DESIGN FOR ADDITIVE MANUFACTURING CURRICULUM: A PROBLEM- AND PROJECT-BASED APPROACH

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ABSTRACT

Additive manufacturing education is of key importance because unfamiliarity with AM technologies is one of the barriers to its widespread adoption. In this paper, the authors describe their efforts to address this need via an undergraduate/graduate course in Additive Manufacturing. Their courses, offered at the University of Texas at Austin and Virginia Tech, cover the science of AM as well as principles of "design for additive manufacturing." The courses use both problem-based and project-based pedagogies to present students with opportunities to gain hands-on experience with the technologies of AM. Examples of project activities are presented along with student feedback.

Keywords: Additive Manufacturing, Engineering Education, Design Education

1. ADDITIVE MANUFACTURING EDUCATION

1.1. Motivation

There has been significant investment in advancing the US's manufacturing presence in the global innovation economy in the past few years. This need has been a key focus of the United States' federal government: the "Manufacturing Enhancement Act of 2010" was created to promote investment in the manufacturing sector [1] and the Advanced Manufacturing Partnership was launched last year [2]. The President recently proposed a "National Network for Manufacturing Innovation" (NNMI) to boost manufacturing research and workforce development [3]. The pilot NNMI institute is focused on Additive Manufacturing (AM), further illustrating its importance to our nation's global competitiveness.

There is also considerable public interest in improving US manufacturing. In a recent study by Deloitte and the Manufacturing Institute, 77% of respondents believed that the U.S. needs a more strategic approach to develop its manufacturing base, and 74% said that the U.S. should further invest in manufacturing industries [4]. However, in the same survey, it was found that *the youngest respondents were the least likely to think that manufacturing is important to our economic prosperity (71%) or thought of manufacturing as "high tech" (59%).*

To address this fundamental disconnect, advancing manufacturing workforce development is of great importance. The need to educate future manufacturing engineers is a core focus of the "2009 Roadmap for Additive Manufacturing," as unfamiliarity with AM technologies is seen as a barrier to adoption. The roadmap urges the development of university courses and "programs for educating the general population to enhance the interest in AM applications and generate some societal 'pull' for the technologies" [5]. While some AM courses at the undergraduate and graduate levels do exist (e.g., [6]), their limited quantity does not match the recent interest in, and suggested national importance of, the technology. To answer the call posed by the AM Roadmap the authors have designed and implemented an undergraduate/graduate AM course at their respective institutions.

1.2. Design for Additive Manufacturing

AM's layer-by-layer fabrication approach removes many of the geometric constraints imposed by traditional manufacturing processes. Its capability to selectively place material allows for the fabrication of complex geometries that are specifically designed to support and improve multiple design objectives, and thus has the potential to significantly alter how products are designed. To realize the full potential of AM, engineers must know how to design products for fabrication via AM. In addition, engineers must not only understand AM technologies and materials, they must also be able to synthesize its economic and environmental impacts on a manufacturing value chain. As such, the primary objective of the authors' courses is in advancing engineers' ability to design and fabricate complex systems via AM.

This design focus dictates the design of the authors' courses. Design is considered to be the central or distinguishing activity of engineering [7]. Research on engineering design thinking and learning has established that design is hard to learn and harder to teach [8]. Design instructors cannot simply "teach" design principles through lecture since the unique context of each student's design prevents the canned delivery of common content. Such deductive modes of instruction do not reflect what engineering education research has discovered about learning and effective pedagogical practice.

Instead, engineering design pedagogy follows the constructivist learning theory, in which it is postulated that students form knowledge representations of new information by building on their previous knowledge and experiences [9]. If the new information has few connections to what they already know, learning will not occur, nor will students be motivated to learn [10]. Thus, effective instruction must provide experiences in which students actively construct knowledge by adjusting, rejecting, or modifying their prior beliefs and understanding based on their experiences [11]. Deductive instruction does not facilitate this mode of learning; its "skill-and-drill" approach allows students to approach learning passively, and does not challenge them to modify their prior understanding. Design educators must augment content delivery with individual coaching and mentoring of students as they progress through their design efforts [12]. They must follow an inductive teaching approach wherein students are presented problems and projects in which to apply and synthesize their prior knowledge through a design methodology.

In this paper, the authors present their approach to educating future engineers about AM. Their design-focused approach is based on problem-based and project-based pedagogies. These inductive pedagogical approaches are presented and differentiated in Section 2. A general overview of the course is presented in Section 3, and examples of posed problems and projects are presented in Section 4. Closure is given in Section 5.

2. PROBLEM-BASED AND PROJECT-BASED LEARNING

Following calls from the National Academy of Engineering [13] and the American Society of Engineering Education [14] for more inductive teaching in engineering education, the authors' AM course is centered on inductive problem-based and project-based pedagogies. In inductive instruction, students are first introduced to complex and realistic problems before being exposed to relevant theory and equations (Figure 1). Students then learn what is needed to solve the presented challenge [15]. Inductive teaching methods include inquiry-based learning, problem-based learning (PmBL), project-based learning (PjBL), case-based teaching, and just-in-time teaching.

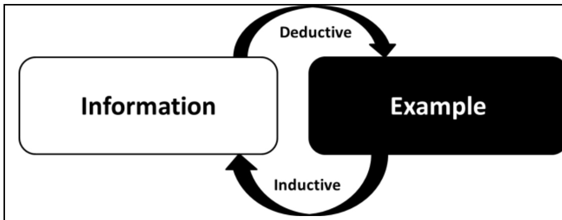


Figure 1. Inductive and Deductive Instructional Approaches

Inductive instructional approaches are "supported by the best research on learning currently available, compatible with the currently most widely accepted theories of learning, and promotive of the problem-solving skills and attitudes that most instructors would say they desire for their students" [11]. The problems/projects are designed to be representative of authentic problems, which have been shown to motivate students, maintain their interest, and actively engage them in learning [11]. PBL learning approaches have been found to improve the development of critical thinking and problem-solving [11], and to enhance understanding of critical engineering concepts [16].

2.1. Problem-Based Learning (PmBL)

With origins in medical school programs, the central principle of the PmBL approach is that students' fulfillment of learning objectives is accomplished through the solution of an open-ended problems, rather than through a deductive presentation of information [17]. The problem, which is carefully designed to be authentic and reflective of professional practice, serves as the motivation for learning the content. Students work in small groups to solve the problem by first identifying what they already know, what they need to know, and how and where to access the information that will assist them in solving the problem. The problems are used as an opportunity for students to acquire the desired knowledge while simultaneously enhancing their problem solving skills and their competency for self-directed learning [18].

Simply providing students with an open-ended problem is not considered true PmBL. The role of the faculty is a crucial component to successfully implement PmBL. The instructor's role is not to act as a "sage on the stage," but instead to serve as a facilitator or guide [18]. The instructor must guide the learning process while also leading students through reflection and debriefing at the conclusion of the experience. The facilitator's role is akin to that of a consultant, wherein they provide scaffolding throughout the process to the support a student's learning and understanding.

Research in PmBL has shown that students tend to acquire a more complete understanding of concepts and ideas than those who have received traditional instruction [19]. Additional benefits include an increase in student knowledge, skill acquisition and transfer, and improving positive attitudes about the course and profession [20]. There is also evidence of an increase in students' metacognitive skills (e.g., self-awareness of ability to learn, retrieve knowledge, etc.), which translates to an improved ability to transfer knowledge across different contexts [21].

2.2. Project-Based Learning (PjBL)

PmBL and PjBL are often confused as they are both grounded in the pedagogical approach of providing students self-directed learning opportunities via an open-ended challenge. The faculty's role is also similar, wherein scaffolding is provided through facilitation and tutoring. The design of the project statement in PjBL is similar to that of the problem statement in PmBL: the project must be open-ended and representative of the profession; although, the projects in PjBL tend to be larger in scope (and time) and thus closer to professional reality. Students work in groups to complete the project assignment in PjBL, thus providing intrinsic motivation to demonstrate better teamwork and motivations skills [22].

A key difference between PmBL and PjBL is that the project of PjBL results in a concrete and explicit artifact (e.g., model, report, computer program, artifact, etc.) that can be shared and critiqued [22]. In this regard, PjBL is focused on the *synthesis and application of knowledge*, whereas PmBL is focused more on the *acquisition of knowledge* [23]. In effect, PmBL serves as a scaffolding necessary to complete the synthesis tasks of PjBL [24]. In addition, PjBL courses are supported by the theoretical basis of situated cognition. The situated cognition theory of learning notes that knowledge is contextual and is a product of the activity and situations in which it is created [25]. By providing an authentic activity in PjBL, the domain knowledge and concepts of the field are employed and allows students to act purposefully in the activity. PjBL also offers students the opportunity for cognitive apprenticeship wherein metacognitive skills and processes are learned through interaction with the project advisor [26].

3. General Class Structure

The development of the course's learning objectives were guided by the need to further the advanced manufacturing workforce (Section 1.1) and the stated importance of linking design and AM (Section 1.2). Specifically, once successfully completing the course, the students should be able to:

- Explain the capabilities, limitations, and basic principles of alternative AM technologies.
- Evaluate and select appropriate AM technologies for specific design-manufacturing applications.
- Explain the fundamental causes of errors and irregularities in AM parts.
- Apply AM techniques to a challenging design and manufacturing application.
- Identify, explain, and prioritize some of the important research challenges in AM.

These stated learning objectives highlight the need for students to be able to synthesize their knowledge of AM technologies' strengths and limitations in order to successfully design and fabricate a product. These objectives provide a foundation for selecting course topics and their relative importance. A generalized list of the course's topics is presented in Figure 2 along with the percent of class meetings (~30 meetings in total) devoted to each class topic.

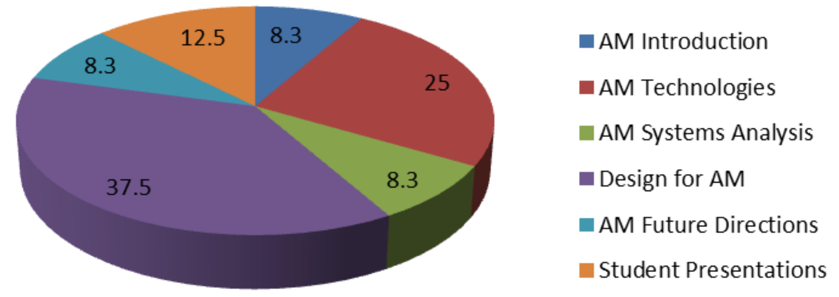


Figure 2. Overall AM Course Structure and Allocation

At the beginning of the course, the instructors provide a high-level introduction to the AM technologies through the use of a functional classification framework [27]. Case studies and commercial applications of AM are also presented to motivate student learning and to situate their learning in the context of AM professional practice. Students are then introduced to the AM technologies at a more detailed level. Typically, a single AM technology (e.g., powder bed fusion, material extrusion, vat photopolymerization, etc.) is discussed during a class meeting. The instructor leads the students through the identification of the strengths and weaknesses of each technology while also exposing them to the processes' fundamental science. Explorations of AM science is guided by the literature produced by the AM research community and an AM textbook [28]. Students are also guided through an exploration of "AM Systems Analysis," which focuses on technology selection and cost estimation decision strategies.

This coverage of AM science accounts for ~25% of the course; it provides students the technical foundation necessary to design novel AM products. Occupying 25% of the course content, "Design for AM" class topics are focused on a structure similar to systematic engineering design methodologies proposed by [29] and [30]. Specifically, the following topics are discussed:

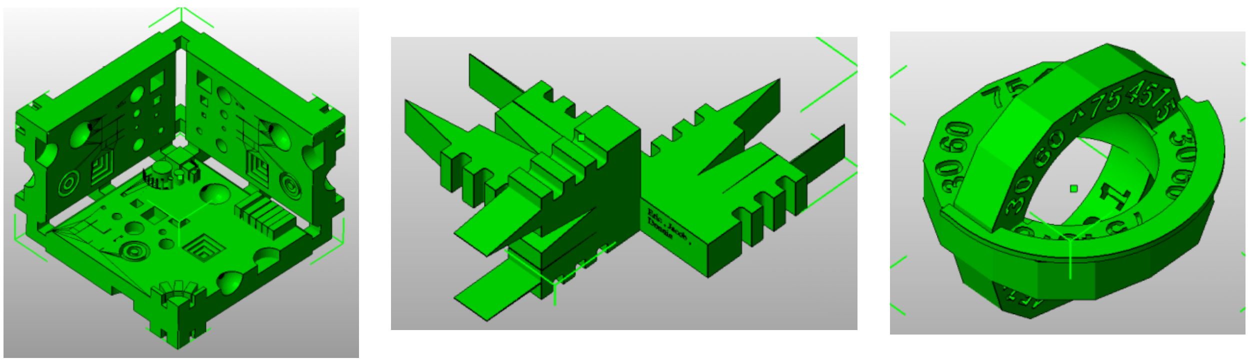
- *Identifying Opportunities*: In this module, students learn about the types of applications for which AM is best suited. Students are introduced to techniques for identifying AM product development opportunities and customer needs.
- *AM Project Planning and Economics*: Students learn project planning and cost estimation techniques. Specific to AM, they discuss the impact of the digital manufacturing paradigm.
- *AM Concept Generation*: In this module, students learn concept generation techniques and learn to employ idea generators that are unique to AM (e.g., customization, low-volume production, assembly reduction, and complex geometry).
- *AM Embodiment Design*: Students learn how best to design the structure of their product for AM in this module. Considerations of AM tolerancing for various part features (e.g., through holes, snap-fits, living hinges, etc.) are explored.
- *AM Detailed Design*: Content in this module is focused in AM common build strategies (and potential errors) caused by part orientation, poor interlayer bonding, and resolution limitations of various AM technologies.

As discussed in Section 2, the design focus of the authors' courses mandates an inductive approach to instruction. The authors employ various PmBL and PjBL activities throughout the semester to engage students in each of the course topics. Examples of these activities are detailed in Section 4.

4. Problem and Project Examples

4.1. Problem-based Learning: Design of Benchmarking Part

The first PmBL activity of the course is focused on the learning objective of enabling students to explain capabilities and limitations of AM technologies (Section 3). Instead of rote learning AM process specifications, students actively explore the technology limitations by designing and measuring a part for benchmarking one of three metrics: resolution, accuracy, or surface finish. The part is to be designed to enable students to observe the effects of potential sources of AM build error (e.g., orientation, presence of support material, layer thickness, etc.) on the chosen metric. Example student work is presented in Figure 3.



(a) (b) (c)

Figure 3. Example Student-Designed Benchmarking Parts; (a) Accuracy, (b) Resolution, (c) Surface Finish

The students work in small teams (3 people) to respond to the challenge. The instructor guides the students through (i) defining their assigned metric (e.g., "What's the difference between resolution and accuracy?"), (ii) identifying appropriate metrology techniques, and (iii) designing the part to measure the effects of all potential sources of build error.

Once the part is designed, each of the team's submissions is built on a Laser Sintering machine, a PolyJet 3D Printing machine, and a Fused Filament Fabrication machine. Each team then performs the appropriate measurements and analysis on each of the three parts to identify the capabilities of each AM process. Finally, the students present their work to the class in order to educate their peers (i.e., thus the team assigned to study resolution learns about accuracy and surface finish).

This PmBL example provides an opportunity for students to actively investigate sources of AM process build error. In addressing the proposed challenge, students also learn metrology techniques, and abstract AM processes' strengths and limitations. In addition to fulfilling a core learning objective of the course, it also provides a useful foundation (and motivation) for learning AM process selection techniques (Section 4.2). Finally, students often return to their results while completing their semester AM design project (Section 4.3).

4.2. Problem-based Learning: Dissection/Selection

This assignment provides students an opportunity to investigate the advantages and limitations of available AM technologies, compare the capabilities of those technologies to conventional manufacturing processes, and practice selecting an appropriate technology for a specific application.

To begin the assignment, each student selects a mechanical consumer product of interest to him/her. The product is required to be of low to moderate complexity (20-40 parts) and disassemblable with standard tools available to the students. Each student disassembles his/her product, takes photographs of exploded views of the disassembled product, and creates an accompanying bill-of-materials complete with the name of the part, its function, dimensions, mass, and likely manufacturing process and material. Students often perform background research to identify the most likely constituent materials and manufacturing processes, especially when the material is not labeled (e.g., with a plastic recycling number) and the manufacturing process is not evident (with injection molding and sheet metal stamping being two of the most common and easily recognizable processes).

Next, each student is required to identify two components from the BOM that are fabricated with significantly different manufacturing methods. Students often choose an injection-molded plastic part and a metal part that is either cast or fabricated via sheet metal stamping. For each component, students must establish a set of criteria for evaluating the quality of the component (e.g., dimensional accuracy, strength). At the beginning of the assignment, the class and the instructor construct a list of candidate criteria, including dimensional accuracy, surface finish, tensile strength, and cost. A target value is established for each criterion for each component, based on values that are reasonable for the parent manufacturing process.

Finally, each student constructs a selection decision matrix to identify the most appropriate AM technology for fabricating the part in small lot sizes. Populating the decision matrix requires knowledge of the capabilities of each candidate AM process/material combination, including the typical accuracy of each process and the expected material properties (e.g., tensile strength, density, Young's modulus, operating temperatures) associated with each process/material combination. Students compile this information in a chart as each AM process is discussed in class. Each student summarizes his/her recommendations, including a discussion of the strengths and shortcomings of the selected AM processes in a written report and brief classroom show/share discussion. Students are required to evaluate the sensitivity of their conclusions to shifting priorities; e.g., would the selected AM process be different if aesthetics were emphasized over strength?

This assignment requires students to traverse the entire range of Bloom's taxonomy. They accumulate data on the capabilities of leading AM process/material combinations and organize it into a table that offers side-by-side comparisons of the alternatives. They apply their knowledge of manufacturing processes and materials to identify the most likely material and fabrication route for components in their product. Many students find this task much more difficult than expected, because it sometimes requires considerable knowledge of different processes and the strengths and capabilities of each one and sophisticated reasoning about the most likely fabrication path. Selecting the most suitable AM process/material for reproducing the part (and justifying that selection) requires students to evaluate the capabilities of each alternative very carefully. By the end of the assignment, they begin to think less like a naïve customer and more like a service bureau advisor making a recommendation on a particular part.

4.3. Project-based Learning: Semester Design Project

This project provides students an opportunity to learn how to design for AM by creating a new product that is uniquely suitable for AM. These actions represent the highest levels of Bloom's Taxonomy of learning [31].

In small groups of 3-5 participants, students identify, design, fabricate, and test a product that is suitable for AM. When selecting a design problem to solve, students are required to identify compelling technical and/or economic reasons for additively manufacturing the product, rather than utilizing more conventional manufacturing techniques. For example, AM is often driven by the need for customization, rapid cycle times, and/or small lot sizes; economic viability is also important to consider.

Once the design opportunity is identified, students proceed to further clarify the task and develop concepts. Each group generates a formal problem statement and a requirements list (or specifications sheet). They also design and implement a procedure for customer needs analysis and concept generation, leading to a set of preliminary concepts (often in the form of hand sketches). Each group refines and selects a leading concept for embodiment and detailed design. They perform detailed technical and economic analysis of the chosen concept by, for example, conducting FEA analysis of the mechanical performance of the product and economic analysis of the cost of fabricating the product at a service bureau. They iteratively refine the design as necessary, culminating in a CAD model and .stl file of the final design. The instructional team fabricates the part with in-house AM machines. After receiving their fabricated parts, students design and implement a testing and evaluation procedure for assessing the technical performance of the fabricated product (as well as its usability, if applicable). Finally, students critically evaluate their results and document their projects in the form of final presentations and reports.

Figure 4 illustrates a selection of final projects from the UT Austin class. Many students pursue products that are customized for individual users. For example, the back support in the upper left is designed to be a form-fitting support between a chair and the back of a specific student with recurring back pain. A clay mold of the student's back was generated and converted to an equivalent CAD surface with a 3D scanner. Similarly, the tennis racquet handle in the lower right is customized for the grip of a female student. The car radio compartment insert in the upper right is customized with an individual student's name and personalized design, and it is tailored to hold an iPod and fit snugly into the car radio slot in a typical dashboard. Other groups choose to make functional retail products with highly complex or specialized shapes or topologies. The gear shift handle (bottom row of Figure 4, second from right) assumes an organic shape that fits the palm and fingers of a typical user ergonomically. The desktop novelty clock in the middle of the top row includes a path for a marble to wind into and out of the body of the clock, along with customized geometric shapes around the outside of the clock. Other students build single-lot prototypes with special features, such as the energy harvesting device in the bottom row (second from left). The device houses inductive energy harvesting components that can be attached to a bridge. Rotating the top cap of the device tunes the harvester to the fundamental frequency of vibration of the bridge. The device replaces an experimental prototype that required more than 40 additional parts and twice the bounding volume. The device on the bottom left is intended to be a small- or single-lot production device for teaching and outreach. It is comprised of rotating elements to represent many of the facets of mechanical engineering, including moving gear trains (fabricated in their assembled state), a radial engine with moving pistons, a biomechanical leg with a flexing knee, and a rotating turbine.

At UT Austin, the semester culminates with a final presentation and a best-of-show award sponsored by a local company. Select projects are displayed in hallway display cases. Many students find the project both challenging and enjoyable. Unlike other design projects in the curriculum, students must adopt a very entrepreneurial perspective to identify and justify an appropriate AM-related design opportunity. The design problem is not provided or strictly bounded. They also follow the product development process from idea inception to fabrication and performance verification. Students often learn important lessons about design for AM when their products take unexpected forms, such as features that mate imperfectly, walls that are too thin to be watertight, or gears that either fuse or mate so loosely that they frequently slip.

Figure 4. A selection of final projects from the AM course at UT Austin

5. Closure and Future Work

In this paper, the authors present their work towards designing an Additive Manufacturing course. Given its central role in the profession of engineering, the crux of the course is the topic of Design for Additive Manufacturing. As engineering design pedagogy follows the constructivist learning theory, the authors chose an inductive instructional approach to their course. In this approach, students are presented challenging problems (Problem-based Learning) or open-ended projects (Project-based Learning). In addition to promoting a desired skill-set, this pedagogical approach aligns with what engineering education research has discovered about learning and effective pedagogical practice. Specifically, inductive approaches provide students an opportunity to learn experimental skills, mirror professional practice, and build and test designs, while encouraging discovery and independent learning, and improving motivation, teamwork, and communication [32].

The authors present three sample activities in this work. In one activity, students are challenged to design, measure and analyze a benchmarking part for understanding AM part surface finish, resolution and accuracy (Section 4.1). Students learn how to evaluate and select Additive Manufacturing processes for product fabrication via a problem-based activity centered in product dissection. Finally, students apply their newly-acquired knowledge of design for AM by carrying a final project through the entire product development process from idea inception to AM to testing.

Anecdotally, the authors have received significant positive feedback from their students in this course. The authors look next to formalizing an assessment strategy for exploring student learning as a result of the class. The authors will investigate how this course affects students' opinions of advanced manufacturing, self-efficacy, and metacognition.

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