Concept to Creation: Fundamentals of Additive Manufacturing with Design Thinking

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Abstract: Additive Manufacturing (AM) builds three-dimensional parts from a digital design. AM represents a paradigm shift in how products are designed, prototyped, and manufactured. This article explores instructional design methods to teach AM to undergraduate students. The purpose of this research is to understand better how to specifically concentrate on shifting focus from instructor-led teaching to participant-centered practice-based learning, providing insights useful to other instructional designers. The research question was, "How was the additive manufacturing course designed to provide students with a participant-centered practice-based learning environment?" The theoretical framework for the study was Design Thinking (DT). Findings from this research highlighted how DT informed and shaped the instructional design decisions and facilitated designing a participant-centered practice-based professional development workshop for K-12 schoolteachers. Insights from the workshop will inform the design of a summer program aimed at reaching more educators. This program will focus on creating a pipeline by engaging K-12 students in AM, equipping them with essential skills to build a competitive future STEM workforce that supports the AM industry.

Keywords: Additive manufacturing, Design Thinking, Design for manufacturing, Instructional design, 3D printing,

Introduction

Additive Manufacturing (AM), which is sometimes also referred to as 3D printing, can create/print a physical object from a geometrical representation using the technique of layer-by-layer deposition of material directly from a Computer-Aided Design (CAD) model (Shahrubudin, Lee, & Ramlan, 2019; ISO/PRF 17296-1,2015; Tofail et al., 2018). Commercialized by Charles Hull in 1980, this innovative technology has emerged and revolutionized the industrial production line due to its increased speed and reduced cost (Holzmann et al., 2017). AM enables the production of high precision products facilitating prototyping with complex geometries and minimal material waste using drawings or so-called CAD (Mayandi et al., 2024a; Mayandi et al., 2024b). There are several advantages for advancements in additive manufacturing (Holzmann et al., 2017): i) User-friendly interfaces, ii) Affordable hardware, iii) Cloud-enabled 3D printing platforms and iv) Eco-friendly material innovation. Additive Manufacturing printing impacts human lives and economy by contributing to the aeronautics and aerospace industries, medical industries, fashion and jewelry sector, and architectural models (Gokhare et al., 2017).

Integrating additive manufacturing into educational frameworks provides an innovative avenue for active and interdisciplinary learning. Through hands-on learning, additive manufacturing transforms theoretical concepts into tangible experiences, enabling students to design and create objects that reinforce their understanding of geometry, physics, and material science. In Project-Based Learning, students use additive manufacturing to address real-world challenges—such as designing prosthetic limbs, creating architectural models, or developing functional prototypes

—bridging the gap between classroom theory and practical application (Jiménez, 2019). The interdisciplinary nature of 3D printing aligns seamlessly with STEAM (Science, Technology, Engineering, Arts, and Mathematics) education, encouraging students to combine artistic creativity with technical precision for holistic skill development (Meisel, 2024). Moreover, teaching students how to operate 3D printers and using modeling software equips them with valuable technical skills that are increasingly in demand across industries, providing them with a competitive edge in the workforce.

The rapid pace of technological advancement necessitates a teaching approach that is dynamic, hands-on, and adaptable. Designing an effective instructional strategy for an additive manufacturing course requires integrating practical skills with theoretical knowledge while fostering creativity and problem-solving (Simpson et al., 2017). For educators and instructional designers, understanding the state of the art in additive manufacturing offers unique opportunities to foster innovation, creativity, and technical skills in learners. Exploring the design and challenges of teaching additive manufacturing to undergraduates through the lens of instructional approaches emphasizes the methods for knowledge and skill development among learners.

To prepare for a competitive future workforce it becomes imperative that researchers, innovators, and educators work together to support additive manufacturing as a profession by creating a pipeline from K-12 schools by engaging and retaining students (Simpson et al., 2017). Learning additive manufacturing in middle school will help build foundational ideas and skills to be applied later. If schoolteachers are not trained in additive manufacturing, it will result in low self-efficacy and confidence to teach additive manufacturing. This article will discuss the instructional design approach that instructors use to teach additive manufacturing to undergraduate students and use the findings to design a workshop for teachers' professional development for teaching additive manufacturing to middle and high school students. Gaining knowledge from the workshop we want to develop a summer program for a larger number of teachers to be held in the next iteration.

The purpose of this research is to better understand how to specifically concentrate on shifting focus from instructor-led teaching to participant-centered practice-based learning, providing insights useful to other instructional designers. This paper will discuss the instructional design process for creating a workshop for teachers and students to learn additive manufacturing. The workshop will support K-12 teachers who will be able to create effective learning designs and additive manufacturing activities for their students.

Theoretical framework: A Design Thinking approach

Design thinking encompasses the cognitive skills, thought processes, and methodologies designers use to address problems and generate ideas (Henriksen, 2020; Zainal et al., 2021). A structured process that produces multiple potential solutions is a key aspect of this approach (Hatzigianni et al., 2021). Evaluating the economic, environmental, and social implications of these solutions is emphasized in design thinking (Zainal et al., 2021). A multidisciplinary team of experts with diverse skills adds value to this approach by enhancing problem-solving and fostering effective product development (Cross, 2023). This human-centered approach aims to improve the human environment and is particularly effective for developing teachers' knowledge (Blundell, 2024), as a creative method for solving problems especially in professions like teaching (Zainal, 2021), and engaging teachers in designing new instructional practices (Koh, 2015; Blundell, 2024). It improves student confidence, encourages expression and communication of ideas, and increases engagement (Hsu et al., 2021). Applying design thinking stages, instructors improved their problem-solving skills and addressed practical challenges by integrating them into curricular frameworks (Henriksen et al., 2020). Koh et al. (2015) advocate for making design thinking a priority in education, emphasizing its connection to human culture and civilization. The design thinking model developed by the Hasso Plattner Institute of Design at Stanford (the "d.school") includes five key stages (Fabri, 2015; Zainal, 2021):

Empathize: This stage focuses on deeply understanding the problem by researching user needs, consulting experts, making observations, and developing an empathetic perspective on the challenge that the product design aims to address.

Define: Here, the information gathered from the empathized state is analyzed to clearly define the problem. The goal is to refine and structure the insights ensuring the problem is approached with a human-centered mindset to generate meaningful ideas.

Ideate: This phase encourages creative problem-solving by exploring a broad range of potential solutions. Techniques such as brainstorming, mind mapping, and questioning are used to foster free thinking and generate as many ideas as possible.

Prototype: In this stage, ideas take a tangible form through the development of multiple prototypes, creating, testing, and iterating. These early versions are tested within the team, across departments, or with a small external group. Feedback is gathered to refine, improve, or discard certain concepts, helping to shape a clearer understanding of user interactions with the product.

Test: The final stage involves presenting prototypes to users and collecting feedback through observations and interviews. This process helps refine the product by understanding real user experiences, ultimately leading to a more effective and well-developed final version.

Context

In this paper we share key design elements in the additive manufacturing curriculum for our face-to-face undergraduate courses. It focuses on introducing different manufacturing processes (including casting, forming, and machining) emphasizing product creation with the appropriate techniques. Below we provided a structure summarizing the elements: course learning objectives, the course modules, additive manufacturing stages aligning with the Design Thinking approach, and outline of a sample project.

Course Learning Objectives: The students will be able to i) explain the principles and applications of various traditional and non-traditional manufacturing processes, ii) select the most suitable manufacturing process for a given product design and material, iii) explain the basics of metal cutting and working of different types of machine tools, and iv) explain the conventional and advanced metal forming processes and composite fabrication, v) analyze and access the use of casting processes in manufacturing and understand the working of various casting processes.

Course Modules: The course was divided into four modules. Module 1 focused on additive manufacturing processes, module 2 focused on casting manufacturing processes, module 3 focused on forming manufacturing processes, and module 4 focused on machining manufacturing processes.

Stages of Design and Production: In an additive manufacturing course, students would progress through the following stages as they design and produce a functional prototype (Gibson et al., 2021, Pou et al. 2021):
i) *Design a 3D model* (*Empathize*): Using CAD software to design a 3D model of the birdhouse and save it in an STL (Standard Tessellation Language) format.
ii) *Preparation* (*Define*): Configuring slicing and printer settings, such as build orientation, layer thickness, infill percentage, nozzle temperature, support structures, and print speed. This step also involves generating a G-code for the printer.
iii) *Execution* (*Ideate, Prototype*): Operating the printer and observing the print process.
Select the appropriate filament or material for your project. Common materials include PLA (polylactic acid), ABS (acrylonitrile butadiene styrene), PETG (polyethylene terephthalate glycol), and various specialty materials.
Preparing the printer involves loading the filament into the printer and ensuring the print bed is level and clean.
iv) *Troubleshooting* (*Test*): Analyzing and resolving issues, such as warping or filament jams.

v) *Refinement* (*Test*): Iterating the design and settings based on print results. Perform any necessary post-processing steps, such as sanding, painting, or assembly.

Sample Project: Students work on a course project (team of two to three students) in which they manufacture a product, using an AM process. For example, the project is to design and produce a functional birdhouse. Below are some parameters that students apply as they design and manufacture the product using the design stages.

a) The size and shape of the birdhouse should match the nesting preferences of the desired bird species.
b) The entrance hole size and location should be species-specific and prevent predators from entering.
c) The ventilation and drainage holes should be placed on the sides and bottom of the birdhouse to allow air circulation and water runoff.
d) The roof and predator guard should be angled and extended beyond the entrance hole to protect the birdhouse from rain and predators.
e) The cleanout door and/or latch should be easy to open and secure to remove old nests and debris.
f) The mounting and installation options should suit the birdhouse location and height.

Methods

The research motivation for this study is twofold. First, for instructors to concretize the shift from instructor-led knowledge creation to participant-centered practice based learning spaces through collaboration, the basis of a constructivist learning approach. Second, to create workshops for teachers and students to explore and engage them in tasks to design and print, blending engineering with computer science. We then will iterate on our process, returning to design and construction to create activities engaging in further evaluation and reflection.

The research question was, "How was the additive manufacturing course designed to provide students with a participant-centered practice-based learning environment?" Data sources consisting of the archived course, including the syllabus, course map, modularly developed content focusing on resources, activities and assignments used by the instructor to create a design perspective on the course and address the research question. Participants and authors are two researchers and instructors in a Southwest borderland university in the United States. One of us is an industrial engineering professor and instructor of an additive manufacturing course who designed and taught the course to undergraduate students in industrial engineering majors. The other researcher is a STEM Education professor and teacher educator with an educational learning design and technology research background, designs and provides professional developments to K-12 teachers.

For data analysis we focused on the structure of the course, planning, and steps designed to achieve course learning objectives and creating a participant-centered learning environment (Durak & Ataizi, 2016). After analyzing the design, the next step was to figure out revision for the next iteration to improve design and execution. For example, selecting appropriate methods, tools, and strategies to ensure that the intended outcomes are met (Durak & Ataizi, 2016). In instructional design, the analysis phase helps gather relevant information about learners, objectives, and potential obstacles which enables designers to break down complex problems and convert them into specific tasks or solutions that can be effectively implemented (Hodell, 2011). By doing so, instructional designers ensure that the learning experience is structured, targeted, and responsive to the needs of the audience.

Together we thoroughly analyzed the archived syllabus, curriculum development process, course development journals and research notes to gain deeper insights into our instructional design. Additionally, we deconstructed our collaborative conversations about the course development process, examining the challenges encountered, the strategies employed, and the insights gained along the way. Furthermore, we explored key criteria for designing and selecting activities and assignments, emphasizing elements such as learner choice, relevance and interest to emphasize the shift from instructor-led knowledge creation to participant-centered practice. Realizing that a student-centered course design takes into consideration the ever-changing needs of students regarding technology tool use, modular design and streamlining of activities (Chatterjee & Parra, 2020). Since AM is widely acknowledged for its significant potential in design innovation (Rias et al., 2016); we continuously reflected and evaluated the course design steps and processes to recognize the potential tools to formally support communication, collaboration, and creativity skills which could be intentionally integrated and leveraged in informal learning spaces as well (Chatterjee & Parra, 2022). As we analyzed the instructional design and reflected, we focused on contextual problem-solving and our role in scaffolding learners.

Findings and Discussions

There are two major findings of this research. First, as instructional designers and instructors we focused on one design technology (3D printing), components of the process of designing products (prototypes or models) and how to shift the instructor-led knowledge dissemination teaching to participant-centered practice based collaborative learning space. The outcome can help researchers and practitioners such as instructors and faculty members by providing an insight into how to use design technologies, develop curriculum and create an experiential learning environment. Second, after teaching the AM course and reflecting on the design process, elements and outcomes for the course where students created the prototype by hand or given access to 3D printing equipment, we conceptualized the design of a workshop (see Addendum for Workshop Proposal) for educators both for K-12 and higher education. Providing AM learning opportunities and teaching resources to K-12 teachers would enable them to prepare for teaching and teach AM to K-12 students. Early engagement of students in science and engineering practices builds their confidence to inquire, define problems, investigate, analyze data, develop models and design solutions, evaluate, and communicate findings (Bybee, 2011). This process of early engagement in engineering practices can encourage learners to follow future STEM careers which would create a pipeline for K-12 students to engage in industrial processes and build a competitive STEM workforce in the coming years.

The key stages of the Design Thinking framework directly informed and shaped the instructional design decisions. (a) Empathize stage (understanding learner needs) influenced the learner-centered design of the course; (b) Define stage (clarifying learning goals and challenges) influenced instructional design that guided content development such as clear learning objectives and a problem statement and assessment criteria; (c) Ideate: Brainstorming Instructional Strategies influenced instructional design that encouraged modeling and scaffolding, collaborative learning and reflective practice; (d) Prototype (developing and structuring the learning experience) influenced instructional design focus on developing a working version of the learning experience, refining content delivery models, and integrating interactive elements. To ensure that instructional design supports active engagement feedback from pilot study was gathered before full-scale implementation; (e) Test (refining based on learner feedback and reflection) influenced instructional design for continuous improvement, ensuring the course effectively meets learner needs, and reflection is integrated at both learner and designer levels to assess engagement, comprehension, and impact.

Research on design principles for how to best engage teachers for professional development emphasized three practices: structure, modeling, and reflection (Chatterjee & Warr, 2024). Analyzing the instructional design for the AM courses provided us with the opportunity to find a structure for developing the workshop. Through the workshop we want to encourage teachers to model their own thinking, as a result preparing them to take responsibility for developing their own instructional design, forming questions and evaluating responses. Research has demonstrated that teacher participants need support and guidance for preparing themselves to practice what they have learnt, which is possible through carefully scaffolded interactions. Interaction supports reflection, guided interaction through a process for example a workshop would help teachers develop their reflection skills which is critical for effective instruction. The Design Thinking framework ensures instructional design is learner-centered, iterative, and problem-focused. Each stage of Design Thinking plays a crucial role in shaping course structure, modeling, and reflection, ultimately leading to more effective and engaging learning experiences.

We want to model practices for teachers, by engaging them in a way so that they can observe, think and reflect more critically about what it means to design the curriculum and teach additive manufacturing to specific groups of learners. Creating a collaborative learning space for participants in the workshop will help build relationships among participants and foster a supportive network of researchers, educators, instructional designers and practitioners. As we were developing the workshop proposal focusing on a participant-centered learning environment based on what we learnt while analyzing the instructional design, it became clear that learner agency, responsibility and management are critical factors for making teaching and learning effective (Chatterjee, 2021).

Implications and Future Study

Investigations into design conceptualization (how ideas take shape) and cognition (how designers think and make decisions) can be deeply informed by specific elements of the Design Thinking approach—namely Empathize, Define, Ideate, Prototype, and Test. Each stage provides insights into cognitive processes, problem-solving strategies, and creative workflows in instructional design. Investigating design conceptualization and cognition through the lens of Design Thinking provides valuable insights into how instructional designers frame problems, generate ideas, process information, and refine solutions. Each phase of Design Thinking offers a structured way to explore the cognitive mechanisms underlying instructional design processes.

Instructional designers highlight that the goal is not only to teach technical skills but also to inspire a mindset of continuous learning, curiosity and innovation. Thus, effective instructional approaches for any technology courses with a balance between theory and practice can foster ideation, collaboration, and adaptability. Experiential learning approaches empower learners to thrive in an ever-evolving technological landscape. The continued evolution of 3D printing technology promises exciting possibilities for instructional approaches. Artificial intelligence and machine learning are expected to enhance design processes, while advancements in bioprinting and nanotechnology could introduce new educational opportunities in basic sciences. Additionally, virtual reality (VR) and augmented reality (AR) tools may integrate with 3D printing, enabling immersive design experiences.

It is found that students connect ideation to implementation and new technology impacts the design process and design strategies (Greenhalgh, 2016). In future we would like to investigate the impact of design technology (3D printing) on learners' i) design conceptualization, ii) design cognition, and iii) learning experiences, iv) knowledge to compare hand-constructed and 3D printed models, and v) attitude towards model revision and refinement. Investigations of the above would provide insights into the design processes approached by learners.

Conclusion

From fostering creativity and innovation to building technical skills, additive manufacturing is an invaluable tool for modern education. By adopting an instructional approach, educators can harness its potential to prepare students for the challenges and opportunities of the future. The integration of additive manufacturing into learning environments not only enriches traditional curricula but also inspires a new generation of makers and problem-solvers. Experiential learning transforms technology education by immersing students in hands-on, practical experiences that foster deep understanding, skill acquisition, and innovative thinking. By engaging with tools and processes directly, students not only master technological competencies but also develop confidence and problem-solving abilities essential for navigating an increasingly complex and technology-driven world.

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Addendum

Workshop
Additive Manufacturing: A Hands-On Approach to Innovation

Objectives
This workshop aims to:
1. Introduce participants to the fundamentals of additive manufacturing (AM), including 3D printing technologies, materials, and processes.
2. Explore design thinking methodologies as applied to AM to foster innovation and problem-solving.
3. Providing hands-on experience with 3D printing software, hardware, and techniques for prototyping and production.
4. Discuss real-world applications and emerging trends in AM across industries.

Intended Audience
This workshop is designed for:
- Experience Level: Educators at all levels (K-12 and higher education), instructional designers, and technology specialists.
- Prerequisites: No prior experience with 3D printing is required, although familiarity with CAD software is beneficial.

Proposed Length of Workshop
Five hours

Agenda
Table 1. Agenda with Activity and Design Thinking stages

Time	Activity	Design Thinking Stage
30 min	Fundamentals: Introduction to AM and Case Studies	Empathize
30 min	Advanced Design Strategies: Defining Design Challenges & Framing Problems	Define
1 hour	Brainstorming & Developing 3D Model Concepts	Ideate
2 hours	Hands-on Prototyping & 3D Printing	Prototype
1 hour	Testing, Presentation, Troubleshooting, Iteration, Reflection, Discussion	Test

Abstract
Additive manufacturing (AM), commonly known as 3D printing, is revolutionizing industries by enabling rapid prototyping, personalized production, and innovative design solutions. This workshop offers a practical introduction to AM, equipping participants with the knowledge and skills needed to harness its potential. Designed for beginners

and those with intermediate experience, the session will explore the core technologies, materials, and processes behind AM while highlighting its applications in industries such as healthcare, aerospace, and education. Through a combination of lectures and hands-on activities, participants will learn how to create and prepare 3D models using design thinking principles. They will operate 3D printers, troubleshooting common issues, and understand post-processing techniques. The workshop will also delve into emerging trends such as bioprinting, sustainable materials, and large-scale AM. By the end of the session, attendees will have a foundational understanding of AM and the confidence to integrate it into their professional or academic projects.

Topical Outline

1. **Introduction to Additive Manufacturing**
   - Overview of AM technologies (e.g., FDM, SLA, SLS)
   - Comparison with traditional manufacturing methods
2. **Materials and Processes**
   - Common 3D printing materials and their properties
   - Step-by-step process: Design to finish product
3. **Advanced Design Strategies, Defining Design Challenges, Framing Problems**
   - Principles of design thinking
   - Strategies for innovative problem-solving
4. **Hands-On Activities, Developing Models, Prototyping, Printing, Testing**
   - Designing 3D models using CAD software
   - Operating 3D printers and troubleshooting common issues
   - Post-processing techniques (e.g., sanding, painting, assembly)
5. **Applications and Trends**
   - Case studies: Industry-specific applications (e.g., healthcare, automotive, education)
   - Emerging trends: Bioprinting, sustainable materials, and large-scale AM
6. **Wrap-Up: Future Directions and Resource Sharing**
   - Recap of key concepts
   - Resources for continued learning
   - Questions and Answers
   - Participant feedback

Summary of Instructor's Qualifications:

- The instructor is an expert in Additive Manufacturing research and teaching.
- The instructor is an expert in learning design and technology with a focus on the intersection of teacher education, creativity, and technology.
- The instructor is an assistant professor at a major university.
- The instructor has a background in conducting research on educational technology adoption, problem-based learning, and design pedagogy.
- The instructor has presented at several conferences on this topic and has published on the topic.
- The instructor regularly collaborates with other experts in the field.
- The instructor has practical experience using AM tools for both teaching and research.

Equipment Note: An instructor PC, projector, screen, and WIFI will be provided for the room. A lab of computers will be furnished. Participants are encouraged to BYOL-Bring Your Own Laptop.