solving the right problems? Do we understand the problems? The class is user and people focused. Prototyping is the afterthought. The customer needs are the priority of the class.”*

The first half of the semester is students learning and conducting PDP activities such as preparing a product mission statement, identifying customer needs, performing a competitive benchmarking, setting target product specifications, concept generation, and concept selection. The first author’s group developed the idea of a mailbox hide-a-key (see Figure 4 above). During the first author’s internship this past summer, this class textbook was the one she referenced the most for the work she was doing.

ME 351 Mechatronics is a class that focuses on the detail design phase of the PDP. It takes the basic electronics learned in ME 265 and has students dive deeper into those types of systems. One instructor reflects:

> *“The vision for the class is less about person and more about making sure the design has the right details. The class will soon resemble a mechatronic version of ME 126L.*”

Students are tasked in looking for three key features when it comes to the class projects. First, does it work? Second, is it refined? Third, is it economical. The class projects are typically centered around making basic robots, which could be path following robots, boats, catapults, and more.

ME 477/479 senior capstone design is a two-semester course sequence, allowing for the scope to be larger than a 1-semester experience. There is a strong emphasis on authentic problem-solving and multidisciplinary projects. A course coordinator for senior design recruits companies to identify project opportunities for the students. The department also allows for students to come up with project proposals as well. The first author’s senior design project was proposed by students. Her team saw PLA filament going to waste in the 3D Print Lab and proposed a PLA plastic recycler. The ME Department has been the main driver across campus to get departments to work together in the capstone senior design experience. A faculty member says, “The ME department leads the effort to have multidisciplinary teams.” Teams with multiple majors involved are more realistic to company projects. It allows the students to learn to work in diverse creative environments. With senior design being the culmination before graduation, students are able to practice the engineering profession.

Findings from Faculty Reflections

Growing Endeavor

The Product Development Process (PDP) emphasis in the undergraduate program has been in place for the quite some time. By 2017, there was a seed in the sophomore product design and development course grown by a long-time faculty member. But as a faculty member describes, the focus on product development needed help:

> *"I fanned the flames, encouraged faculty, renovated spaces, and hired staff to help build the program further." The two main hires? Dr. [A] and Dr. [B]. The PDP here at mines is nothing compared to any other engineering school in this country."*

Different Approach

In addition, a faculty member active in ABET nation-wide and through a professional society at the nation level relates:

> *"We have a unique program. I've never seen it before; I haven't heard of another school doing this. Most ME programs have no project work until the senior year. It is the benefit of smaller school; we can do that. We can provide the resources, we can run the shops, we can hire the [student] mentors to help. Compared to other schools, we are innovative."*

Different from my own undergrad

South Dakota Mines is an undergraduate STEM focused university. As one faculty member relayed, the undergrads here are earning a degree that is preparing them better for industry than many other colleges. Speaking from the experience of being an undergrad at a R1 school, one faculty member indicated the following: "We produce better practicing engineers than the research schools." The research side of engineering is important, the practical side is where the innovation is. Another faculty member agrees:

> *"I'm jealous of the undergrads here. My undergrad was very analytical. I had one lab, and it was chemistry. It made my senior design difficult. It was the only time I was allowed to be creative and without practice in being creative it made it hard."*

The PDP is an advantage to every mechanical engineering coming out of South Dakota Mines. This is validated by some many employers (170+ companies) attending out local career fairs looking to hire students.

Discussion

Engineering design is orthogonal to the engineering science, analysis, math and physics parts of the holistic undergraduate mechanical engineering curriculum. While the product development process can be interpreted slightly differently depending on being at an introductory, mezzanine, or capstone level, it can be very beneficial to new engineering graduates. As the first author reflects on her own experience through the program: “It made me be creative again and enjoy engineering. Prototyping is very important and helps to communicate. The first idea is never your best idea; always keep thinking of more. Ideas can always be improved on; difference perspective add so much value.”

According to the Mines ME Department website and product development brochure, it is “a sequence of steps or activities that are followed in order to conceive, design, and commercialize a product.” It is a very broad definition that can be adapted depending on the need. For our campus, we can limit the commercialization aspect. All the products students make are small scale, and do not need to be prepared for a production setting. That allows Mines [students] to focus on the beginning of the PDP. This allows the classes to interpret what they need to teach form each section of the PDP flow chart. Those sections are generally brainstorming, user evaluation, prototype development, detail & system design, and testing & iteration. These mindset modes for product development are listed below in Figure 5.

Figure 5: Mindset modes for product development

The five classes focused on PDP, takes an in depth look into different sections of the PDP. The culminating senior level class is meant to encompass every aspect of the PDP flow chart and encourage seniors to follow the flow chart from the beginning to the end over the course of their two-semester senior design. When compared to other PDP’s, these are the key components of the ME curriculum on our campus. It is tailored directly to what we teach in these five classes. Those five bubbles in the figure above are the building blocks that will not only implement creativity across all years of schooling, but it will prepare the students for the back half of the product development process when they go into industry.

Each class in the subject of the PDP has some sort of focus from the diagram seen above. All of these are taught and given to students as tools, in the hopes of them being useful in future classes. Introduction to Mechanical Engineer (ME 110) and Design for Manufacturing Lab (ME 126L) focuses on the first bubble in the diagram, Brainstorming. User Evaluation is the attention on customer needs, requirements, and specs. This is the focus of the department's Sophomore Design Class (ME 265). Prototype Development is seen being taught in all the PDP classes, but it is only the main priority in ME 126L and ME 110. Detail & System Design are discussed extensively in Mechatronics and the lab portion of the class (ME 351L). The final class is the PDP for Mines is Senior Design (ME 477 & ME 479) this is the first time we take attention to the Testing & Tuning section of the flow chart. This course should also encompass the entire flow chart as well. Below you can see the spine of classes and their focuses that the department has adopted.

Table 1: Relative Courses to the PDP Flow Chart

PDP Phase	Classes & Lessons Taught
Brainstorming	▪ ME 110, ME 126L, & ME 477/479 ▪ How do we brainstorm effectively in teams and individually? ▪ What are the goals of brainstorming? ▪ How can we use these tactics in the future?
User Evaluation	▪ ME 265 & ME477/479 ▪ How do we find customer needs? ▪ How do we determine requirements and specs? ▪ How do we meet customer needs through design?
Prototype Development	▪ ME 110, ME 126L, & ME477/479 ▪ How can we convey our ideas in an economic way? ▪ What resources can we use for concept generation? ▪ What machines are available to use for prototyping?
Detail & System Design	▪ ME 351 & ME 477/479 ▪ How can we ensure our design has the correct details needed? ▪ What are the right materials, products, etc. for our design? ▪ Is our design economical?
Testing & Tuning	▪ ME 477 & ME 479 ▪ How can we refine our product? ▪ How can we test our product to make sure it hits our customer needs? ▪ How can we improve our prototype?

Opportunity: Engaging Students to Persist in Mechanical Engineering

Product development overlayed mechanical engineering gives students collaborative applied learning, progressive educational opportunities. Placed within their mechanical engineering education, such practice and work can help students persist, from first to second year, from sophomore to junior, on to graduation. The current increasing popularity of engineering design as an undergraduate engineering course is the result of engineering institutions' response to calls from employers in industry, ABET, and the National Research Council for reform in the way engineering graduates are trained. Product Design and Development project spine courses are fashioned to allow students to work in teams while solving ill-structured problems that may have multiple "correct" solutions and undefined constraints that influence the choice of solution.

Students and faculty alike adopt a mindset that favors product development in their classrooms and their work practice. At South Dakota Mines we have found:

- Stronger integration of product development into project and non-project classes
- Faculty culture change toward more active learning techniques to engage students
- Improved student outcomes (e.g., content knowledge, self-efficacy)

All of these educational efforts are meant to forge better future engineers.

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