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STEAM Powered: An Argument for the Robust Integration of Artistic and Engineering Practices in Design for Additive Manufacturing

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Abstract

Additive manufacturing (AM) has been widely integrated in engineering institutions as it can enable designs of seemingly infinite complexity. Despite this potential, research has demonstrated the difficulty in encouraging engineering students to think beyond traditional manufacturing boundaries. Undergraduate programs in the arts have likewise embraced AM for the complex artistic concepts it enables. But, when contrasted against engineers, art students may be more inclined to leverage the geometric freedom of AM by virtue of fundamental differences in which creativity manifests in STEM practitioners and artists. As such, there is a need for the robust convergence of STEM and Arts disciplines in an undergraduate STEAM design framework, which encourages engineering students to adopt arts-based practices to create new, innovative, products outside the realm of conventional design concepts. In this paper, the authors make an argument for such a framework, grounding it in fundamental epistemic practices within both engineering and artistic design.

1. Introduction

Additive manufacturing (AM), colloquially 3D printing, has been widely integrated in engineering institutions across the nation because of its capabilities not only as a means for rapid prototyping, but because of its ability to enable designs of seemingly infinite complexity, far beyond what has previously been possible with traditional manufacturing. However, despite this design potential, previous research has demonstrated the difficulty in encouraging engineering students to think beyond traditional manufacturing boundaries [1]. The result is that, even with the capabilities enabled by AM, engineering students often fail to take full advantage of the technology in their designs. However, the use of AM technology is not limited only to engineering undergraduates; undergraduate programs in the arts have likewise embraced the technology for the complex artistic concepts it makes possible. But, when contrasted against engineers, art students and practitioners may be more inclined to leverage the creative and geometric freedom of AM by virtue of fundamental differences in the way that creativity manifests in Science, Technology, Engineering, and Mathematics (STEM) practitioners and artists [2].

When considering product design, fully leveraging AM's overall design freedom through the lens of artistic practice may result in products that are more innovative and transformative. As such, there is currently a large push in the field of AM for the convergence of disciplines in a Science, Technology, Engineering, Arts, and Mathematics (STEAM) framework in undergraduate education [3]. Such a STEAM framework aims to encourage engineering students to adopt arts-based practices of inquiry to improve their designs for AM. A motivating comparison of a traditional approach versus a STEAM approach is shown in Figure 1, which shows six different designs, all produced via AM; while typical STEM solutions (top row) may leverage certain elements suitable for AM design (e.g., lattice structures), products still maintain a similar overall structure as to those created via conventional manufacturing processes. By contrast, products that also consider the artistic side of the design (bottom row) can better leverage the geometric complexity enabled by AM to create new, innovative, products outside the realm of conventional engineering design concepts.

Figure 1. Motivational Comparison of STEM (top) vs. STEAM (bottom) AM Designs

The motivational comparison in Figure 1 illustrates an opportunity to advance the cutting edge in design for additive manufacturing (DfAM), but also highlights the need for designers capable of transdisciplinary thinking. Indeed, there is an ever-increasing push for the integration of the arts in STEM education to improve student interest and retention, as well as to leverage the natural synergies between these seemingly disparate fields in the practice of design [4,5]. The potential for this synergy is further amplified when considering the complex, organic geometries that are achievable with DfAM [6]. However, there is currently no rigorous scientific understanding of how the inclusion of arts-based practices of inquiry in engineering DfAM education may ultimately affect students' design exploration, generation, and evaluation. Without this understanding, the ultimate potential of STEAM as an inherent part of undergraduate AM design education remains severely limited. This paper will discuss one potential framework that could help drive a rigorous integration of arts-based practice into the engineering design process as applied to AM. This is fundamentally different from existing STEAM research which traditionally focuses on either the larger structural challenges to integrating STEAM curriculum [7] or conducts ad-hoc investigations without formally defining the role of "art" within a STEAM construct [8,9].

2. Background

To understand the opportunities inherent in a synergy between engineering and the arts within undergraduate education, it is imperative to first understand the convergence of STEAM as a fundamental need in undergraduate design education and its role as a transformative catalyst in design for additive manufacturing practice.

2.1. The Need for STEAM in Undergraduate Education

Increasing the success of undergraduate students is connected to creating experiential learning opportunities [10]. Further, expanding instructors' pedagogical repertoire to involve active learning is essential to "national efforts to improve diversity in STEM disciplines, while providing benefit to all students" [11]. While this experiential, active emphasis can take many forms, utilizing interdisciplinary approaches to complex problems that draw upon STEM and arts-based inquiry methods has had positive impacts on students' self-efficacy [12,13], self-concept [14], and realizing creative solutions [15]. Since the call from federal legislatures for "reintegrating the two [STEM and Art disciplines] in our classrooms" [16], STEAM education has gained momentum as a curricular approach benefiting students and teachers in connecting concepts, exploring ideas, and increasing participation [17]. Research from the NSF funded The Art of Science Learning initiative indicates that student participants benefited from arts-based learning via greater collaboration, increased creative thinking, and longer sustained benefits in school and extracurricular participation [18].

STEAM initiatives may provide an opportunity to actualize a resurgence of the fundamental importance of experiential learning through hands-on approaches championed by Seymour Papert's constructionism learning theory transforming mathematics and computer science education [19]. This resurgence can be seen in the energy around digital media and learning [20,21] and in the growing prominence of a maker movement that maintains a primacy on sharing, connecting and do-it-yourself tinkering [22,23]. The importance of "thinking through materials" [24] becomes a central foundation for impactful STEAM curricula. The combination of experiential learning and thinking through materials involves a range of inquiry that can be supported through iterative methodology that emphasizes process and involves different stages of divergence and convergence in exploring solutions. Design thinking utilizes iterative methods and conceptual stage development and has been explored in art education [25,26]; design education [27]; and in rationales for the inclusion of design in both arts and sciences [28]. Research in STEM education recognizes the importance of design thinking for students and developing design pedagogy for teachers particularly in engineering and technology education [29,30]. From engineering to graphic design, design thinking can provide a core methodology by which scientists, engineers, and artists pursue inquiry. In addition to design thinking, understanding creativity across disciplines continues to be an important area of research in undergraduate education [31,32] and engineering in particular [33,34]. Research in makerspaces as sites of learning, often involving innovative technologies of AM, has extended focus on creative production in art, science, and engineering [35–37].

As an example, Meisel and Knochel have previously studied and demonstrated the use of hands-on, STEAM-based practices to increase engagement for both engineers and artists alike [38,39]. Specifically, they created a mobile makerspace capable of being deployed in a range of environments and contexts (as shown in Figure 2). This makerspace drew from best practices in both engineering AM design education and arts AM design education to help students leverage the natural synergy between the different domains. The result was a novel educational setting that helped to facilitate organic, creative participation in the design process for engineers and artists alike. However, despite this successes, and similar ones from other researchers, there is still a need for a fundamental understanding of how the epistemic practice of both groups can potentially affect the measurable design outcomes of various stages of the engineering design process, especially as applied to AM education.

Figure 2. Promoting STEAM Engagement Through an Interdisciplinary Mobile Makerspace

2.2. Design for Additive Manufacturing as a Showpiece for STEAM Education

AM is a rapidly evolving process with extensive interest and development through the maker movement as well as growing prevalence in industry [40,41]. A wide range of AM processes allows manufacturing from nano-scale fabrication to large-scale production and appeals to many different makers in research, industry, and education. Unlike traditional subtractive and forming manufacturing methods, AM utilizes layer-by-layer material deposition to "grow" previously impossible designs from the ground up through one of several different processes: material extrusion, powder bed fusion, vat photopolymerization, material jetting, binder jetting, sheet lamination, and directed energy deposition [42]. This layer-by-layer approach enables a variety of unique opportunities to create more complex geometries [43,44], unique material compositions [45], optimized designs [46,47], customized products [48,49], consolidated designs [50], multi-material specimens [51], embedded components [52,53], integrated electronics [54], and functional assemblies [55]. Despite the many opportunities, designers also face many challenges in AM. Problems such as long build times, support structures, surface roughness, and anisotropic behavior arise in different AM processes [56,57]. With its unique opportunities and challenges, AM requires the development of specialized design processes and practices, collectively termed Design for Additive Manufacturing, or DfAM, to ensure AM is reaching its full potential [58,59].

DfAM requires a different way of thinking about product design due to the opportunities for increased complexity of parts and processing capabilities. Often, engineers may struggle conceptualizing how best to use such design freedom, and instead rely on geometries better suited for traditional manufacturing [1]. By contrast, artists often seek to embrace the fundamental possibilities behind a chosen medium [60], which can serve them well when faced with the complex design potential enabled by AM. If engineers can be taught to leverage artistic practices of inquiry in their designs, and thus embrace the potential of the AM medium, this could have a seismic impact on their designs. Fortunately, the steady increase in the number of shared-used, AM-driven makerspaces may help engineers and artists to interact more frequently [61], as both derive usefulness from AM technology. For engineers, this is often in the form of using AM to for prototyping or end-use manufacturing [62]. For artists, AM acts as a novel medium through which to create unique geometries to communicate meaning (e.g., [63]). While the end-goals of these two groups are often different, the digital nature of AM means that they leverage similar design tools and methods to arrive at their final outcomes [64]. For example, CAD software (e.g., Autodesk Fusion, Blender, Rhinoceros) and 3D scanning tools can be used by both groups to generate the digital geometries that are a necessary precursor to a final printed product [65]. It is possible that elements of the two groups' design thinking are also shared; a popular example is work by Bathesheba Grossman [66], an artist who uses mathematical models to generate unique, complex structures which would be impossible without computational design methods and AM technology. Similarly, stop-motion animation studio LAIKA uses the same voxel-based, multi-material design techniques to create their detailed puppets [67] as researchers in the medical field use for patient visualization prior to surgical procedures [68]. Unfortunately, these examples of STEAM innovation are outliers in the greater AM design landscape; there is a need for methodical understanding of how to prepare engineers to leverage artistic practices of inquiry to improve the quality of their AM designs.

3. Understanding the Use of Art to Support Engineering Education in Design for Additive Manufacturing

This previous body of research highlights the emergent opportunity to establish a robust understanding of STEAM education that advances the use of AM across undergraduate design coursework. In response to this opportunity, this paper promotes and discusses the introduction of arts-based epistemic practice to influence the outcomes of the early-stage design process within the context of additive manufacturing. This is conceptualized through a three-pronged framework that uses art-augmented design practice across the entirety of the engineering design process. This overall approach is summarized in Figure 3.

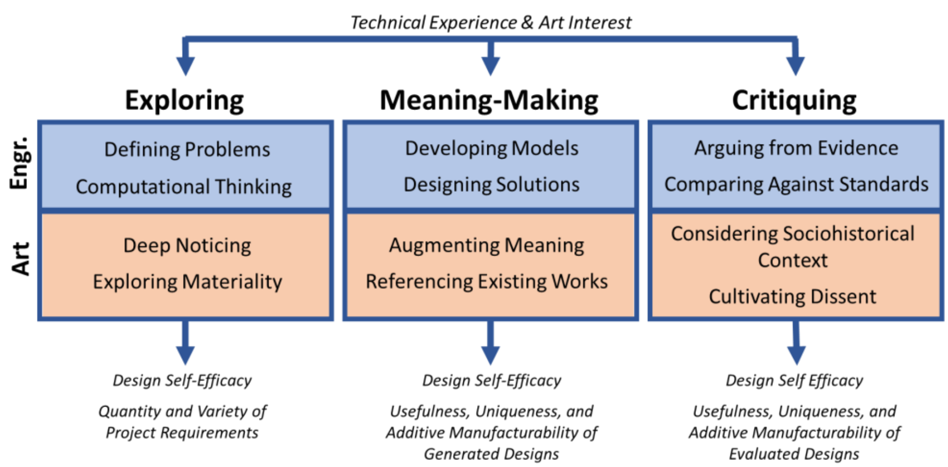

Figure 3. Overview of Emergent Opportunities in DfAM Education based on Bevan's STEAM Framework

The approach in Figure 3 is based on the theoretical framework of epistemic STEAM practices proposed by Bevan [69]. The framework compares the underlying mechanisms that drive both STEM and art practice in three phases of design common to both engineers and artists: (1) Exploring, (2) Meaning-Making, and (3) Critiquing. In the context of engineering, these phases correspond to the activities of *problem definition*, *concept generation*, and *concept evaluation/selection*. Within each of these three phases, Bevan's framework further identifies the key epistemic practices that make engineering and art unique. It is these differing epistemic practices that serve as one of the driving opportunities within DfAM research; if engineering students are instructed in both engineering and art epistemic practices, will this have a positive effect on their designs generated for AM? Though both engineering and the arts follow a similar structure through the process of design, the specific practices of inquiry used are fundamentally different, yet complementary. Due to these differences, it is essential to discuss each phase of the design process in turn, to compare and contrast arts-based epistemic practice against similar engineering design practice, especially as applied to the field of AM. Specific details regarding the comparison of practice in each phase are described in the following three subsections.

3.1. Role of Arts-based Practices of Inquiry on Engineering *Exploration* within AM

Based on the fundamental STEAM framework presented in Figure 3, it is first necessary to explore potential ramifications on the initial exploration phase of the design process. In the practice of engineering design, the exploration phase often manifests in the identification of the problem space as well as understanding customer requirements. However, within the context of STEAM, such an exploration requires designers to look deeply at the problem to identify latent nuance that may not be immediately visible. Understanding the role of arts-based practices of inquiry within this initial phase is essential before moving onto efforts to better understand implications in solving the problem and making meaning. In creating this understanding, it is possible to explore the extent to which the inclusion of arts-based epistemic practice may affect the establishment of problem requirements in the engineering design process, as applied to AM tasks. One possible outcome is that the inclusion of arts-based epistemic practice will result in (1) increased design self-efficacy and (2) increased quantity and variety of identified project requirements. When considering this outcome, it is possible and likely that any such increases will be directly related to participants' technical experience and art interest.

Engineering Approach: Engineering approaches to exploration typically focus on the epistemic practices of *defining problems* and *computational thinking*. Learning to understand a problem space is one of the first skills engineering students acquire in cornerstone design coursework [70,71]. Most often, this includes a focus on (1) the technical requirements needed for a successful functionality of a solution and (2) the specific needs of the user to encourage adoption of the solution (e.g., ergonomics) [72]. Computational thinking is an additional capacity available for students to explore the potential bounds of the problem space. In short, computational thinking intends for students to consider the problem space knowing full well the capabilities of modern computational tools [73,74]. This is especially relevant given the current overwhelming interest in artificial intelligence (AI) tools, such as generative design, as they might help engineers in solving the complex challenges associated with modern society, while also leveraging the seemingly infinite geometric complexity inherent in DfAM.

Arts-Augmented Approach: Arts-augmented approaches for exploration can supplement the engineering approach by adding the epistemic practices of *deep noticing* and *exploring materiality.* Deep noticing is a common technique used in the arts to better understand the world around us through our situated knowledge and personal experience. It involves trying to see details and nuances of a given context beyond just normal observation, which enables the artist to capture what makes something truly unique and better investigate its essence [75]. Deep noticing is inductive and generative, deriving connotative significance from layered observational detail and personal experience. For engineers, this skill can be used to help them better understand user interactions with existing solutions; rather than surface "looking," skill in deep noticing techniques can help them to identify smaller, but potentially transformative, nuance that would otherwise be missed. The practice of exploring materiality involves a similarly in-depth focus on the opportunities, challenges, and improvisational opportunities posed by materials within the problem and solution space. It includes emphasis on feel, texture, color, moldability, and more [76]. In the arts, an artist's work is seen as inextricably linked to the medium used to create it [60], hence the crucial importance of materiality in the process. Though engineers may concern themselves with different aspects of materials (e.g., elasticity, strength, etc.), materiality is still at the heart of many problems [77]. In the context of AM, the range of possible material systems (e.g., polymer, ceramic, and metal) further supports the need for the inclusion of materiality in exploration.

3.2. Role of Arts-based Practices of Inquiry on Engineering *Meaning-Making* within AM

While Section 3.1 focuses on understanding the role of STEAM integration in problem requirements, the second phase of the framework from Figure 3 focuses on elucidating the concrete benefits of STEAM education when generating concepts in the engineering design process. This is the stage of the design process where existing research suggests that arts-based practices of inquiry appear to have the most readily apparent advantages [78]. This raises the question, to what extent might the inclusion of arts-based epistemic practice affect the generation of design concepts in the engineering design process, as applied to AM tasks? As with the earliest stages of the engineering design process, it is possible that the inclusion of arts-based epistemic practice in the concept generation phase may again lead to greater design self-efficacy, while also increasing the usefulness, uniqueness, and additive manufacturability of generated design concepts. However, as discussed in Section 3.1, it is also possible that such changes will depend on individual students' technical knowledge and art interest.

<u>Engineering Approach</u>: Engineering approaches to meaning-making often focus on the epistemic practices of *developing models* and *designing solutions*. The practice of designing solutions can be interpreted quite broadly in engineering. Often, this involves using sketching to generate a possible set of solutions using techniques such as brainstorming [79], storyboarding [80], or collaborative sketching [81]. At this stage, designing solutions focuses on generating as large a set of solutions as possible, reserving critique and evaluation of viability for later in the design process [82]. The practice of developing models in engineering can also be implemented in a variety of ways. One interpretation is the creation of either physical models (i.e., prototypes) or digital models (i.e., CAD models). These models can often help with understanding the form and fit of possible solutions and establishing a clear visual representation of the possible solution. Alternatively, model development could also include the creation of theoretical or computational models, where engineers establish predictive methods for the functional behavior of possible solutions (e.g., [83]). Within the bounds of DfAM, computer modeling of designs is necessary; the digital nature of AM requires digital design input in order to physically construct a final artifact.

<u>Arts-Augmented Approach</u>: Arts-augmented approaches for meaning-making can supplement the engineering approach by adding the epistemic practices of *augmenting meaning* and *referencing existing works.* In the context of this paper, augmenting meaning specifically focuses on augmentation through artistic "principles of possibility". This includes students learning about, appreciating, and applying artistic principles to their designs to change the user's emotional response to them [84,85]. Formal design characteristics such as size, color, pattern, movement, etc. can all serve to augment design. Principles of possibility suggest aspects of design that take into consideration context-driven issues of juxtaposition, hybridity, and representations of experience. To extend these possibilities, referencing existing works aims to help artists and designers create original work by understanding existing work through recombination, recontextualization, and remixing [86]. Ultimately, this serves to leverage existing art as inspiration for one's own work. Though engineering designers will often engage in similar practice

[87], the integration of the artistic practice of referencing existing work may result in more transformational modification and reconsideration of designs by referencing artistic exemplars and synthesizing personal experience. This may help avoid the slight, incremental adjustments that might be seen when only referencing engineered products, due to design fixation [88]. Further, given the number of online repositories for AM designs, there is no shortage of opportunities for engineering designers to refer to, recontextualize, and remix existing design concepts.

3.3. Role of Arts-based Practices of Inquiry on Engineering *Critique* within AM

While Section 3.2 emphasizes the generation of ideas through the inclusion of arts-based practices of inquiry, the final phase of an integrated design process must focus on critique as a process of evaluating ideas. Though engineers may be capable of generating innovative and creative design solutions, research has shown that, if not properly considered, the concept selection process may lead to such solutions being filtered out in favor of more conventional design concepts [89,90]. The hope for this final piece of the proposed framework is that assessing a design through the lens of STEAM will result in designs of greater creativity and quality propagating through the design process when applied to additive manufacturing solutions. As with the other two phases within the framework, the inclusion of arts-based epistemic practice in the concept evaluation phase may again lead to greater design self-efficacy, while also increasing the usefulness, uniqueness, and additive manufacturability of final selected design concepts, subject to students' technical knowledge and art interest.

Engineering Approach: Engineering approaches to critique often focus on the epistemic practices of *arguing from evidence* and *comparing against standards*. When learning to evaluate designs, engineering students are often taught to look at the objective elements of a design, often through evidence presented via models or prototypes. The heart of engineering design is to create functional solutions to given problems; as such, mathematical and scientific evidence has an outsized role in the selection of a final design [91]. Without evidence that a solution will function, a design concept is not often looked at as a viable candidate, and for good reason. Typically, candidate designs and evidence of their potential performance will also be compared against existing engineering standards during the evaluation process. ASTM and ISO standards, for example, will often set minimum thresholds for successful performance that must be met for a design to be considered viable; such standards encompass AM and DfAM as well [92].

Arts-Augmented Approach: Arts-augmented approaches for critique can supplement the engineering approach by adding the epistemic practices of *considering sociohistorical context* and *cultivating dissent*. Contrasted with the evidence and standards-based evaluation practices common to engineering evaluation, an arts-augmented approach requires much more consideration of context and personal experiences. For the former, artistic critique often looks at designed objects through the lens of the social and historical contexts used to create them and to use them. Sociohistorical context significantly drives the meaning of a given piece of art not only by the techniques used to generate it but by its use and adoption within a given context [93]. Engineers may see similar effects, with specific eras reflecting the use of particular technologies in problem solving. As an example, prior to the 1980's, the use of AM would not be seen in any engineering solutions, instead demonstrating extensive use of injection molding or machining [94]. Lastly, critique in the arts may rely more heavily on the notion of individual dissent in the evaluation of created objects. This is because the role of personal experience and emotional response is more key in the arts, compared to the typically evidence-based evaluation of engineering [95]. The cultivation of such dissent is realized in many different formats from a gallery presentation of artistic work where a committee of experts provide feedback to an artist to a one-on-one consultation between the artist-learner and instructor-mentor [96]. Cultivating dissent is a generative process of critique where underlying assumptions and operations of the status quo may be challenged to extend outcome possibilities. Given a desire to move beyond traditional designs that might be seen from subtractive manufacturing, a focus on cultivating dissent could help engineers better question their underlying reasoning behind designed products that they intend to be created for AM.

4. A Conceptual Demonstration of a STEAM DfAM Framework in Practice

To show how the STEAM framework from Section 3 may be applied to a real-world DfAM challenge in practice, this section focuses on a conceptual demonstration based in the execution of the exploration, meaning-making, and critique phases. For this demonstration, the authors turn to an example design challenge that derives inspiration from those previously explored in engineering and arts-based DfAM literature [97,98]. This theoretical challenge tasks participants with the following:

Design a fully 3D-printable solution to assist users with the day-to-day handling of a smartphone device. You can design your solution to fit any phone of your choice. Consider necessary print material and print time as you design your solution.

What follows in this section is discussion of two versions of designing a solution to this task. For the first, a standard engineering approach is assumed, using the techniques from Section 3. For the second discussion, an arts-augmented approach is assumed, where the engineering-focused outcomes from each phase are further evolved through the arts-focused techniques in Section 3.

4.1. An Engineering Approach to the Smartphone Design Challenge

To begin, a standard engineering approach is applied to the smartphone design challenge, following the exploration, meaning-making, and critique phases enumerated in Figure 3.

<u>Exploration (Engineering Approach)</u>. Based on the discussed STEAM framework, the engineering approach to the exploration phase is likely to include techniques such as *defining problems* and *computational thinking*. For the smartphone stand challenge, students are likely to start by examining their own phone or possibly multiple phones, such as those of their colleagues, to better understand the scope of the challenge. Often, this includes trying to recreate the problem by recreating standard manipulations that may be involved in their day-to-day handling of their phone. As an example, students may decide to pursue a way to help users support their phone for viewing of on-screen content. To better understand this context, students might practice leaning their phone up against another object to understand the angles at which it might fall over. Additionally, students will typically collect key specifications for the phone of their choice, such as external dimensions and weight. These specifications are usually collected from online resources.

Depending on their familiarity with the nature of computational thinking, students may begin thinking about the efficient use of material and the potential of applying techniques such as topology optimization, generative design, or lattice structures. Beneficially, such computational thinking techniques are well-suited for the seemingly infinite complexity enabled by AM systems.

Meaning-Making (Engineering Approach). After conducting exploration, the engineering approach moves to the meaning-making phase, which may include techniques defined as *designing solutions* and *developing models*. Though these techniques may be interpreted broadly, there are often key steps followed by engineering students as they work toward viable DfAM solutions. First and foremost, student designers will often begin with the use of simple sketches to create an initial set of possible design solutions. Typically, such sketches are of low fidelity and intend to communicate the basic functionality of a design solution. Following on from the defined problem of content viewing in the exploration phase, engineering students may emphasize the use of relatively simple wedge-type geometries meant to hold the phone with minimal extra consideration beyond functionality; examples of such an approach can be seen in Figure 4. However, depending on their experience with DfAM, some engineering students may start to incorporate the advantages offered by AM into their design embodiments, essentially giving form to some of the computational thinking from the exploration phase.

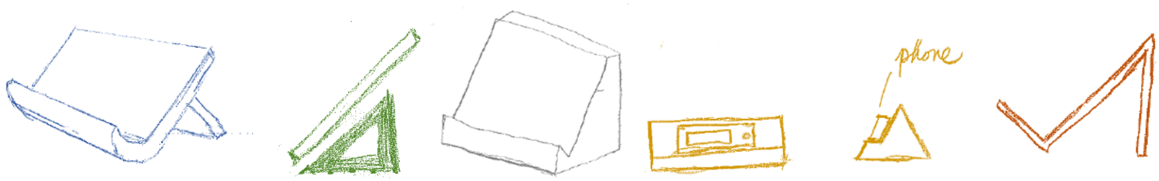

Figure 4. Candidate Designs Produced in the Engineering Approach to Meaning-Making

After deciding on a functionally viable candidate design, students will often quickly move to creating a CAD model of their design concept. Though such a model will give more detail to the design and allow them to incorporate key DfAM restrictions (e.g., self-supporting angles, minimum feature size, etc.), the modeling phase may also lead students to compromise their initial design concept. Given the limitations of modeling complex, organic topologies in traditional engineering CAD software, it is possible that students will simplify their design concepts to make them more viable for modeling.

Critique (Engineering Approach). Lastly, the final phase of the engineering approach focuses on critique, using techniques such as arguing from evidence and comparing against standards. With the engineering approach to meaning-making resulting in a CAD model, evidence related to functionality can be derived directly from this model. One such means for this is using FEA to ensure that the designed structure is significantly strong to support the smartphone in use. However, as the loads in this case are relatively small, a physical prototype is more likely to be used to establish suitable evidence for critique. For a DfAM task such as this one, a prototype of the smartphone stand is likely to be printed directly using a desktop material extrusion system. Even if the final design is intended to be manufactured with a higher-end process (e.g., powder-bed fusion), material extrusion is often able to provide students with sufficient evidence of functionality. It can also provide them with a practical assessment of how well the final design adheres to DfAM heuristics while still maintaining functionality.

In comparing against standards, engineering students will typically turn to existing AM standard to confirm that their designs are of sound quality. As an example, ISO/ASTM52910-18 can provide students with reassurance that they have fully considered the role of DfAM in their products [99]. Similarly, ASTM F3529-21 can provide students with more specific guidance on process-specific limitation in material extrusion, should they decide that process is the most appropriate for their final product [100]. By directly comparing their prototype design against these already published DfAM standards, students will be able to better argue for the quality of their final design.

4.2. An Arts-Augmented Approach to the Smartphone Design Challenge

Having considered the traditional engineering design approach, what follows is an art-augmented discussion of the same design challenge, drawing from the epistemic practices in Section 3.

<u>Exploration (Arts-Augmented Approach)</u>. The arts-augmented intervention for exploration supplements the engineering approach by adding the epistemic practices of *deep noticing* and *exploring materiality.* Characteristics of *deep noticing* in this context would involve the actions, processes, and possibilities that the smartphone presents as an everyday tool and how the physical dimensions of the device lend themselves to acts of posing and holding that enable these processes. As an example, snapping selfies or using the phone to capture extreme angles suggest different ways to hold and interact with the smart phone that then requires specific armature configurations in the design. Likewise, through this exploration via deep noticing, students could further frame the design challenge as an assistive device whereby the problem space is expanded for a range of possible physical and mental disabilities that create a world of difference informed by principals of access and universal design. Exploring materiality, within this sense, supports these aspects of deep noticing: the tactility of the device holder may affect the posing and holding that has been explored as needed in the act of handling and interacting with a smart phone. Additionally, the actual tools, both hardware and software, that are used when the smart phone is perceived as integral part of the everyday are themselves perceived as materials that have properties and impacts to design decisions and interaction possibilities. Both aspects of this first phase would be heavily informed by personal experience meaning deep noticing and material exploration are driven by self-acts of creatively using the smart phone which can expand to incorporate imagining how others may perform tasks such as movie making, taking images, or engaging with virtual content.

<u>Meaning Making (Arts-Augmented Approach)</u>. The arts-augmented intervention for meaning-making supplements the engineering approach by adding the epistemic practices of *augmenting meaning* and *referencing existing works.* This phase would build off personal experience to develop empathic capacity to anticipate creative acts by others using the smart phone which would then be encountered as insights as to design parameters. For example, evaluating personal experience with smart phone mechanics and utilities such as its capacity as a photographic device may cause investigations into how photographers use the smart phone as a tool in their artmaking that could then present scenarios of use that provide design insight. Additionally, exploring participatory design communities that are focused on assistive solutions may also present a range of possibilities for recombination and remixing in sourcing design solutions that are both functional and aesthetic in nature. This may lead to pencil and paper sketching, but also can lead to exploring social media sites like Thingiverse.com to generate a range of options that recontextualize or remix similar products as seen in Figure 5.

Figure 5. Potential Designs for Referencing in the Arts-Augmented Approach to Meaning Making

Critique (Arts-Augmented Approach). The arts-augmented intervention for critiquing supplements the engineering approach by adding the epistemic practices of *considering sociohistorical context* and *cultivating dissent*. In this phase, the design prototypes are brought out to preview their functionality but also, importantly for the arts, to question their efficacy within a sociocultural context of adoption. In other words, testing the design to make sure it achieves its functional goals is important, but an arts-augmented approach would wrestle with the ethical dimensions of universal design, the role of the designer in relation to who they design for, and the effects of remixing in ideation that results in iterative prototypes. For example, considering sociohistorical contexts for adopting a smartphone holder would search for context-driven test cases to ask what purpose is the phone being held and how do these utilities of the smart phone lend themselves to various prototype solutions? If you are texting in one instance and taking a selfie in the next, how might these various use-cases overlap or differentiate the holder design, or more dramatically, if the user themselves is seen as having the potential for a range of embodied approaches to holding the phone, then design iterations take on more divergent possibilities. These acts of self-reflection would enable cultivating dissent in ways that may invite further participation of stakeholders within the design process or dictate how the design is to enter into the world as open source or as a proprietary model. Important to these moments of dissent may be discussions of how our design process includes or excludes users. Critique at this phase in the smart phone holder design process would invite design possibility that rely on the user in a co-design solution space demonstrating how the smart phone holder operates for differently abled individuals. In this sense, the critiquing phase allows the design in focus to inspire a range of debates about use, adoption, ownership, and accessibility that may not be resolved but rather inform further practice.

5. Conclusions and Future Work

In this paper, the authors proposed and discussed a framework for integrating both engineering and arts-based epistemic practices toward the field of DfAM. This was further contextualized through the common design phases of exploration, meaning-making, and critiquing. As an initial theoretical demonstration of the potential of such an integrated framework, a conceptual design challenge was presented where both the engineering and arts-augmented approaches were applied toward the creation of a final product. Ultimately, the authors argue that such an integrated STEAM framework is a potentially transformative component of advancing the state-of-the-art in DfAM. In doing so, designers will be able to pull from the best practices in both engineering and the arts with the aim of generating, selecting, and implementing creative design solutions that take full advantage of the seemingly infinite complexity enabled by AM.

Though the establishment of the framework in this paper is a crucial first step, there is still a significant amount of research needed to confirm its ultimate impact on DfAM education and practice. Future research will focus on human-subjects experimentation where the proposed STEAM framework is converted to actionable educational interventions. By applying both engineering and arts-based epistemic practices in such interventions, it will be possible to quantify the effect that arts-augmented practice can have on the outcomes of engineering students' DfAM design concepts. Furthermore, these outcomes will be correlated with students' existing experience with the arts and their intrinsic belief in the arts as a crucial companion to engineering design practice.

6. References

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