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DESIGN FOR(E!) ADDITIVE MANUFACTURING: IN SEARCH OF A COMPREHENSIVE DESIGN CHALLENGE SUITABLE ACROSS AM EDUCATION

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Abstract

Modern engineering design education relies heavily on the concept of problem-based learning (PBL). Driven by the constructivist theory of education, PBL enables students to build knowledge organically, rather than through rote memorization. As such, design for additive manufacturing (DfAM) education also tends to emphasize the use of PBL to encourage student learning. Unfortunately, dedicated DfAM education is still nascent. The result is a wide range of educators leveraging an equally wide, and often unproven, range of design challenges to support DfAM PBL. Because of this, there is the possibility that a chosen design challenge will not represent AM as a true end-use manufacturing process nor promote a design space that can benefit from the full consideration of all opportunistic and restrictive DfAM concepts. In this paper, the author discusses the creation and implementation of a comprehensive design challenge that is suitable across the range of AM education. Specifically, the author proposes the use of a golf putter DfAM design challenge. This concept draws from lessons learned over years of DfAM instruction at undergraduate and graduate levels and is based in the need for three key aspects for a successful DfAM challenge in education: (1) clarity, (2) applicability, and (3) demonstrability.

1. Introduction

Modern engineering design education relies heavily on the concept of problem-based learning (PBL) [1]. Based in the educational framework of constructivism, PBL leverages an organic approach to learning, where students naturally construct understanding through contextualized, hands-on learning [2]. This framework aligns naturally with Design for Additive Manufacturing (DfAM), which requires engineers to reconsider existing rulesets surrounding what makes a traditional design "manufacturable." Through PBL, engineering students can engage with DfAM in a way that allows them to tangibly challenge their existing design intuition. Especially with the rapid advancement of desktop material extrusion in the classroom, it is becoming easier and easier to engage students with AM and DfAM in the classroom.

However, even though the use of AM in the classroom continues to grow quickly, DfAM education is still fractured. Most commonly, DfAM forms one portion or module of a more general AM course [3]. To support this module, many courses will leverage a design challenge, where students are tasked with designing or redesigning an object with the specific intent of using AM to manufacture the solution. This mirrors the growing popularity of internet-based DfAM challenges, such as the well-known GE bracket challenge [4]. Unfortunately, chosen DfAM PBL challenges are widely varied, which can introduce a range of inconsistencies in AM education across institutions and educational levels. The result is that students, upon entering industry, may not all demonstrate the same command of DfAM knowledge, since they have constructed their DfAM knowledge through different contexts. This commands the need for the DfAM education community to coalesce around a common design challenge, capable of meeting the best-practices associated with design PBL, while also demanding students consider the entirety of AM's design opportunities and restrictions. This paper takes the first steps toward proposing such a unifying design challenge driven by the key characteristics of (1) clarity, (2) applicability, and (3) demonstrability. The result is an argument for the golf putter as a potential candidate for DfAM educational challenges.

2. Background

2.1. The Challenge of Addressing Dual DfAM in the Classroom

Before creating a consistent approach to teaching DfAM in higher education, it is first necessary to establish a shared mental model about what defines DfAM. One approach is through a dichotomous view of DfAM separated into 'opportunistic' and 'restrictive.' In this model, the DfAM principles that leverage AM capabilities can be collectively thought of as 'opportunistic' DfAM, which consist of (1) mass customization [5,6], (2) part consolidation [7] and printed assemblies [8], (3) free shape complexity [9–11], (4) embedding external components [12], and (5) printing with multiple materials [13]. Meanwhile, design guidelines meant to account for AM limitations and minimize failure [14] can be considered as 'restrictive' DfAM. This encompasses (1) the need for support structures [15], (2) warping of parts due to thermal stresses [16], (3) anisotropy and weakness in build direction [17,18], (4) surface roughness due to stair-stepping [19,20], and (5) limited feature size and accuracy [21]. When considered simultaneously, restrictive and opportunistic DfAM come together to form a paradigm of 'dual DfAM,' which can help support the integration of all DfAM concepts into the engineering design process [22–29]. Table 1 summarizes some of these key DfAM considerations, divided into restrictive and opportunistic categories.

Table 1. Key Restrictive and Opportunistic DfAM Considerations

Restrictive DfAM	Opportunistic DfAM
Support Structure Accommodation	Geometric and Hierarchical Complexity
Warping Due to Thermal Stresses	Multi-Material Printing
Delamination and Material Anisotropy	Part Consolidation and Printed Assemblies
Stair-Stepping and Surface Roughness	Mass Customization
Minimum Feature Size	Functional Complexity and Embedding

Even after identifying the concept of dual DfAM as framework for AM education, there is still a need to identify how best to appropriately integrate it within engineering education. It is not enough for a DfAM educational intervention to introduce students to different AM processes and DfAM concepts; it must also naturally encourage students to integrate both opportunistic and restrictive DfAM into their design process [30]. Fortunately, a range of DfAM initiatives have been introduced into the engineering curriculum, as summarized in [31]. However, research shows that if students are not motivated to fully explore the solution space enabled by AM [32], they may still generate simple, easy to manufacture geometries despite being trained in opportunistic DfAM [33]. Students may also focus only on avoiding build failure, which could lead them to apply only restrictive DfAM and not fully leverage opportunistic DfAM. This is problematic though, since sufficient emphasis on both opportunistic and restrictive DfAM is necessary for students to generate the most high-quality design concepts for AM [34]. Because of this, it is essential to understand how different design challenges can encourage students to engage with the design process while motivating them to fully leverage dual-DfAM [35].

2.2. Existing Efforts in Problem-Based Learning for DfAM Education

As discussed, research has shown that task-based learning helps students develop their problem solving capabilities [36], which have been identified as crucial for the continued growth of successful AM engineers [34]. Because of this, a key characteristic of DfAM education is that it encourages students to actively use AM and DfAM concepts to solve problems [37,38]. Task-based learning techniques can help achieve this. One of the first instances of DfAM task-based education focused on technical and economic viability of introducing AM as a prototyping tool in engineering education [39]. More extensive use of PBL to solve a DfAM task was demonstrated in [3], where students were tasked with designing an AM solution for a problem of their own choosing. A similar, though more extensive use of PBL was also demonstrated through the implementation of a university-wide vehicle design competition, where students were tasked to create printable ground and aerial vehicles capable of maneuvering across obstacles while carrying a defined payload [35].

Even beyond these initial examples, the use of PBL across AM and DfAM education is extensive. This includes researchers combining short design activities focused on restrictive AM (geometric accuracy, strength, resolution, and process parameters) as well as longer design activities focused on opportunistic DfAM (cellular structures and lightweighting) [40]. In this particular case, students were encouraged to leverage DfAM concepts to design a car bumper capable of minimizing damage in the event of a collision with a wall. PBL for DfAM education is also demonstrated in [41], where students were asked to identify a problem of interest and generate solutions to solve it; information about AM and DfAM was presented to students as their worked through the design process to help students adapt their thinking to DfAM. Longer-form DfAM workshops have also leveraged PBL methods, such as the redesign of a block manifold across four days in [42] and the redesign of a vehicular air breather in [43].

Though this review is non-exhaustive, it provides a representative cross-section of the range of design challenges present in PBL across DfAM education. Often, design challenges are (1) student-identified and inconsistently scoped based on personal interests, (2) instructor identified ‘toy’ problems with clear bounds but limited design opportunities, or (3) industry-driven redesign tasks with vague bounds, but significant design opportunities. However, the author argues that successful PBL in DfAM requires a design challenge at the intersection of these three options. A task is needed with opportunities for personal design creativity, but with clear design bounds for an end-use industry product. Even further, the task must encourage students to consider *all* aspects of both restrictive and opportunistic DfAM, rather than just a limited number of concepts (such as a lightweighting task which might only require consideration of lattice structures or shape complexity).

3. The AM Golf Putter Design Challenge

Considering the current state of the art for PBL in DfAM, there is a need for a unifying design challenge that can engage a range of students from across educational levels with the totality of dual DfAM concepts toward a true, end-use product. To that end, this section details an argument for the use of a golf putter design challenge to support DfAM based on the fundamental principles of *clarity* (whereby the task is grounded in a familiar problem with digestible design requirements), *applicability* (whereby the task benefits from full consideration of all aspects of restrictive and opportunistic DfAM), and *demonstrability* (whereby the task results in an end-use product that can be created and tested in a classroom environment).

3.1. *Clarity*: Familiar Problem with Digestible Design Requirements

The first characteristic of a successful DfAM challenge is the notion of *clarity*. Clarity is based primarily on the idea that the chosen task is grounded in concrete, real-world product design, with established objectives and constraints. Further, the task should be easily digestible to a range of students with a variety of backgrounds.

<u>Common familiarity/access to real-world experience</u>. Since the onset of the COVID-19 pandemic, participation in golf has grown at a rate not seen in 17 years [44]. This is especially relevant for universities, as many have affiliated golf courses for student use. Despite this, it is still possible, and likely, that students have not participated in a full golf course. However, the ubiquity of mini golf as a recreational activity drastically increases the likelihood that students have hands on experience with golf putters; annual participation in mini golf involves 18 million players [45]. This familiarity with the challenge's context naturally primes students for participation.

<u>Clear, concrete design constraints</u>. The governing committee behind golf in the United States, the USGA, has a freely available document detailing all design constraints associated with golf putters [46]. Example constraints are shown in Figure 1. This gives students easy access to a series of concrete rules driving the size, weight, and form of compliant golf putters. This includes specifics regarding how AM's "free complexity" may ultimately support or conflict with established rules, such as the requirements that clubs be "plain in shape." Crucially, though there are a series of guidelines, they are not so limiting as to make the solution space trivial.

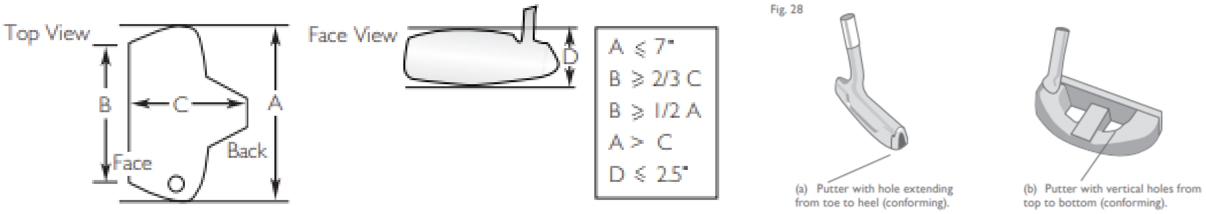

Figure 1. Example Guidelines as Provided by the USGA [46]

<u>Performance driven by singular engineering objective</u>. In putter design, modern products are typically driven by strict consideration of the putter's moment of inertia (MOI). By increasing the MOI, the putter is generally considered to be more stable. The result is that the club face is less likely to be unintentionally opened or closed when swinging to impact the ball. The goal of increasing moment of inertia is understandable for engineering students early in their education and is typically intuitively addressed by the notion of moving weight to the perimeter of the putter.

Abundance of existing, varied design inspiration. Due to the constant advancement of golf technology and design, there is an abundance of design inspiration available to students to help encourage their creativity and understanding of the task. Putters are typically categorized as blade, half-mallet, and mallet designs, all of which approach the concept of moment of inertia and usability differently. Industry is also starting to explore the use of AM in putter design, though efforts are still nascent. Currently, Cobra Golf is the only company with a commercially available putter with AM components, as seen in Figure 2. The prevalence of such numerous putter designs enables students to quickly understand the potential breadth of the solution space.

Figure 2. Commercially Available Putter with AM Components (Adapted from [47])

3.2. *Applicability*: Benefits from All Aspects of Opportunistic and Restrictive DfAM

The second characteristic of a successful DfAM challenge is the notion of *applicability*. As discussed in Section 2, many existing design challenges tailored to DfAM benefit from only a select number of DfAM considerations, most frequently geometric complexity and support material elimination. By contrast, the design of a golf putter has the potential to beneficially leverage the entire spectrum of restrictive and opportunistic DfAM. A non-exhaustive list of such examples follows in the rest of this sub-section, considering opportunistic DfAM first, followed by restrictive DfAM.

O-DfAM 1: In-situ embedding. Though typically not as common as other aspects of opportunistic DfAM in product design, the putter challenge naturally encourages students to consider the use of in-situ embedding as a DfAM opportunity. This is especially true if their printer access is limited to common desktop-scale material extrusion systems. Such systems are unable to generate products with sufficient mass capable of matching traditional putter designs (approximately 350g). As such, students tend to quickly recognize the need to embed additional weights into the putter.

O-DfAM 2: Shape complexity and topology optimization: As discussed in Section 3.1, increasing the MOI of the putter head can improve stability during the swing and reduce undesired twisting. By leveraging DfAM's shape complexity, when combined with topology optimization or generative design, it is possible to distribute material toward the perimeter of the club head to achieve a lightweight, yet stable putter in a way that is not traditionally possible with conventional manufacturing.

O-DfAM 3: Hierarchical complexity and lattices. As with shape complexity, hierarchical complexity and lattice structures can be used to redistribute material to increase the MOI of the putter. However, they can also be used to provide texture to the face of the putter to change the feel on impact, as well as change the way in which the ball rolls when struck. In conventional putter design, such textures are typically achieved through milling the face or using specialized secondary inserts. However, AM can enable complex patterns to be integrated directly into the face itself during the printing process.

O-DfAM 4: Multi-material distribution. Related to the use of hierarchical complexity for complex face patterns, multi-material AM can be used to strategically tailor the properties along the face to achieve the desired level of softness or hardness upon impact with the ball. Beyond only the stiffness, multi-material AM can also be used to improve the durability of the face, such as with carbon fiber AM. Materials with different densities may also be used to further distribute weight according to the golfer's preferences.

O-DfAM 5: Customization and one-off designs: The putter is the most frequently used club in a round of golf since it is often used on every hole. Because of this, a cottage industry has grown up around the customization of putters, with the intent of allowing golfers an opportunity for personal expression through the design of their clubs. Such customization can be purely aesthetic, such as adding a name or logo, or functional, such as adding customized weighting or patterns to the face of the putter to achieve a specific feel. Customization, as well as other opportunistic DfAM considerations are shown in Figure 3 as they have previously manifested in published AM putter designs.

Figure 3. Examples of Opportunistic DfAM in AM Putters (Adapted from [48] and [49])

R-DfAM 1: Printer accuracy and tolerances. Transitioning to R-DfAM, the accuracy of the putter's manufacturing process becomes crucial, assuming the task is to manufacture solely the putter head itself. This is due to the need for the putter head to attach successfully to a provided third-party golf shaft. Though an adhesive is often used to secure a final fit to the shaft, tight tolerances are still needed on the hosel of the putter head. This is especially important in an educational context, where putter heads are swapped in and out during the testing process.

R-DfAM 2: Consideration of support material. As with most AM products, support material is a constant consideration for the design and manufacture of a golf putter. Barring the simplest designs, it is highly unlikely that any putter generated by students will completely avoid the need for support material. This becomes especially relevant as students begin to leverage the shape and hierarchical complexity relevant to opportunistic DfAM in their putter design. Even a traditional blade-style design will require consideration of support material, given the shallow angles present under the heel and toe of the putter head.

R-DfAM 3: Limitations on minimum feature size. As with the consideration of support material, all but the simplest putter geometries will be required to account for the minimum feature size achievable by the chosen printing system. For positive features, this may manifest as lattice structures or organic topologies on the main body of the putter head. For negative features, minimum feature size will likely become an important consideration when creating any patterns on the face of the putter to affect the feel of a ball strike. Given the maximum dimensions dictated by the USGA design rules, features in most students' putter designs will in some way approach the minimum feature size of a printer.

R-DfAM 4: Accounting for Anisotropy. As the putter is intended to be an end-use product which will come under load during use (i.e., when striking the ball), students will naturally be required to consider any effects due to material anisotropy that could cause premature failure in the product. In most cases, this will likely be of largest concern in the hosel portion of the putter, which tends to be long and slender and the point at which the pre-built shaft will attach to the printed putter head. Given other considerations for build time and support material avoidance, the hosel will also likely be built upright, placing the printed layers perpendicular to the direction of the impact force when the ball is struck. This orientation will naturally cause decreased strength that must be accounted for in the design.

Figure 4. Examples of Restrictive DfAM in AM Putters (Adapted from [50] and [51])

3.3. *Demonstrability*: End-Use Product That Can Be Created and Tested in the Classroom

The third and final characteristic of a successful educational DfAM challenge is the notion of *demonstrability*. This ultimately drives the ability to not only manufacture student designs easily in the classroom, but also to test them as true-end use products without the need for extensive testing equipment.

Build inherently suited for desktop AM size. While some universities allow students access to large, industrial AM systems, most coursework or individual projects are conducted on small, desktop AM systems, owing to their relative affordability and ease of use. This places a manufacturing size constraint on any design challenge given to student participants. In the case of a golf putter, USGA rules place the largest allowable dimension at 7 inches, which falls approximately in line with most desktop-scale AM systems, creating a natural synergy between the required product size and the size of the available manufacturing equipment.

Suitable throughput for typical course size. Due to size constraints dictated by the USGA, a typical putter can be easily manufactured overnight or within one 8-hour operation period. This has the potential to enable a generally rapid turnaround time for a single team to design, print, and test their design. Given an available makerspace or openly available 3D printing facility, this should ensure that student teams are able to generate multiple design iterations on a timetable that works for either a shorter educational module or a semester-long project. However, it is worth noting that throughput could still prove challenging if only one printing system is available or if course enrollment is atypically large.

Integrates simply with external components. For the final product to be fully realized for testing, all that is needed is a single external component, that being a standard golf shaft with a grip. Though commercial putters use adhesive to connect the putter head to the shaft, making for a semi-permanent attachment, this is not necessary for testing in a classroom environment. Instead, this attachment can be easily mimicked using friction tape affixed to the lower end of the shaft where it inserts into the hosel. In this way, the putter heads can be easily removed and attached to the shaft for testing. Similarly, should students desire to incorporate extra weight into their putter head, via in-situ embedding, a range of simple, everyday items can be used, such as washers, fishing weights, or coins.

Easily, quickly testable in a classroom environment. After printing and attaching the putter head to the shaft, the putters can be easily tested in a classroom environment. This can be either on the bare floor, carpet, or, if desired, using a putting mat. Alternatively, for universities with golf courses, students can perform in-situ testing at a practice facility. The flexibility of this testing enables students to quickly get a feel for the performance and stability of their design, while also gaining feedback from their peers. Given additional space and putter shafts, multiple putters can also be tested simultaneously. Finally, the nature of printing a significant component for an athletic activity naturally introduces the potential to include a competitive element to testing.

Viable as end-use product, rather than solely as prototype. It is important that, through DfAM coursework, students begin to understand the validity of the technology as a means for end-use, functional products. This is especially important when students primarily have access to desktop polymer systems, which they may associate with prototypes or aesthetic pieces only. For a golf putter, there are no limitations on what the USGA allows for them to be built from. While putters are often made of metal, they can just as viably be made from polymer or wood, due to the relatively low loading they undergo when striking a ball. The result is a manufactured product that may avoid the feeling of students simply working with a “toy” problem or arbitrary academic exercise.

4. Implementation in Undergraduate Coursework

To demonstrate the use of the golf putter design challenge in practice, the remainder of this paper focuses on discussing the implementation of the activity in an undergraduate, DfAM-centered course during the Fall of 2022. The challenge took place over 16 weeks in a course with 24 students at a large, northeastern R1 university. Broadly speaking, student participants were tasked to *design, print, and test a golf putter head that accounts for restrictive and opportunistic DfAM, where the head must successfully mate to a provided golf shaft and adhere to all USGA requirements*. The design challenge in full can be found in the Appendix of this paper. The challenge was introduced at the beginning of the semester, and all topics in Table 1 were covered over the course of the semester, with restrictive DfAM accounting for approximately the first 6 weeks of content and opportunistic DfAM accounting for the remaining 10.

To help guide the execution of this project, students were given instructions to perform two iterations of the design. The first iteration was to focus solely on restrictive DfAM, leveraging existing golf putter designs and adapting them to be printable via desktop AM. During this iteration, student teams explored the design rules set out by the USGA, the governing organization that drives golf club design. They then conducted an extensive search of existing golf putter designs, including blade, mallet, and half-mallet designs to identify viable options to inform their own designs. Finally, most teams chose what they felt to be the most opportune design and began to adapt it for the characteristics of restrictive DfAM discussed to that point in the semester. At the end of the first iteration, all student teams presented their manufactured designs for review by the rest of the class. Figure 5 shows two such iterations made from black PLA filament.

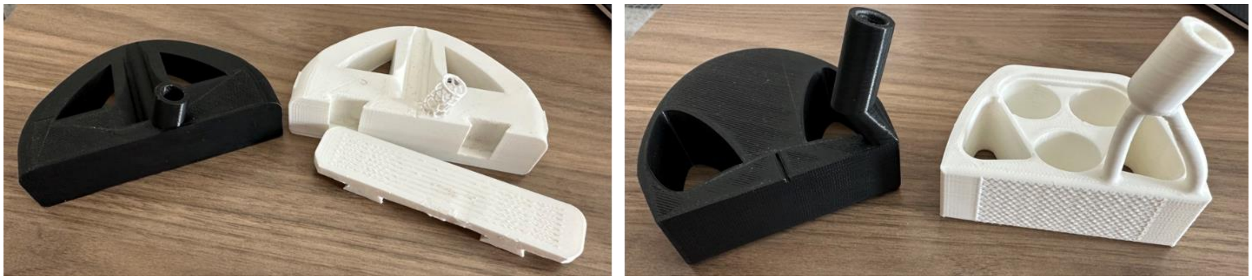

Figure 5. Restrictive (Black) and Opportunistic (White) Iterations of Student Designs

Through this first iteration, student teams came to a shared understanding of how AM limits the design and creation of golf putters. Foremost, student teams realized that PLA, by default, is too light and weak to leverage as a functional putter, even at a 100% infill. The teams that aimed to maximize the mass of PLA in the original design ended the first iteration with a large block of material as a final design. However, when testing, they noted that such large blocks of material do not feel stable or smooth during a swing. Several teams also suffered fracture in their hosel designs due to the anisotropy of the printed material. Additionally, few of the student teams were successful in designing a putter head that was able to fit and secure to the provided golf shaft. This reinforced the importance of tolerances when designing for AM.

For the second iteration of their designs, student teams were instructed to not only continue to consider restrictive DfAM, accounting for the feedback gained from testing the first iteration, but they were also instructed to introduce the use of opportunistic DfAM to their design. This approach mimics previous research that notes restrictive DfAM should be considered first, followed by opportunistic DfAM to maximize the technical quality of generated design solutions for AM [52]. Beneficially, the limitations students identified in their first iterations synergized well with several opportunistic DfAM characteristics. The first opportunity identified by almost every team was that of in-situ embedding for the putter heads. To increase the weight of the initial PLA designs, teams embedded fishing weights, coins, etc. to raise the weight of the putters closer to conventional metal designs. Cavities for such weights can be seen in the parts made from white filament in Figure 5.

In conjunction with this, students in several teams investigated the use of geometric complexity to strategically redistribute material with the aim of adjusting the moment of inertia to increase putter stability. Given the lightweight nature of PLA, this often coincided with in-situ embedding; embedded weights were moved to the perimeter of the head where possible. Similarly, during the initial design review, one team experimented with translating a milling texture from a known putter face to test the resolution of their chosen printer. After this review, the remaining teams made intentional efforts to likewise include hierarchical complexity as a means of adjusting the texture of the putter face to improve putting feel. Further, one team combined this complexity with the use of modular customization into their putter through a series of removable putter faces with custom designed hierarchical textures (seen in the leftmost white printed part in Figure 5). Finally, one team customized/personalized the bottom of the putter with an imprint of a university mascot; this team's design (seen in Figure 6), also incorporated geometric complexity, in-situ embedding, and hierarchical complexity, alongside a series of restrictive DfAM considerations. This helps to demonstrate the ultimate potential of this design challenge in practice; where students can organically incorporate a range of opportunistic and restrictive DfAM considerations into a true end-use product. Note that, while no teams leveraged multi-material printing, several expressed interest. However, the one accessible multi-material extrusion printer was out of service at the time of the second iteration.

Figure 6. Restrictive (Grey) and Opportunistic (Blue) Iterations of Winning Student Design

5. Conclusions and Future Work

In this paper, an argument has been made for using a golf putter design challenge as an educational catalyst for DfAM via PBL. This challenge offers clear design guidelines, a simple to understand end-use context, a robust need for both restrictive and opportunistic DfAM concepts, and is easily manufactured and tested in a classroom environment. This leads to one of the fundamental contributions of this paper: the notion that, to be a successful design challenge for DfAM PBL, a task must adhere to the three principles of *clarity, applicability, and demonstrability*. If a design challenge falls short in one of these three aspects, then there is the possibility that the DfAM instructor or students may encounter unnecessary roadblocks in the implementation and execution of the challenge, hindering its ultimate usefulness as an educational tool. To demonstrate the usefulness of the golf putter challenge in practice, its implementation in an upper-level undergraduate design course was shown, along with example student designs and lessons learned throughout the progression of the challenge over the course of the semester.

While initial efforts at deploying the golf putter were promising, this research is still a work in progress. Future work requires more formal and rigorous evaluation of the deployed design challenge and its effect on student design outcomes and learning. Further, it is necessary to understand how variations in the putter challenge (e.g., explicit constraints/objectives, team-based vs. individual project, etc.) and student demographics (e.g., year of study, existing knowledge of DfAM) may change its effectiveness. Lastly, the design challenge must be directly compared against other existing design challenges to validate its usefulness against the wide range of tasks already available in support of DfAM PBL.

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Appendix: The Design For(e!) Additive Manufacturing Putter Challenge

Design For(e!) Additive Manufacturing

A DfAM Challenge Developed by Dr. Nick Meisel

Why are you doing this?

For this design challenge, you're going to investigate the potential that AM offers for the creation of highly customized, complex, and high-performing end-use products. One of the realms of greatest benefit for such products is in the design and creation of high-end sports equipment that address a variety of athletic needs. This design challenge will focus specifically on the design and creation of an additively manufactured golf putter.

What are you going to learn?

After successfully completing this activity, you will be able to:

- Compare and contrast designs for traditional manufacturing and additive manufacturing
- Demonstrate a capacity to use CAD and AM to create unique, user-centered products.
- Utilize both restrictive and opportunistic DfAM to generate a robust, end-use product.
- Effectively and professionally communicate design through verbal, oral, and visual means.

What do you need to do?

For this assignment, your mission is to **design, manufacture, and test a high-performance, user-centric golf putter** that is suitable for creation using a standard desktop-scale polymer 3D printer. You should consider economic, technical, and usability aspects of your design. Details of the project are as follows:

- *USGA Guidelines:* As your putter is meant to be used "as-is," all designs must conform with the equipment rules given by the USGA. These rules can be accessed online at usga.org.
- *Project Iterations*: The project will consist of two main design iterations, with smaller iterations occurring as you deem necessary. The first iteration will focus solely on restrictive DfAM ("can I print it?"). The second iteration should account for feedback received from iteration 1 and implement innovative design potential derived from opportunistic DfAM ("should I print it?").
- *Putter Manufacturing*: Each putter iteration will be manufactured using a standard desktop material extrusion AM system. This can be a personal system, or one available to you on campus. Note that only the putter head needs to be manufactured; the hosel of the printed putter should be designed to mate with a putter shaft provided by the instructor. Measurements from the putter shaft can be collected before printing.
- *Project Design Reviews*: With each iteration of the project, each manufactured putter will be subject to a design review. As part of this review, the putter will be made available to the rest of the class for hands-on testing on a provided putting mat in the classroom. As students gain hands-on experience with the product, they are expected to provide feedback on the putter's feel, stability, and overall manufactured quality.

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