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Research article

Teaching Design for AM to Science Materials Engineering Graduate Students: Hand-on Approach

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Abstract

This work introduces a new approach to engineering education focusing on hands-on experiential learning in design for additive manufacturing (DfAM). This method provides students access to additive manufacturing (AM) software and online platforms, enabling practical exploration and mastery of software functionalities. The emphasis on DfAM principles guides students through optimizing components for AM production. By blending theoretical knowledge acquisition with practical application, students develop components adhering to DfAM rules. Implementing this approach improves student proficiency with software and understanding of AM processes, where evaluating student-developed components for AM production fosters innovation and critical thinking skills. Overall, the outcomes demonstrate the effectiveness of hands-on learning in enhancing student engagement and preparing them for modern engineering challenges. This approach imparts technical skills and cultivates creativity and adaptability, which are essential for success in the evolving field of AM.

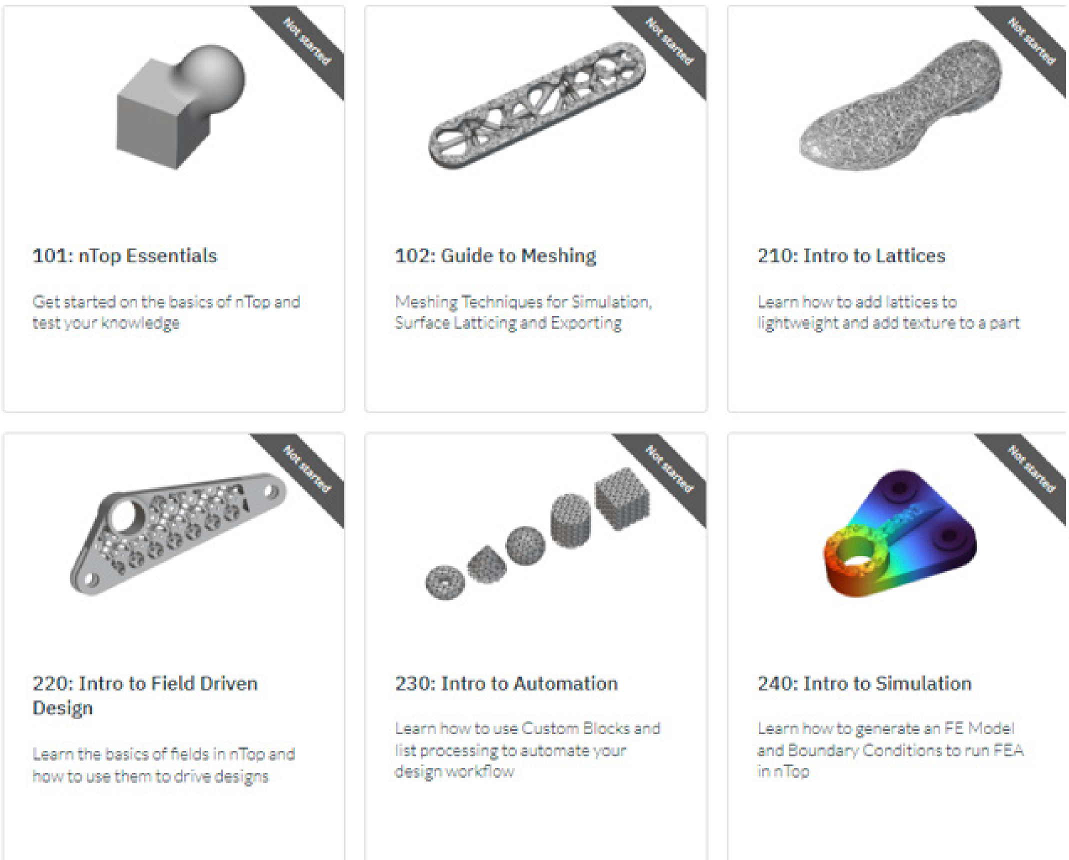
Keywords: Additive Manufacturing; Experiential Learning; Design for Additive Manufacturing; Engineering Education; Hands-on Approach; AM Software; Materials Engineering Graduate Students

Literature Review

Engineering education is currently experiencing a significant transformation, driven by the changing needs of industry and the technological advancements shaping the profession. This transformation is marked by a growing emphasis on hands-on experiential learning methods, aiming to narrow the gap between theoretical knowledge and practical application, thus better-preparing students for real-world engineering challenges [1,2]. Within this context, AM presents unique opportunities and challenges, calling for innovative pedagogical approaches to educate the next generation of engineers effectively. AM has transformed traditional manufacturing methods by creating exceptional efficiency and adaptability with intricate shapes [3-5]. To reach AM's full potential, it's crucial to possess advanced technical knowledge of software and equipment and a deep understanding of design principles specific to additive processes. DfAM has emerged as an essential aspect of education, concentrating on optimizing components for AM production, and its principles encompass geometric complexity, support structures, material properties, and manufacturing constraints [6-10]. Figure 1 illustrates a gear bearing that was optimized for AM production.

Figure 1: Gear bearing optimized for weight reduction, by using lattice structures.

Recognizing the significant role of hands-on learning in cultivating expertise and innovation, a hands-on approach to teaching engineering involving immersive AM experiences is proposed [11,12]. This approach enables students to have autonomous access to software and online learning platforms, empowering them to delve into the complexities of design and fabrication in a guided yet self-directed manner [3,13]. By equipping students with the necessary tools and resources to interact directly with AM technology, the goal is to promote a culture of exploration and creativity, where learning arises not just from textbooks and lectures but also from practical experience and real-world application. In Figure 2 is possible to see the entry page of the nTop learning page, with different lessons about different topics related to DfAM, to gain experience with their software.



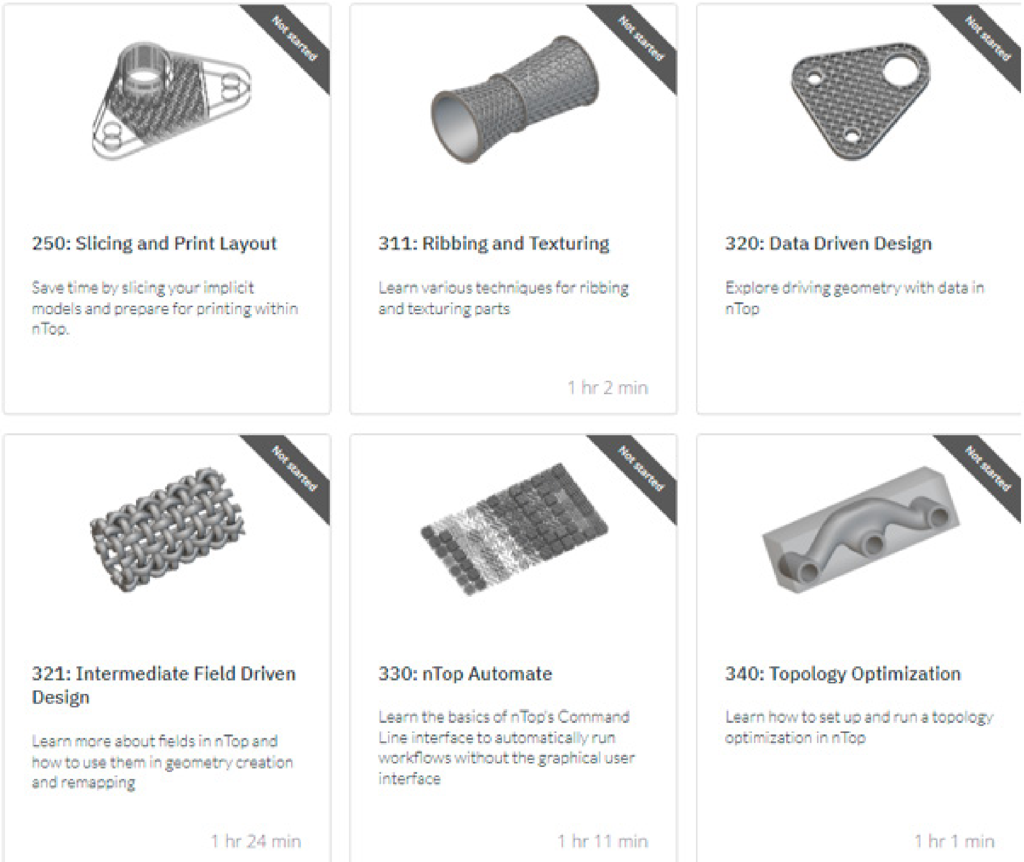


Figure 2: Image from the nTop Learning Center website, with lessons about different topics related to software learning [14].

The landscape of engineering education is undergoing significant changes in response to the evolving needs of industry and technological advancements. Traditional lecture-based teaching methods are giving way to more interactive, hands-on approaches that better prepare students for the complexities of modern engineering practice. Innovative pedagogical approaches are becoming increasingly important [15-17]. By empowering students with skills to create components for AM and encouraging them to share their work, often in the college magazine, the goal is to cultivate a sense of ownership and achievement beyond the typical classroom environment [18,19]. The objective is to provide students with technical expertise and foster a mindset of innovation and adaptability that are essential for their future careers in engineering. This innovative approach to engineering education is designed to advance the field and nurture a new generation of engineering leaders ready to confront the next decade's challenges [18,19].

Research on engineering education emphasizes the value of experiential learning and practical application in promoting deep understanding and retention of concepts. Project-based learning, design competitions, and laboratory exercises have enhanced student engagement, motivation, and overall learning outcomes [20-22].

Some studies have highlighted the effectiveness of various instructional strategies in AM education, particularly emphasizing the value of project-based learning and the integration of practical experiences like prototyping and experimentation in enhancing student performance and understanding [23,24]. Integrating AM software into the curriculum can enable educators to promote active learning and empower students to develop innovative solutions to real-world problems [25,26].

Despite the advantages of hands-on learning in AM and DfAM education, challenges persist regarding access to resources, faculty expertise, and institutional support. Furthermore, the fast-paced technological advancements in the field require curricula and instructional methodologies updates. This paper describes how students are instructed to optimize components for AM using DfAM principles. By combining theoretical teaching with practical exercises, the effectiveness of this approach in improving student competency with AM software and comprehension of AM processes is showcased.

Material and Method

The teaching methodology utilized in this research aims to fully engage graduate students in materials engineering with the hands-on application of AM principles while providing them with a thorough theoretical groundwork. This approach comprises interconnected components, each focused on nurturing comprehension of DfAM principles and practical experience with AM software and technologies:

1) Software Access and Online Learning Platform: Students can access industry-standard AM software packages through university licenses or cloud-based platforms. This access is complemented by the online learning platform, which offers an extensive array of instructional materials, tutorials, and resources specifically tailored to assist students in utilizing the software and understanding the principles of DfAM.

2) Curriculum and Guided Assignments: The curriculum includes a series of guided assignments (predefined in the learning platforms) and final projects intended to allow students to delve into and master AM software tools and techniques. These assignments cover various topics, encompassing geometric modeling, lattice structures, support generation, and build orientation optimization, all within the framework of DfAM principles. Faculty members and teaching assistants offer continuous support and guidance, providing feedback and help as students progress through the assignments.

3) Project Development Process: As part of the project development process, students are responsible for optimizing components for AM production. This involves considering material properties, build constraints, and post-processing requirements. Using simulation tools integrated into the AM software, students can evaluate the manufacturability and performance of their designs before fabrication. Based on material and application requirements, selected components are fabricated using appropriate AM processes.

4) Final Project: Students are given a final project to apply their acquired knowledge and skills to real-world design challenges. These projects, which can be done individually or in teams, are chosen to emphasize specific aspects of DfAM, such as lightweight, topology optimization, or part consolidation. There is a focus on iterative design, encouraging students to explore multiple design iterations and assess their performance using AM software simulation tools.

5) Documentation and Publication: Students are urged to document their design process and outcomes, culminating in preparing a technical report or scientific paper detailing their findings. There are opportunities for publication, such as submission to the college magazine or other publications, to provide students with valuable experience in scientific writing and communication. Additionally, selected projects may be presented at conferences or symposiums, showcasing students' accomplishments and contributions to the field of AM.

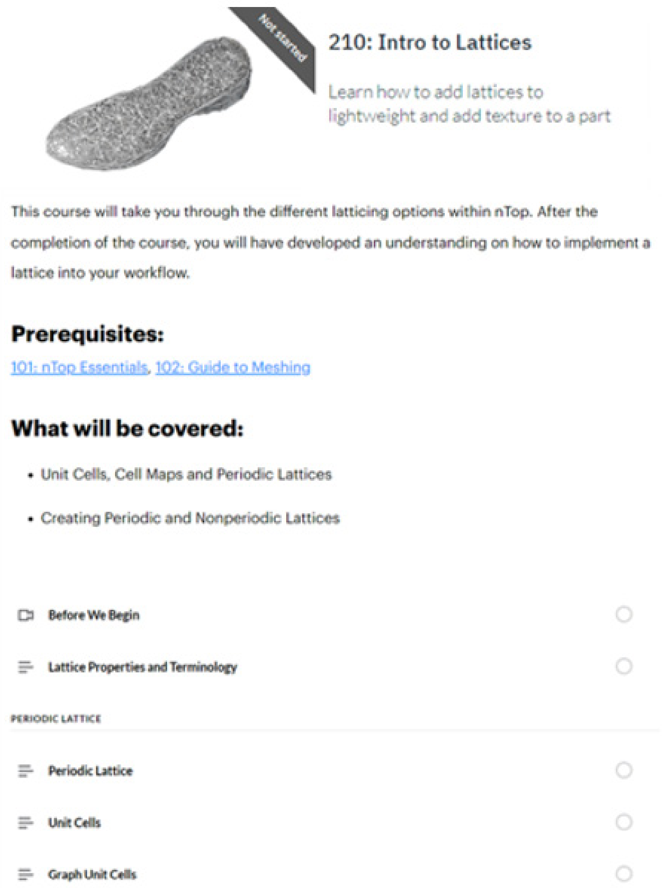


Figure 3: An example of a nTop lesson –Intro to Lattices [27].

This comprehensive approach aims to equip students with the practical skills and theoretical knowledge necessary for success in the rapidly evolving field of AM. The methodology's effectiveness is evaluated through various means, including student feedback, performance assessments, and analysis of project outcomes. The approach is continually refined based on lessons learned and best practices in engineering education.

Result

The pedagogical approach we have adopted, focusing on hands-on engagement with AM technologies, has precipitated noteworthy positive outcomes, illustrating the profound impact of experiential learning on enhancing student engagement, mastery, and innovation in the field of AM. The principal outcomes derived from the pedagogical strategy are delineated as follows:

1) Enhanced Proficiency: Students demonstrated a pronounced improvement in their ability to utilize AM software tools and functionalities. This was evidenced by their adeptness in navigating software interfaces, manipulating three-dimensional models, and optimizing designs for AM processes. Furthermore, feedback from students indicated a significant increase in their confidence in utilizing AM software. This feedback also highlighted an enriched understanding of software's critical role in the AM operational workflow.

2) Augmented Understanding of DfAM Principles: Through structured exercises and project-centric learning endeavors, students were able to acquire a comprehensive understanding of DfAM principles. These principles encompassed aspects such as geometric complexity, the necessity for support structures, and the optimization of build orientation. Furthermore, students demonstrated the ability to apply DfAM principles to tangible design challenges. This application of knowledge was evident in their creation of optimized components that were apt for AM production.

3) Cultivation of Creativity and Innovation: The project-focused methodology fostered an environment of creativity, exploration, and innovation among the students. Students could devise innovative solutions to complex engineering challenges by utilizing AM technologies. They defied design limitations to create functional, lightweight, and structurally refined components, demonstrating the transformative potential of AM in modern engineering practice.

4) Recognitions and Achievements in Scholarly Publications: Numerous student projects were selected for inclusion in collegiate academic publications (Table 1), a testament to the caliber and significance of their scholarly contributions. These opportunities for publication served as a platform for students to disseminate their findings and achievements. This not only garnered acknowledgment for their academic contributions but also highlighted their significant impact on the domain of AM education.

Table 1: Published papers under the scope of hands-on experiential learning within AM education.

Title	DOI	Authors	Journal
Topology Optimization of a Robot Gripper with nTopology	10.24840/2183-6493_010-001_002051	Monteiro, B.S. Rocha, F. Costa, J.M.	U.Porto Journal of Engineering Vol. 10 p. 11-19
nTopology Optimization of an Additive Manufactured Support for Smart Glasses	10.24840/2183-6493_0010-001_002057	Nunes, F. Trindade, M. Costa, J.M.	U.Porto Journal of Engineering Vol. 10 p. 20-33
Design and Optimization of a Gripper Clamp	10.24840/2183-6493_0010-001_002059	Cunha, M.S. Alves, E.S. Costa, J.M.	U.Porto Journal of Engineering Vol. 10 p. 34-44
Topology optimization applied to additive-manufactured hydrofoil wing components	10.20935/acadmatsci6213	Mata, M. Bencatel, R. Sequeiros, E.W. Vieira, M.F. Costa, J.M.	Academia Materials Science
Topological Optimization of a Metal Extruded Doorhandle using nTopology	10.24840/2183-6493_009-001_001620	Mata, M. Pinto, M. Costa, J.M.	U.Porto Journal of Engineering Vol. 9 p. 42-54
Production of an Office Stapler by Material Extrusion Process, using DfAM as Optimization Strategy	10.24840/2183-6493_009-001_001635	Oliveira, C. Maia, M. Costa, J.M.	U.Porto Journal of Engineering Vol. 9 p. 28-41

5) Affirmative Student Feedback: The students responded positively to the hands-on learning paradigm. They highly valued the opportunity to engage directly with AM technologies, which allowed them to hone their practical skills. Furthermore, they appreciated the chance to apply their theoretical knowledge within real-world contexts.

6) Equipping Students for Professional and Research Endeavors: The competencies and insights gained through the pedagogical approach have effectively prepared students for careers in both industry and research, where AM

technologies are increasingly being used for rapid prototyping, product innovation, and manufacturing processes. Students have expressed confidence in applying AM principles and methodologies professionally. They attribute the practical experience acquired during the course as an indispensable part of their preparation for the workforce. This feedback underscores the effectiveness of equipping students with the skills and knowledge necessary for the rapidly evolving engineering field.

By facilitating direct engagement with AM software, endorsing the application of DfAM principles, and fostering the development of innovative solutions, students are equipped with the requisite skills, knowledge, and mindset to excel in the dynamically evolving engineering discipline. Moving forward, it is intended to continuously refine and enhance our pedagogical strategy based on evaluative feedback and acquired insights to advance engineering education and prepare students for the challenges and prospects of the 21st century.

Discussion

Implementing a hands-on, experiential learning framework within the realm of engineering education, with a specific emphasis on AM, has provided valuable insights into the transformative potential of this pedagogical approach. This study has demonstrated how this innovative methodology aligns with the evolving requirements of the engineering profession, equipping students with a blend of practical skills, robust theoretical understanding, and a creative mindset.

(a) (b)

Figure 4: Examples of works developed under hands-on experiential learning within AM education: (a) door handle [28] and (b) desk stapler [29].

The hands-on nature of this educational approach has been instrumental in fostering a culture of innovation and problem-solving among students. Students can navigate real-world scenarios and comprehensively understand AM principles by providing direct access to AM technologies and software. This has resulted in creating optimized components suitable for AM processes, indicative of a deep understanding of DfAM principles. Figure 4 presents two works made under the scope of hands-on experiential learning within AM education.: a door handle Figure 4a) and a desk stapler (Figure 4b)

The opportunity for students to publish their research findings has served as a platform for disseminating knowledge and advancements in AM, contributing to the academic literature in the field. This provides recognition for their scholarly contributions and highlights the significant impact they are making in the field of AM education.

However, the implementation of this educational approach has its challenges. These include limited resources, the need for faculty expertise in AM, and the development of a curriculum that keeps pace with rapid technological advancements in the field. To address these challenges, ongoing support and professional development for faculty members are essential.

Looking ahead, there is an opportunity to further refine and enhance this educational model based on feedback and insights gained. Collaborations with industry stakeholders can provide students access to cutting-edge AM equipment and real engineering projects, enriching their academic experience and strengthening the ties between academia and the industrial sector.

Introducing a hands-on, experiential learning framework within AM education has yielded positive outcomes. By advocating for innovation, promoting collaborative efforts, and fostering a culture of continuous learning, we are advancing engineering education and preparing students to meet the challenges and leverage the opportunities.

Conclusion

This research investigates an avant-garde pedagogical paradigm in engineering education, spotlighting the transformative capacity of hands-on experiential learning in AM. This study's findings highlight this method's efficacy in narrowing the chasm between theoretical comprehension and practical expertise, thus equipping students for the dynamic and ever-evolving terrain of engineering.

Employing practical methodology has facilitated students' proficiency in AM software tools while developing an in-depth understanding of DfAM concepts. Such empowerment has enabled the production of optimized components designed for AM processes, illustrating the significant influence of experiential learning on student involvement and proficiency in AM instruction.

Moreover, offering students the prospect to disseminate their research contributions has accorded scholarly recognition and underscored their notable influence in AM education. Many student endeavors were selected for publication in collegiate academic journals, evidencing the quality and importance of their scholarly work. Nonetheless, deploying this educational strategy encounters challenges, including scarcity of resources, the requisite for faculty expertise in AM, and creating a syllabus that aligns with the swift technological advancements in the sector. Forward-looking, there is potential to refine and improve this educational model, leveraging feedback and insights obtained.

Introducing a hands-on, experiential learning model within AM education has engendered positive ramifications. By nurturing an innovation and perpetual learning ethos, this approach advances engineering education and capacitates students to confront challenges and exploit upcoming years' opportunities. This study substantiates the critical role of hands-on experiential learning in cultivating future engineering leaders and significantly contributes to the advancement of AM technologies.

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Author Contributions

Conceptualization: J.M.C. and M.F.V.; investigation and writing – original draft preparation: J.M.C.; methodology and resources: J.M.C. and M.F.V.; writing – review and editing: J.M.C. and M.F.V.; supervision: J.M.C. and M.F.V.

All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The author(s) declare no conflict of interest.

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