Learning through Product-Based Learning with Emphasis of People, Process, and Product Across Multi-Disciplinary Courses

Abstract

This research paper extends the frameworks of PBL as project-based learning to describe a concept of "product"-based learning – learning experiences that focus on the deliberate design and making of tangible products with some engineering complexity as the learning goal of a course. A multiple case-study approach is used to apply and illustrate a "product"-based learning framework to multiple multi-disciplinary courses: a global design innovation course with corporate project sponsors, and a mechatronic (smart products) design course. We develop and describe three dimensions for considering the pedagogical intent of such courses along axes of people-focused, product-focused, and process-focused in their efforts to give students practice as engineers and engage in industry and community partner projects.

Keywords

Design Education; Pedagogy; Product-based learning; Project-Based Learning; Multi-Disciplinary Learning

1. Introduction

The frameworks of PBL as project-based learning are extended to define a concept of "product"-based learning – learning experiences that focus on the deliberate design and making of tangible products with some engineering complexity as the learning goal of a course. Both because of more available and accessible digital fabrication tools and a rise on maker-based pedagogy, such educational approaches are progressing past just learning experiences that are project-based but more and more one can realize a functional and desirable product (in addition to the underlying technology). This greater availability of rapid prototyping and maker spaces can support these types of learning experiences, allowing student teams more access to holistically imagine, design, and more readily build their solutions. The more authentically these learning experiences can be curated and staged by instructors, the more meaningful and useful such courses can be for our students as future engineers.

Professional preparation of engineers, as with the law, and medicine, necessitates the application of knowledge through an applied rehearsal in authentic learning situations. The clinic of law or medicine is sometimes practiced as a capstone educational experience in fields of engineering. Having engineering students work together on a project is becoming a prominent pedagogical approach in upper-level engineering undergraduate courses and graduate courses. This directly supports the professional practice and professional formation for many fields of engineering and addresses many ABET student learning outcomes.

A multiple case-study approach was used to apply and illustrate a "product"-based learning framework to multiple courses: a global design innovation course, a mechatronic (smart products) design course, a designing for the developing world design course, and a measure of comparison, a beginning statics course. We also develop and describe three dimensions for considering the pedagogical intent of such courses along axes of people-focused, product-focused, and process-focused. By identifying and describing aspects relevant to the deployment of a product-based learning approach, crossed with considerations of developing the people, product, and process of the learning intent and concentration of appropriate activities can be helpful to better place classes across a learning spectrum as well, making better informed educational experiences. It can also be of use to be able to start to understand how contextual and pedagogical approaches can be applicable across the extent of a number of considerations such as balancing breadth and depth, abstract and concrete concepts, and engineering science and engineering design.

2. Motivation

2.1 Practicing Creativity and Innovation

The evolution of this paper has been due to an ongoing research project to better understand the long-term and sustained utility and effect of in-depth project-based learning educational experiences for students as they enter the workforce. It is curious how coursework can support students' learning of both technical content in their studies, but also additional collaborative learning settings can also develop additional desired learning goals that may translate to the success of alumni and their professional advancement. For the National Academy of Engineering's *The Engineer of 2020* [1] project, for example, emphasis areas for the characteristics of future engineer included to-be-expected aspects such as technical expertise. Additional qualities like creativity, flexibility, practical ingenuity are also of note. In considering how making can be infused into engineering curricula, one can map some aspects of making in the Maker Community [2], to *The Engineer of 2020* [1], to 21st Century Skills [3] to ABET student outcomes [4]. This is summarized in Table 1 below.

Table 1: Learning Traits Summarized from Different Community Resources

maker community [2]	*engineer of 2020 [1]*	*21st century skills [3]*	*ABET [4]*
creative confidence	creativity	creativity & innovation	*n/a*
playful invention	practical ingenuity	critical thinking & problem solving	identify-formulate-solve engineering problems
self-directed learning	lifelong learning	initiative & self-direction	lifelong learning strategic thinking

How might we support engineering students' learning? And what is authentic engineering or professional activity, or professional preparation. Perhaps the ambiguity of creativity, creative confidence, or creativity and innovation is too broad to be included in ABET student learning outcomes. It is curious how some of these areas may be present in addition to technical content.

2.2 Mindful Design Education Efforts

Increasingly, design-focused coursework is including novel and (relatively) new approaches such as more emphasis on human-centered design and design thinking. Dym et. al. [5] captured many approaches for design to be used as pedagogical innovation itself. This can now be extended to encapsulate also what Making and makerspaces provide in support of such educational activities [2, 6, 7] There is wider adoption of digital and rapid fabrication tools such as 3D printers, as well as additional models for community engagement such as community-based design and co-design in makerspaces [8, 9]. By having students focus on solving problems that they themselves care about, or at least identifying a problem that has a person in the middle of the system, there are increased possible opportunities to engage in social justice, and applied ethics [10] in doing engineering work. For the purposes of accreditation, ABET has also propagated a definition for engineering design more broadly as "a process of devising a system, component, or process to meet desired needs and specifications within constraints" [4]. Additionally additional context and inputs about the global, societal, cultural, and environmental aspects of an engineered system are now also part of the expected student outcomes ABET delineates.

3. Context

We examine a number of mechanical engineering courses at [university] that are project-based learning extended design-based courses that have the creation of an artifact of some engineering complexity. The students are similar enough across the courses as Master's students in Mechanical Engineering (and have some students taking both courses) but also have different types of emphasis on developing technical solutions and solutions that are designed as technology that appropriately addresses a latent need for a group.

ME 200 A-B-C (a pseudonym) and ME 301 A-B-C (a pseudonym) are both examples of course sequences in design that leverage a project-based learning approach to allow students to dive deeply into designing and building functional systems of some engineering complexity. For both courses, the pedagogical approach is through project-based learning; though with a target deliverable of a functional engineered systems, it is not just the application of an engineered design but the ingenuity of developing a technology into a product. This focus of a widget gives some indication that that such a tangible end-goal may provide some additional motivation and guidance for student teams, both as a product-focus on learning and as a type of Maker-based pedagogy [11]. A humanitarian-engineering design course are also to be examines; an undergraduate ME 10 (a pseudonym) Statics class is also included to provide a baseline example.

4. Goals

Goals for this work is developing and to contribute a framework for defining and comparing courses with an emphasis on design, design process, and a designed artifact. Many of these courses use a project-based learning approach. We do not aim to have a singular pedagogical approach for all courses, but rather to add vocabulary to how these courses are conceived, designed and assessed, relative to overall/overarching learning goals. To identify common features and distinguish elements across courses, studied three design course sequences at [university].

5. Theoretical Framework: PBL

PBL is used to describe both problem-based and project-based work at present. The characteristics of PBL [12], as described in the literature, include student-centered learning, small groups, instructor as guide, design challenge focused, and self-directed learning and skill development by students. Some of these items are structured as part of course design and others are a reframing of the role of instructors and students in the classroom. Much is centered on the pedagogical approach, irrespective of specific technical content.

Prince [13, 14] provides this definition:

> *Problem-based learning (PBL) is an instructional method where relevant problems are introduced at the beginning of the instruction cycle and used to provide the context and motivation for the learning that follows. It is always active and usually (but not necessarily) collaborative or cooperative using the above definitions. PBL typically involves significant amounts of self-directed learning on the part of the students.*

Problem-based learning is typically an application where the problem is well-enough defined to be solved. The instructor can define the problem, the solution unknown to the students until they invoke the problem-solving procedure. Project-based learning can be an unknown open-ended problem to be explored. The characteristics of PBL, as described in the literature, include student-centered learning, small groups, instructor as guide, design challenge focused, and self-directed learning and skill development by students. Some of these items are structured as part of course design and others are a reframing of the role of instructors and students in the classroom. It is centered on the pedagogical approach, irrespective of specific technical content.

The types of knowledge applied is a range as well. PBL is a situated learning setting, with groups collaborating and creating new knowledge. There can be an application of cognitive knowledge such as declarative knowledge (facts) and procedural knowledge (how-to) as well as deployed as strategic knowledge [15].

MIT's New Engineering Education Transformation Initiative report on global engineering education [16] was full of noun phrases that underscored aspects of PBL, and provide synonyms for aspects of PBL, below listed in Table 2.

Table 2: Noun Phrases from MIT report on global engineering education [16]

design- and maker-based learning a collaborative culture a multidisciplinary approach a breadth of education intrinsic motivation	adaptability a common curricular structure applied across all engineering departments multidisciplinary	work-ready environment underpinned by self-directed learning deep disciplinary knowledge design-centered learning

Constructivism [17] offers that student produce knowledge based on their experiences. By having an approach to doing, knowledge is created and made contextual. In these courses where ideas are translated into artifacts, Vygotsky's theory of zone of proximal development [18], can be applied to the scaffolding of problem- to project- to product-based learning (who know the answer) through efforts that a student can do and can do with aid. Structured deliverables provide guidance as to what elements of a design process may be appropriate to move through the engineering design process. The scaffolding to emphasize prototyping and adoption of a prototyping mindset may help as a pedagogical tool [33]. Artifacts that are created in these courses reflect tangible evidence of activity. From the idea to realization, there are means to describe the role, purpose, and creation of prototypes. Gerber & Carroll [19] describe the connection and process of prototype creation. Houde & Hill [20] discuss different types of prototypes as what do prototypes prototype (function, looks-like). Makerspaces also provide additional context for the tools, mindsets, and community of practice [21-23, 11].

Design can be placed across the undergraduate curriculum. Capstone design courses are an application of engineering know-how, practiced through a range of teaching practices. Pembridge & Paretti [25] identified practices commonplace: challenge, protect, coach, promote employability, provide exposure, role models, counsel, build rapport, challenge, provide realistic experiences. Strong et. al. [26] further made distinction between technical content knowledge and pedagogical content knowledge in design-specific capstone courses and what instructors might do to facilitate the former using the later. First-year cornerstone introductory courses are also a common place for foundational design. Sheppard et. al. [27] characterized first-year engineering courses with axis of *what* and *how*: individual to group activities, and "domain specific content knowledge" to "key design qualities."

6. Research Methods

To identify common features and distinguish elements across courses, studied three design course sequences at [university]. Methods involved in the research included documentation analysis (course syllabi, course descriptions in academic course catalog) [28, 29] as well as student and alumni feedback obtained through structured qualitative interviews. This qualitative set of descriptions are augments to a larger research project surveying alumni of each course [31-33] with respect to its short- and long-term effectiveness such as impact on career and professional development, and big takeaways on effectiveness of these "product"-based learning courses. Course alumni were invited to participate in online surveys distributed via email distribution lists and individual emails culled from course alumni, assisted by the school of engineering. 801 participants completed surveys from alumni from 1992-2017. This range was selected as 1992 served as an inflection for the types of projects solicited, now from outside company sponsors. The survey instrument was designed to ask alumni to reflect on their course experience, career pathways since graduation, and reflections on their learnings from such an educational experience. 2 dozen alumni were selected by maximum variation to be invited to semi-structured qualitative interviews asking about the same topics. We specifically use this additional interview data collected from alumni asking specifically about their imagined future project-course experience. These learning experiences are similar in pedagogical approach in that students have some autonomy to explore and direct their design challenges through effects of prototyping, supported by scaffolded activities, labs and milestones and engage regularly with a supportive teaching team of instructors and teaching assistants as design process and technical coaches. A cross-case comparison [30] is undertaken to be able to compare and contrast these learning experiences more specifically. Methods are more fully discussed in Sheppard [31]. The responses about what beneficial and necessary elements of such a future course were abstracted from the larger interview set. The qualitative data collected emergent thematic analysis [47] was conducted to better understand the data as well as to compare it with data collected by other studies.

7. Descriptive Nature of Courses

We have focused our attention on alumni from two specific graduate course sequences, *Global Project-Based Engineering Design Innovation & Development* (Mechanical Engineering [200* A-B-C]) and *Smart Product Design* (Mechanical Engineering [301* A-B-C]:) (* these course numbers are pseudonym for blind review), in order to gain a deeper understanding of how particular course elements and strategies are directly linked to what alumni retain and take away from their education. These course sequences represent two possible Mechanical Engineering depth areas that leverage a project-based learning approach to allow students to dive deeply into designing and building functional systems of some engineering complexity.

Both Global Design and Smart Product Design share similar pedagogical approaches of a product-focus on learning [22] and a type of Maker-based pedagogy [11]. Students have some autonomy to explore and direct their design challenges through the effects of prototyping [22, 19], scaffolded by activities, labs, and milestones [33]. Students not only engage in the applicable of a mechanical engineering design process but are mentored in the ingenuity of developing a technology into a product with regular engagement with a supportive teaching team of instructors and teaching assistants as design process and technical coaches [33, 26]. This high degree of interaction between the students and teaching team translates to a healthy network of course alumni who participate on the periphery as coaches or in quarterly events, presentations, or end-of-year activities.

The specific content of Global Design and Smart Product Design differs in significant ways. Global Design has a focus on team-based design processes for innovative product development with industry-sponsored projects. Since the mid-2000s, there has also been an element of distributed collaboration with a number of academic partners around the world [35, 36]. In contrast, Smart Product Design has emphasized the combined engineering disciplines in mechatronics and employed projects as a means for students to learn how to integrate these technologies into discrete functioning systems to achieve operating design goals [37, 38].

Additionally, to highlight the differences across these two courses, Global Design and Smart Product Design, find listed below unique topics generated to deploy as part of a survey construct for alumni to reflect their experiences.

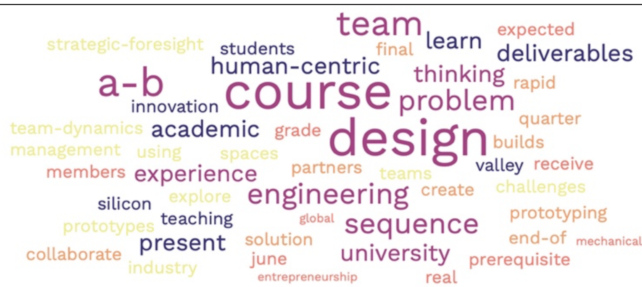
Table 3: Topics included in survey instrument to course alumni

Global Design course topics surveyed	*Smart Product Design course topics surveyed*
Challenging Assumption Building Quick Prototypes Testing prototypes to failure Taking risks with radical design ideas identifying critical questions Building critical systems prototypes	Designing and building electronic circuits Developing software applications (coding) Writing sensor/actuator interface firmware Designing/building integrated mechatronic systems

To provide additional context, the course descriptions for Global Design and Smart Product Design are listed below in Table 4, along with word cloud visualizations showing word frequency. The Humanitarian Engineering course and Statics course are shared as well.

Table 4: Course Descriptions (from [University] academic course catalog, with Word Clouds of word frequency

Mechanical Engineering [200* A-B-C] Global Engineering Design Thinking, Innovation, and Entrepreneurship The [course 200 A-B-C] sequence immerses students in a real-world, globally distributed engineering design experience in the spirit of a Silicon Valley start-up teaching them to manage the chaos and ambiguity inherent in professional design. Teams of 3-4 [university] graduate students partner with a similar team at an international university to work on industry-funded design challenges to deliver breakthrough innovation prototypes. Design challenges are typically at the Human Interface to Robots, AI, Internet of Things, Autonomous vehicles, and Smart Cities. In A you will learn Human-Centric Design-Thinking with the guidance of a teaching team that includes 3 faculty, expert industry coaches, and academic staff. Your team will explore the problem & solutions spaces using strategic-foresight, design thinking, team-dynamics-management, rapid prototyping, and human-centric problem reframing. [200 B] builds on the experience of [course part 1]. You will learn engineering design-creativity focused on RE-EXPLORING the Problem and Solution spaces using strategic-foresight, design thinking, team-dynamics-management, rapid prototyping, and human-centric problem/solution RE-FRAMING. Your will collaborate with academic partners to create and present end-of-quarter deliverables as you continue working towards the final prototype deliverables due in June. [200 C] builds on [course 301 A-B-C]. You will learn to apply pre-production manufacturing techniques dedicated to making your ideas real and testing them with real users to demonstrate serious credibility. Collaborate with academic partners to create and present end-of-quarter deliverables. In June, teams present their results to the world at the [university] Design Experience, a celebratory symposium and exposition where industry liaisons, Silicon Valley professionals, and others converge to explore the final product prototypes.



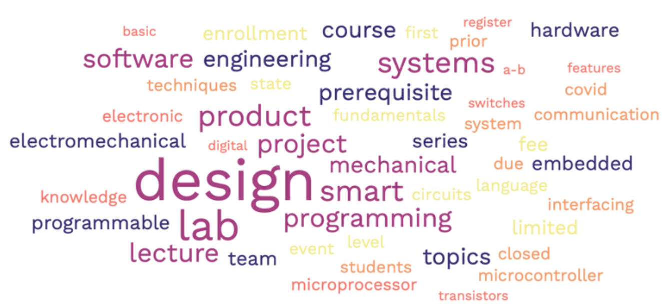
*course numbers are pseudonyms for the same of blind review

Mechanical Engineering [301 A-B-C]: Smart Product Design Fundamentals
Lecture/Lab. First in the team design project series on programmable electromechanical systems design. Topics: transistors as switches, basic digital circuits, C language features for embedded software, register level programming, input/output ports and user I/O, hardware abstraction layers, software design, event driven programming, state machines, state charts. Programming of the embedded system is done in C. Students must have a computer (Win10 or OSX) on which they can install the tools used in the classes and a workspace to complete the lab assignments (in case the lab is closed due to COVID). Lab fee. Limited Enrollment must attend first lecture session. Prerequisite: You should have had a programming course taught in C, C++ or Java and an introductory course in circuit analysis prior to enrolling in [Course 301 A]. Loaner test instruments will be provided in the event that the lab is closed due to COVID.

Mechanical Engineering [301 B]: Smart Product Design Applications
Lecture/lab. Second in team design project series on programmable electromechanical systems design. Topics: More microcontroller hardware subsystems: timer systems, PWM, interrupts; analog circuits, operational amplifiers, comparators, signal conditioning, interfacing to sensors, actuator characteristics and interfacing, noise, and power supplies. Lab fee. Limited enrollment. Prerequisite: [301 A] or passing the smart product design fundamentals proficiency examination.

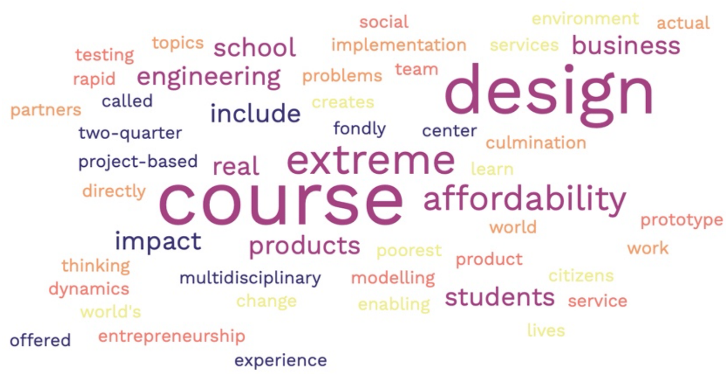
Mechanical Engineering [301 C]: Smart Product Design Practice
Lecture/lab. Third in the series on programmable electromechanical systems design. Topics: inter-processor communication, communication protocols, system design with multiple microprocessors, architecture and assembly language programming for the PIC microcontroller, controlling the embedded software tool chain, A/D and D/A techniques. Team project. Lab fee. Limited enrollment. Prerequisite: [301 B].

Mechanical Engineering [301 D]: Smart Product Design: Projects
Lecture/lab. Industrially sponsored project is the culmination of the Smart Product Design sequence. Student teams take on an industrial project requiring application and extension of knowledge gained in the prior three quarters, including prototyping of a final solution with hardware, software, and professional documentation and presentation. Lectures extend the students' knowledge of electronic and software design, and electronic manufacturing techniques. Topics: chip level design of microprocessor systems, real time operating systems, alternate microprocessor architectures, and PCB layout and fabrication. Prerequisite: [Course 301 C].

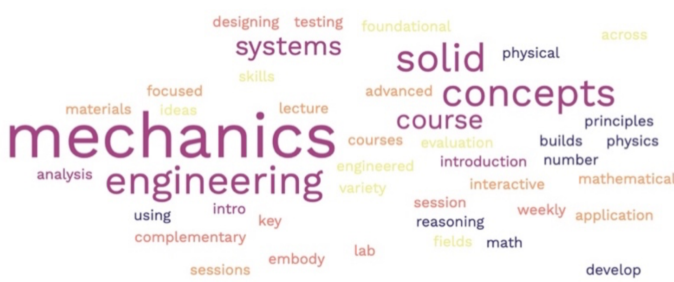


[Course 402 A]: Design for Extreme Affordability
Design for Extreme Affordability (fondly called Extreme) is a two-quarter course offered by the [center] through the [engineering school] and [business school]. This multidisciplinary project-based experience creates an enabling environment in which students learn to design products and services that will change the lives of the world's poorest citizens. Students work directly with course partners on real world problems, the culmination of which is actual implementation and real impact. Topics include design thinking, product and service design, rapid prototype engineering and testing, business modelling, social entrepreneurship, team dynamics, impact measurement, operations planning and ethics. Possibility to travel overseas during spring break. Previous projects include [example companies and products]. Periodic design reviews; Final course presentation and expo; industry and adviser interaction. Limited enrollment via application. Must sign up for [Course 402 A] and [Course 402 B].

[Course 3 B].: Design for Extreme Affordability
Same course description



Engineering [10]: Intro to Solid Mechanics
Introduction to engineering analysis using the principles of engineering solid mechanics. Builds on the math and physical reasoning concepts in Physics [course number] [Mechanics] to develop skills in evaluation of engineered systems across a variety of fields. Foundational ideas for more advanced solid mechanics courses such as [Mechanics of Materials ME course]. Interactive lecture sessions focused on mathematical application of key concepts, with weekly complementary lab session on testing and designing systems that embody these concepts.



8. Results: Alumni Reflections

Select course alumni were interviewed about their professional experiences since graduation and reflections on their Global Design and/or Smart Product Design Courses. The Global Design Course began about 50 years ago [36] , the Mechatronics course at least half of that; there are many course alumni. Some certainly identified the technical content and prototyping aspects of each course sequence experience; more affective aspects of the courses were identified too.

An open-ended question was asked about if one were to create a project-course anew, what aspects would the interview participant suggest retaining from their experiences, either being in Global Design and/or Smart Product Design.

One identified the balancing act between the technical aspects and more broad takeaways:

> *"There's a balance, right, for an engineer or for someone who's sort of technical? I think project-based courses, you learn a lot. You definitely need to begin to express that you'll use later on in the world, but the balance is sort of to not lose sight of the pure technical forces that we have. And I think that's sort of something at Stanford as well. But I know for a fact that some of my peers took Project-Based courses, which really a lot of experience in terms of general problem solving, being able to handle team dynamics, all that stuff. But sometimes you miss out on the technical things that are sort of the baseline requirements that you need to even get the job right. So that's sort of a trap that I think you could fall into a place like [university]…" (Alex a pseudonym)*

It being a class environment, there are instructors, teaching assistants, and other students in a physical space providing support of all kinds: *"You can have a positive failing experience, too. Yeah. And I think that's where that's where the work really needs to be done to improve these courses and to not sustain them, but also bring them to the next level" (Brenda).* And more on the supporting environment:

> *"I really loved how there was a supportive environment that we're there. So, it's not just the professor and it's not like I know some places the mentality is sink or swim. It's sort of you figure it out and if you can't, you obviously are not cut out for this. Well, that wasn't the mentality at [university]. It was a—you know what.. We're all going to try to help one another if you win. It's not like I lose it. We can win together." (Carol)*

The aspect of radical collaboration, that one works in a team, together, for every part of the class experience, renders that collaboration an important takeaway of its own:

> *"And I would have done the team dynamics. …We had issues within the teams. And the first team I was on [there] were issues people, of course, just like any team you get up know, like, OK. You're not pulling your weight, right? OK, what's the dynamic? Give people some tools to be able to deal with that other than doing the typical. OK, we'll just all do more and drag you along. Yeah, that's great. Yeah, it's not the way the world works. Right. You can kick people off the bus. Right. But you have to be able to have that discussion." (Denise)*

The deference given to students exploring their way through these learning experiences too, is something that provides, in the face of ambiguity, to create agency and build self-directed learners:

> *"Yeah, so I think there are there are course aspects and there's general, general thought process that come through. So, one of the big themes … is self-efficacy. Given a problem, figure out how to solve it. Right. It's open ended. Is that right? You may not be the technical expert. You may not be even aware of the background, but it's on you to figure it out. And you can do it right. You don't you don't need to be an expert to solve a problem. This whole project-based learning thing, sort of coupling design thinking leads to this increase in self efficacy similar enough to self-confidence. But I think self-efficacy is the right word here. And so that's a general thing that I think helps. And then specific assignments. I think this learning to really prototype rapidly right. Is probably a generic answer. I'm sure people are giving it to you, but a lot of people come from a place where that's not really the norm. … I'm sure other people come from other places. Rapid prototyping isn't really. Commonplace and sort of to give you an example, just before the summer I joined [university], I was doing an internship at NASA and there I was working on a project which really would have benefited from prototyping." (Eleana)*

These student reflections echo characteristics for classes collected through related work [35-37, 39- 44].

9. People – Process – Product

These courses have all have specific content that is delivered through aspects of focusing students on developing physical artifacts and prototypes. It is pertinent though to note that the concentration of emphasis for each class on the people, process and product is present but present at different concentrations.

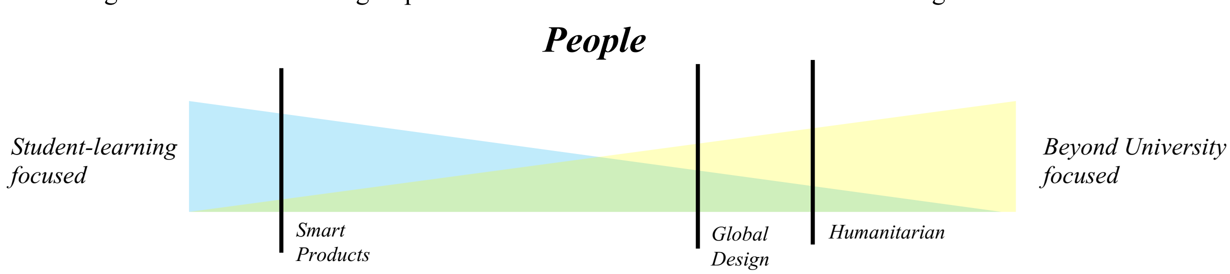
For multiple dimensions to consider a balance of people, process, and product. The categorization scheme that measures relative emphasis of a course on developing *people* as engineers themselves, *processes* of design and development, and *product*-oriented making and fabrication. A description for each course relative to these people-process-product is listed below in Table 5.

Table 5: Summary of People-Process-Product

Course	*People*	*Process*	*Product Intent*
Global Design	International student teams (mostly ME students?), bring in "users" as needed (Human-centered design)	Iterative problem solving, from clarifying problem	New ideas and functional prototype delivered to sponsor
Smart Product Design	Students with ME backgrounds. Focus is on new technology-skill development of students in developing integrated (software, hardware, electronic) products	Scaffolded labs leading into instructor-defined projects. One project per quarter.	Working product to demonstrate acquisition of skills, including integration and development. Some products end up displayed in the lab.
Humanitarian Engineering	ME & MBA students partner w/ community members (co-design)		Leave community with a working prototype.
Statics	Pre-major students interested in engineering–experiences to "try" engineering on. Application of knowledge in a strategic manner.	1-day design project, 2-week bridge design integrating analysis (self-regulated learners)--hand calculations, simulation	Creating and testing a creation.

10. Visualizing People – Process – Product

Positioning the three courses along a spectrum of these three dimensions as shown in Figure 1.



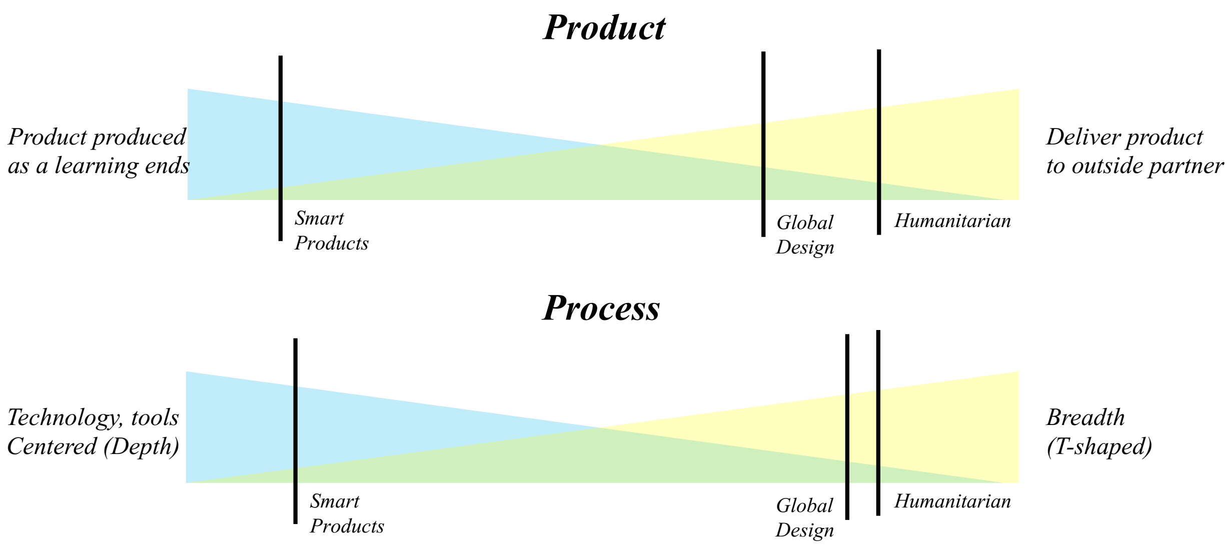


Figure 1: Visualization of People-Process-Product Spectrum

11. Discussion

This Product-based learning framework may allow for a newfound appreciation for the multiple approaches of people-process-product that can be experienced holistically over a whole curriculum. We also use this framework as a lens to look at courses to illustrate how this enhanced "product" language helps to differentiate courses and the types of projects being pursued.

PBL is used to describe both problem-based and project-based work at present. This paper extends the notion to describe "product" focused design courses with a categorization scheme that measures relative emphasis of a course on developing *people* as engineers themselves (and including awareness of the people and communities being designed for), *processes* of design and development, and *product*-oriented making and fabrication.

The cases that we present in this paper are examples of course sequences in design that leverage a project-based learning approach to allow students to dive deeply into designing and building functional systems of some engineering complexity. For all three courses, the pedagogical approach is through project-based learning; though with a target deliverable of a functional engineered systems, it is not just the application of an engineered design but the ingenuity of developing a technology into a product. This focus of a widget gives some indication that that such a tangible end-goal may provide some additional motivation and guidance for student teams, both as a product-focus on learning and as a type of Maker-based pedagogy.

These learning experiences are similar in pedagogical approach in that students have some autonomy to explore and direct their design challenges through effects of prototyping, supported by scaffolded activities, labs and milestones and engage regularly with a supportive teaching team of instructors and teaching assistants as design process and technical coaches.

The reflection of these aspects underscore what descriptors are applied to the general concept of c*ognitive apprenticeship* [45] where the mastery of a skill in imparted on an apprentice. Both in the structure of the courses described about, as well as the presence of knowledgeable instructors, does this happen. Curiously, the structure of the design process itself, as demonstrated in a differentiated manner across courses also serves as a yardstick to provide the mastery guidance. In short, aspects of modeling, coaching, scaffolding, clarity in sequence, reflection and exploration all contribute to a robust learning experience.

Having a prototype as a goal also helps to make learning more visible. Despite having different balance of focus of developing the person, emphasis on the process, and focus on the end-product, it is a mission-based, maker-based, prototyping-minded application of what is learning by design, design thinking, and design activity.

12. Implications

A product-based learning course, or any sort of PBL, does serve to be an inverse of a traditional course. The hierarchy of learning objectives, along Bloom's Taxonomy, for example, is geared towards the creation and evaluation level. Beyond just concerns related to ABET student learning outcomes, the additional overhead and time needed to provide coaching, scaffolding around design projects is justifiable, as learning at the graduate level, above and beyond the engineering fundamentals, and engineering science, to the practical application, the preparation of people, the guidance through a design process, with an artifact produced in the end.

Future exploration can do well to make it even clearer of what the people-process-product balance for be. The expansive iteration to explore both the problem space and solution space of the global Design course is to be considered very different than the recursive iteration (successively through making tech to work) of the Smart Product Design course. The authority for leaning too can develop self-regulated learners and transfer responsibility from instructor to student.

This Product-based learning framework may allow for a newfound appreciation for the multiple approaches of people-process-product that can be experienced holistically over a whole curriculum. This can also provide new ways and new language to think about design experience and course for students, to leverage a new framework for people-process- product foci for the future of PBL and design education.

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