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A framework for implementing engineering design for additive manufacturing education

Lisa K. Murray
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A dissertation submitted to the Faculty of
Western New England University
in partial fulfillment of the requirements for the
Degree of Doctor of Philosophy
in Engineering Management

Springfield, MA

December 31, 2022

Approved by

Dr. Seyed A. Niknam, Co-Chair, Associate Professor of IEEM — 12/13/2022 [date]

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Abstract

Additive manufacturing (AM) is widely used in various industries and has transformed the way products are designed and manufactured. Training workshops in conjunction with a part assessment framework enable designers to use design for additive manufacturing (DfAM) considerations during the process of idea generation. A DfAM training framework will assist researchers, educators, and students to evaluate and improve designs and encourage exploration of changes that need to be made during the design process. Successful implementation of DfAM considerations in engineering design classes is an important step in preparing students for professional careers.

There is currently no proven model for AM education and training. This research investigates the effect of DfAM integration in engineering curricula on student design in first-year engineering classes as well as in a junior-level manufacturing class. Students are given a pre-intervention survey to gather information on their self-efficacy and prior experience with AM. First-year students complete a design challenge prior to the DfAM educational intervention while the students in the upper-level manufacturing class complete a pre-test on AM and DfAM in addition to the pre-and post-surveys. The DfAM education intervention is offered in the form of design workshops in conjunction with multiple lectures and a lab session where students gained hands-on experience with AM processes. Ideas generated are collected and assessed using an assessment framework that encourages the use of DfAM considerations. Parts are scored on a scale of 1 to 4 in the following categories: part complexity, assembly complexity, number of separate parts, functionality, thin/smallest feature size, smallest tolerance, unsupported features, support material removal and the largest build plate contact. A score is generated and assigned to each design pre-and post-intervention. The students in the upper-level manufacturing class complete a post-intervention AM and DfAM test to assess changes in AM and DfAM knowledge post-intervention. A post-intervention survey is given to participants to gather information on changes in DfAM self-efficacy after the intervention as well as to gather feedback on suggested improvements and the usefulness of the intervention workshops. The student outcomes before and after intervention are collected and compared for improvement in the use of DfAM concepts.

Results show that DfAM educational training improves student design scores, DfAM self-efficacy, and AM pre-and post-tests. Integrating technology roadmapping (TRM) and DfAM aims to help the designers to perform technology identification and selection more efficiently. The DfAM training integrated with technology roadmapping and the part assessment tool is intended to equip educators with the necessary tools to successfully incorporate DfAM concepts in the engineering curricula and will prepare novice designers for future design roles and future challenges in the manufacturing industry.

Keywords: additive manufacturing (AM), design for additive manufacturing (DfAM), engineering education, design guidelines, assessment framework, training workshops, technology roadmapping (TRM)

Dedication

This work is dedicated in loving memory to my late mother, Karleen Ann McLeod-Cousins, who is my role model. Your sacrifice, strength and perseverance have made me the successful woman I am today. I will always aspire to make you proud!

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I would like to thank the people who have helped and supported me during this research journey.

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Finally, I would like to thank my husband, Omari, and 4 children, McKenzie, Bailey, Payton, and Timothy, for their support in allowing me to pursue my goal of furthering my education. I could not have done it without you all!

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1. Introduction

1.1. Background

1.1.1. Additive Manufacturing

Additive Manufacturing (AM) has received a lot of attention over the past few years as a result of its emergence as a vital manufacturing process used in various industries. According to the American Society for Testing Materials (ASTM), AM is a "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [1].

AM, also popularly known as 3D printing, is synonymous with rapid prototyping, additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, freeform fabrication, solid freeform fabrication, and direct digital manufacturing. AM processes are used to fabricate physical 3D objects from computer aided design (CAD) models using plastic, ceramic, composite, biological, and metallic materials [2]. AM is different from traditional subtractive manufacturing processes such as forming, casting, machining, etc., that removes material during the manufacturing process and thereby leading to significance material waste. Additive manufacturing processes can broadly be categorized under seven (7) categories: material extrusion, directed energy deposition, vat photo polymerization, powder bed fusion (PBF), sheet lamination, binder jetting and material jetting.

The additive manufacturing industry has grown significantly over the last few years. Revenue generated has grown from $12.8 billion in 2018 to exceed $21 billion in 2020 [3]. The AM market is predicted to produce 2 trillion worth of components and end products by 2030 [4]. A major reason for the broad adoption of AM in various industries is that it offers several advantages over traditional manufacturing methods and allows for design opportunities and freedoms that are not available with traditional subtractive manufacturing methods [5]. Some of these advantages include: (1) on-demand parts that are made for customization and personalization, (2) no special tooling required for part fabrication, (3) reduced material waste, (4) significant reduction in cost and time of manufacturing for low quantity productions and parts that are individualized, (5) ease of the fabrication of complex geometric parts and heterogenous composition parts and (6) a drastically suppressed supply chain [6].

The unique capability of AM technology enables the manufacture of product designs that have increased shape, material, hierarchal, and functional complexity. Products designed for AM can vary in sizes and shapes, and can have customized and optimal geometries. Parts can be manufactured with complex material compositions and design property gradients one layer or point at a time. Some AM machines are used to fabricate functional devices by embedding components and kinematic joints while parts are built [5].

Metals, ceramics, composite, and polymer materials are typically used in AM processes. Polymers were the first material group used in AM, and are still the preferred material in AM. However, metals are broadly used in AM due to their laser absorption power as well as their stability at higher temperatures. Metal materials such as stainless steel, titanium, magnesium, aluminum, and Cr-Co alloys are the most commonly used in AM. Titanium and Cr-Co alloys are preferred in biomedical applications due to their mechanical properties, biocompatibility, thermal, magnetic and electrical conductivity and high temperature resistance [7].

Several industries such as aviation, automobile manufacturing, medical and biomedical, pharmaceutical, and the defense industry, have taken advantage of AM capabilities to explore territories that were previously not attainable [6].

The medical field is a sector that has experienced remarkable advancement due to the adoption of AM technology. In the medical field, AM is used to support the needs of clinicians and patients [8]. Additionally, AM is used in surgical applications, the pharmaceutical industry, disease modeling, the development of customized implants and prostheses, organ printing, veterinary medicine, and tissue engineering applications. Some of the contributions of AM to the medical field include using biocompatible materials to create tissue without damage to living cells, blood vessel production, dental implants, and special medical prostheses [7].

AM technology is now regularly used in the production of customized medical devices that would be very difficult and costly to produce using conventional methods. For example, hearing aids are produced based on patients' ear anatomy. Patient-specific biocompatible implants of knee joints, tibia bones, femur bones, fibula bones, cranial bones and teeth are also successfully produced with AM technologies. Veterinary medicine also benefits from the use of AM in creating specific prostheses, bone models, implants, and planning for surgery procedures [7].

The application of engineering principles and life sciences together for tissue regeneration, regulation, and continuity of organ functions can be described as the main purpose of tissue engineering. The goal is to produce living cells in vitro on support scaffolds that are made of biomaterials for placement in injured or diseased tissue in the body. These scaffolds are used to transport cells to specific areas of the body and provide structural support for newly formed tissue. 3D functional artificial tissues and organs are produced by using cell and tissue scaffold using the evolving technology of bioprinting. AM is used to control the pore size and pore structure of scaffolds with suitable mechanical and physical properties for the intended use in the body. Spinal cord injury can be treated with the use of AM technologies in tissue engineering and regenerative medicine in using 3D printed scaffolds.

Recent advances have also been made in organ printing that have enabled biocompatible materials and cells to be 3D printed on living tissues which can produce tissues and organs that are appropriate for organ transplantation. This has been applied to the production of multilayer heart tissue, cartilage, and bone structures [7].

In addition, AM technologies have played a significant role in improving medical imaging procedures where a patient's anatomical structures are better visualized by surgeons. This has led to enhancements in the creation of surgical templates to guide surgical procedures during the preoperative planning stage to allow for surgical intervention while testing surgical instruments with the assistance of 3D models [9].

Metal-based AM technologies are also widely used in automotive and aerospace industries for manufacturing industrial products such as automotive engines, aircraft assemblies, power tools, and manufacturing tools such as fixtures, jigs, and drill guides. Industrial companies such as electrooptical systems (EOS), SLM Solutions in Germany, Arcam in Sweden, Reinshaw in the UK, Stratasys, 3D Systems, and Optemec in the US are among other industrial companies that have introduced AM technologies to the commercial market [6].

The increased usage of AM technologies in manufacturing industries has led to AM being identified as one of the nine pillars of Industry 4.0, illustrating the potential AM has to play a larger role in future manufacturing operations. Industry 4.0, also known as the fourth industry revolution, is a term used to describe the future of work in production environments. It is basically the use of smart technologies to automate traditional manufacturing and industrial processes [10].

As a result of the emergence of AM technology as a vital technology for Industry 4.0, there has been a huge need for a workforce that understand the principles of AM processes and their application to solve real life world problems in the manufacturing industry. This necessitates the modification of curriculum in our educational system to address this need for a workforce trained in AM technologies and the ability to utilize such technologies in production environments. This research seeks to address this need by formulating a framework for training students to be competent in understanding AM technologies.

1.2. Significance of research

The goal of this research is to provide a DfAM educational training framework along with an objective assessment tool that will assist engineering faculty in teaching design courses and student designers. The assessment tool can be used in engineering educational curriculum to improve student design outcomes and improve student self-efficacy. The training workshops can also serve as a model to incorporate DfAM in design courses. A review of the literature shows that DfAM training workshops have been shown to be effective in improving designers' use of DfAM concepts in educational settings, as well as, in corporate settings.

Although there are numerous AM resources and training materials available in the literature, there is still no proven model for AM education and training [3]. Also, research on the incorporation of AM/DfAM in engineering curriculum as well as the assessment of student outcomes after DfAM integration is limited. There is also limited research that objectively assess the effects of DfAM education on student incorporation of DfAM considerations on AM designs. It is important to understand the relationship between DfAM integration on student design and the designs' fulfilment of a given task because a critical contribution of AM technologies is the ability to improve design performance through added complexity [9].

This work seeks to fill the gap in the integration of DfAM in education and offer a way to objectively assess student design outcomes using a rubric after DfAM intervention in educational settings. Two AM processes (Material Extrusion and Vat Photopolymerization processes) will be utilized in this study. This research is important because the lack of AM and DfAM education could adversely impact students' readiness to utilize AM technologies in the industry [10].

1.3. Research Objectives

The specific objectives of this research study are:

- Develop a DfAM training framework that prepares student designers for design roles in the workforce and decreases the time for mastery of DfAM topics.
- Develop a training framework that enables educators to incorporate DfAM workshops in engineering curriculum. This will increase the utilization of additive manufacturing in design concepts and increase student DfAM self-efficacy.
- Increase student DfAM self-efficacy in preparation for design roles in the industry. This will increase the number of students that are prepared to take on design roles in the workforce.
- Develop an objective DfAM assessment tool that can be utilized during the design process.
- Develop a framework that includes the parameter differences among material extrusion and vat polymerization technologies that emphasizes the design considerations of each

process to assist in the incorporation DfAM considerations during DfAM training. Include a list of design guidelines for each AM technology.

To achieve the stated objectives, this study will investigate the following:

- the effect of DfAM integration in engineering curricula on students' design outcomes and DfAM self-efficacy.
- the impact using a decision-making tool for DfAM on students' learning.
- the effect of prior AM and CAD (computer-aided design) experience on students' performance in the design process.

1.4. Research Questions

The research questions used in the investigations are as follows:

Research Question #1:

Does DfAM training improve designers' design outcomes and DfAM self-efficacy?

Research Question #2:

What effect does prior experience in AM, engineering, and CAD have on DfAM training?

Research Question #3:

What aspects of DfAM can be emphasized to prepare students for future AM applications?

The remainder of this work is organized as follows. Chapter 2, a literature review of on AM and previous efforts to investigate effects of AM training on students' outcomes is presented. In Chapters 3, 4 and 5 the methodologies utilized in investigating research questions 1, 2 and 3 respectively are discussed, as well as the detailed description of the outcome of the investigations.

In Chapter 6, conclusions are presented. Limitations of the study and some thoughts on the direction of future are also presented.

2. Literature Review

2.1. Additive Manufacturing Technologies

The American Society for Testing and Materials (ASTM) defines AM as *"the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies*". AM uses several technologies to manufacture products from different materials such as ceramics, composite, metals and polymers [11]. AM processes are classified under seven broad categories. Table 1 shows the various categories based on ASTM standards classification [12], [13]. For this study, the emphasis shall be on material extrusion and Vat photopolymerization processes.

Table 1. Seven Categories for additive manufacturing processes

Categories	Process	Technologies[14]	Materials
Vat photopolymerization	A vat of liquid photopolymer resin is cured by light-activated polymerization	Stereolithography (SLA), Digital Light Processing (DLP)	Plastics and polymers
Sheet Lamination	Sheets of material are laminated to form parts	Laminated Object Manufacture (LOM)	Paper, plastic and some sheet metals
Material Jetting	Deposition of material droplets on the build platform	Continuous printing (CIJ), Drop on demand (DOD)	Photopolymers, WAX
Binder Jetting	Applying a liquid bonding agent to a thin powdered material layer to build up parts	Binder Jetting	Plastic, metals, ceramics
Material Extrusion	A nozzle or orifice is used to extrude the material onto the build platform	Direct ink writing (DIW), Fused Deposition Modeling (FDM)	Thermoplastic
Directed Energy Deposition (DED)	Using a thermal energy source whether a laser or electron beam to consolidate the material by melting it	Electron beam additive manufacturing (EBAM), Laser Engineered Net Shaping (LENS)	Cobalt chrome, titanium
Powder Bed Fusion (PBF)	Thermal energy source whether electron beam or laser is used to fuse a powdered material by melting them together	Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM)	Stainless steel, titanium, aluminum, cobalt chrome, steel

2.1.1. Material Extrusion AM Process

Material extrusion, developed in the early 1900s, has been widely adopted in many industries. The process supports design freedom thereby enhancing the creation of highly complex models and prototypes. It involves the use of a moving nozzle to extrude material that is heated and deposited layer by layer to build a part. The three-dimensional (3D) models and prototypes produced are created using computer-aided design (CAD) software or cone beam computed tomography (CBCT) systems. Figure 1 provides an illustration of the material extrusion process. Over the years, improvements have been made to the available materials, software and hardware of the material extrusion technology. During the material extrusion process, the printing instructions are produced as an output in a G-code file from a slicing software that processes the 3D digital model. Parts are produced using the slicing software with desired surface quality and density by controlling the following parameters: 1) printing speed, 2) flow rate, 3) layer height, 4) extrusion width, 5) infill percentage, and 6) perimeters. The main focus of slicing software is the focus on requirements of finishing and production speed instead of maximum design freedom [15].

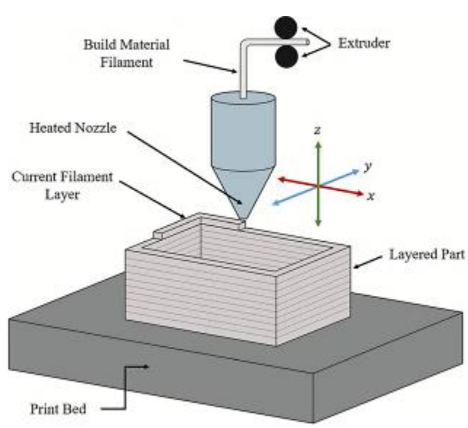


Figure 1. Material extrusion process [16].

A major advantage of the material extrusion process is that the process does not require a post processing chemical step like in processes such as the vat photopolymerization process. In addition, the process yields parts with high stability. On the other hand, a major disadvantage of the material extrusion process is the poor surface quality of printed parts due to the filament thickness. As a result, finishing is required to smoothen the surface of the produced part. In addition, the process is typically slow and large complex parts usually take several days to be built [17].

2.1.2. Vat Photo Polymerization AM Process

Vat photopolymerization is an important additive manufacturing process developed in 1986. Vat photopolymerization, also known as stereolithography (SLA), uses photopolymers and radiation-curable resins or liquid as primary materials for production [18], [19]. During vat polymerization process, bulk liquid is hardened to build an object using photopolymerization. A resin in liquid state is polymerized after being exposed to a light source of a specific wavelength [20].

The process creates objects using successive layers of liquid resin where a UV-laser is focused on the surface of a vat filled with a liquid photopolymer. Each cross-section of the photopolymer resin is selectively polymerized. Figure 2 shows a vat photopolymerization process which includes a vat of liquid resin, a platform for building models, and an ultra-violet (UV) laser. The process uses a "top-down" approach; when the first layer is completely polymerized, a resin filled blade sweeps across the object's cross-section to recoat it with another one-layer thickness of resin. Another section is polymerized while the build platform is lowered in the z-direction. This process continues until the object is built completely [17].

A “bottom-up” approach is used in some devices where the build platform is dipped in the vat and raised along the z-direction while being built. The bottom-up approach has several advantages over the “top-down” approach since less resin is used in this approach and printed parts have less porosities and higher manufacturing accuracies. In addition, there is better control of layer thickness when the “bottom up” approach is used. The remaining resin in the vat can be drained and reused. The produced part is then cleaned in an alcohol bath and later cured in a UV oven to strengthen the part and polymerize the resin groups that are unreacted [17].

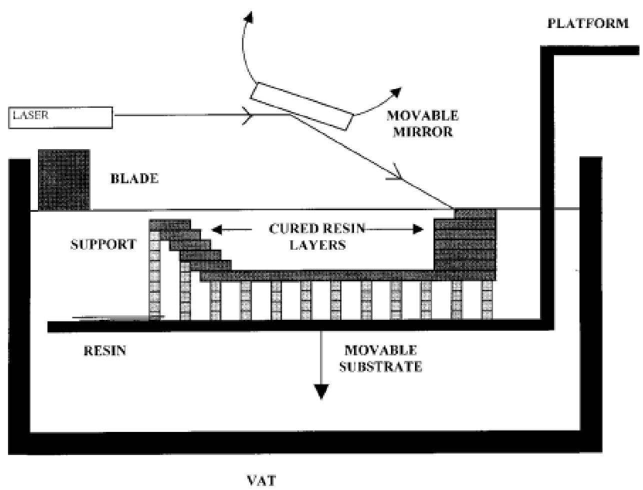


Figure 2. Vat Polymerization AM process [21].

DLP, a sub-category of vat polymerization, is used for printing small objects with complex geometries using liquid photopolymers. During the DLP process, a photopolymer is filled in a transparent vat that is located above a projector that utilizes a digital mirror device (DMD). The projector uses a high-powered LED source. The DLP process produces parts with high accuracy, affordable cost, smooth surfaces, and is faster than the SLA process. Polymerization shrinkage and the need for manual post processing is a disadvantage to using DLP vat polymerization [17].

2.2. Design for Additive Manufacturing (DfAM)

Design for Manufacturing (DFM) and Design for Assembly (DFA) are two important tools used by manufacturers to help designers to better assess the impact of their product designs choices on manufacturing assessment outcomes such as manufacturing and assembly cost. The goal is to provide manufacturing assessment support for designers during the design process to help eliminate manufacturing difficulties and minimize manufacturing related cost [22]. The evolution and wide adoption of additive manufacturing technology in manufacturing environments makes it necessary to broaden DFM and DFA concepts to address AM needs and challenges. This is vital because even though it is possible to produce many products using AM technologies, it may not be cost effective to produce some products using AM technology [23].

Design for Additive Manufacturing (DfAM) is a term used to describe a design process that incorporates the unique attributes of AM in the design phase with the objective of utilizing the manufacturing system's capabilities to optimize the product's quality and performance, while minimizing the development time and the associated manufacturing cost [24], [25], [26]. The main objective of design for additive manufacturing (DfAM) is to maximize product performance that are subject to the capabilities of AM technologies through the synthesis of shapes, sizes, hierarchal structures, and material compositions [5]. The main set of design considerations include product development, usage, sustainability, business principles, geometric principles, material properties, process and communication considerations.

DfAM consolidates new and existing design principles to develop a framework that optimally utilizes the design freedom and capabilities of AM for product design. Decision making, process planning, manufacturability assessment, and product optimization are among the design activities included in DfAM. Creative processes that assist designers to consider new possibilities that are feasible due to AM are the focus of DfAM methods and developing such frameworks to properly exploit the potential of AM in product innovation and manufacturing can be challenging [27].

There are several ways of classifying DfAM. Based on the support focus for designers, DfAM can be divided into the two categories: (1) DfAM for design making and (2) DfAM for design assessment. The first category guides designers through the design process leading to the development of intermediate representations (IR) and consists of guidelines for design features. Acceptability criteria such as cost, time, and manufacturability to IR is created during the design making stage and is deployed in DfAM methods for design assessment. The early stage of design is the most important stage since design changes late in the process are costly. IR creation and evaluation should be incorporated in DfAM methodologies [3].

Another way of classifying DfAM is based on ability to enhance design performance, DfAM can be classified into three different categories such as opportunistic DfAM, restrictive DfAM, and dual DfAM. Opportunistic DfAM assists designers to investigate geometric or material complexity provided by AM. Restrictive DfAM methods utilize the limits of AM which includes the properties of usable materials and their properties as well as the characteristics of AM machines or the manufacturability of products. Dual DfAM method is basically a combination of both opportunistic and restrictive DfAM methods, and accounts for 30% of existing DfAM methods. The dual DfAM method focuses on product innovation and uses AM realistically [16]. Booth et. al [28], observed through interactions with industry that the engineers at small companies view the implementation of AM as a beneficial addition to their company but were cautious of the possible complexities of incorporating the technology. Academic institutions and industry need generalized AM guidelines that guide and educate new and intermittent users on the best practices in AM.

2.3. AM and DfAM Education

An increased demand for workers with expertise in additive manufacturing has raised the need to modify engineering curriculum to incorporate AM technologies. As a result, institutions of learning and educators need to address this need by appropriately integrating DfAM into engineering education to encourage the application of AM in engineering designs. Intervention programs geared towards effectively introducing engineering students across different majors to a variety of AM processes and encouraging the integration of opportunistic and restrictive DfAM in the design process are necessary [29].

Trends in engineering education programs show an increased emphasis on integrating AM technologies into the curriculum. A key driver for this trend is the need to prepare students to be ready for an Industry 4.0 work environment, which has been widely adopted across several industries. The US, UK and Spain are at the fore front in leading the effort to integrate AM into engineering education curriculum, with several specialized courses in AM being offered in institutions of learning. The push is in improving the AM curriculum in these countries is a result of requests made by specific industries and government incentive programs [10].

Mechanical and industrial engineering programs require students to have fundamental competence in AM due to the benefits of learning and using AM. These benefits include an increase in understanding of problems, improved design, and visualization skills as well as an increased ability to use computer aided design applications. Students are also able to learn by making, which facilitates understanding of theoretical topics and stimulates independent learning. Teaching approaches must encourage project-based learning where students are required to engage in active learning and direct participation. AM in educational programs allows students to learn manufacturing and design which provides direct interaction with the results of their efforts. This improves learning and soft skills development [30].

To effectively deliver on the mandate to provide specialized AM technology education in institutions of learning, educators at all levels need to be trained in AM and be knowledgeable about the differences in AM processes. As such, it is vital for engineering programs to understand this need by industry for graduates trained in AM technology, in order to appreciate the need, provide the necessary investment in AM facilities and to support the training of educators to meet the current challenges [10].

Furthermore, such investments have the added benefit of improving students' engagement and learning outcomes. According to Chong et al.[31], high 3D drawing skills and rapid 3D-printed prototypes help students to study common processing equipment, manufacturing, maintenance, logistics, and operations. The impact of having hands-on access to AM technologies shows that there is an increase in ease of learning, perceived interest, and motivation in engineering graduate students. Early exposure to AM technologies helps in the development of a "think-additive" product design style [3]. The Center for BioMolecular Modeling of the Milwaukee School of Engineering (Milwaukee, WI) applied AM to create physical models of protein and molecular structures. This allowed for the creation of innovative instructional materials that can be held by students which allows the molecular world to become real. The freeform fabrication nature of AM allows students to understand complex difficult-to-understand topics such as biological and chemical phenomenon. Surgical planning, training and drug screen modeling can be offered by way of AM to create human scaffolds and tissue models [6].

The incorporation of industry 4.0 in engineering education creates a student-based learning environment that gradually trains students to become proactive lifelong learners that are conscious of the environment and the economy [10]. Studies have also showed that exposure to AM technologies can also help students at high school level to gain a better understanding of STEM related subject matter. FIRST Robotics, an outreach program aimed at getting high school students involved with robotics, typically incorporate AM technology in their activities. Teams use AM to make unique robot parts and machines [6].

The US federal government has been the predominate source for funding AM technology initiative to support AM education in the US. Federally funded programs have been initiated to encourage collaboration between universities and industry researchers in AM. These programs include the Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR) programs of most federal agencies, NSF's Grant Opportunities for Academic Liaison with Industry (GOALI) and Industry/University Cooperative Research Centers (I/UCRC) programs. Apart from the federal government, funding has also been provided from other sources. Non-federally funded programs include the industrial consortia at the Center for Aerospace Manufacturing Technologies (CAMT) at Missouri University of Science and Technology, and the University of Texas at El Paso W. M. Keck Center for 3D Innovation [6].

AM education has seen significant adoption at the graduate level, where there has been an increase in the number of AM graduate programs. Pennsylvania State University offers a Master's of Science in AM with an online education for continuing education to support working professionals. The University of Maryland and Carnegie Mellon also offers graduate programs in AM. Graduate courses are also offered at the following universities in the United Kingdom: Nottingham University, University of Sheffield, and Derby University. A Design and Engineering for AM master's program is offered at The Universitat Politecnica de Catalunya in Barcelona, Spain with collaboration from industry experts [3].

Certificate programs, which are popular among industry professionals, are offered by MIT on the fundamentals, applications, and implications of 3D printing for design and manufacturing. Tailor-made courses in AM are also offered at management consulting firms such as Deloitte, PWC, and Ernst, & Young. Several public-private partnerships are involved in encouraging the implementation of AM in industry and academic settings [3]. America Makes-National Additive Manufacturing Innovation Institute (NAMII) which was established in Youngstown, OH in August 2012 is a major university-industry collaboration in AM in the US [6]. America Makes accelerates the adoption of AM technologies to increase domestic manufacturing competitiveness through AM research, discovery, creation, and innovation, as well as offers apprenticeships, co-ops, and educational facilities that promote AM education and 3D printing. The NSF's Rapid Tech Program also assists in the adoption of AM within the industry and the educational field [3].

However, to effectively address the serious talent gap in industry with regards to AM technology, the first year and second year engineering curricula in institutions of higher learning needs to be a major emphasis. Areas of opportunities to weave AM education into the curriculum at the first-year and second-year level, need to be explored. Undergraduate courses and educational materials that help students to become familiar with AM capabilities and address a negative perception of the manufacturing industry, would be helpful. In addition, highlighting the vast opportunities for developing interdisciplinary STEM skills, and acquiring relevant hands-on or on the job training, are potential efforts that can spur students to seek careers in AM related fields [3], [32].

In 2015, the National Science Foundation (NSF) held a workshop to address the lack of experienced workforce. The workshop addressed the required education necessary to prepare individuals in industry and academic institutions for AM. The following key areas that need additional research and improvement in educational settings were identified at the NSF workshop:

AM processes and material relationships, fundamental knowledge of material sciences and manufacturing processes, professional insight for critical thinking and problem solving, DfAM practices, and cross functional teaming and ideation techniques for seeding creativity. There is limited research literature on AM engineering education that studies creativity, design thinking, teaming, or problem solving in the context of AM in relation to students and practicing engineers. Over the past decade, there has been an increase in the interest in DfAM education [3]. One objective of this research is to investigate the effect of a DfAM training workshop on student DfAM self-efficacy.

2.4. Self-Efficacy

The literature on self-efficacy shows that positive student outcomes and increased retention rates of underrepresented students have been linked to increased self-efficacy. The self-efficacy differences between traditional exams and a two-part practicum used as a mid-semester assignment in a first-year design course was investigated at Pennsylvania University. The traditional exam offered to students was an individual written assignment. The practicum was an in-class team design task along with an out-of-class reflection. Students completed a pre and post assessment design self-efficacy survey. The practicum assessment improved student design self-efficacy more effectively than the exam. Results showed that female students received greater gains in design self-efficacy than their male counterparts. Students that identified as a minority showed significant change in design self-efficacy for the practicum. Mid-semester practicums are a successful assessment of design competency that contributes to increased design self-efficacy in first year engineering students [33].

2.5. GAPA Framework

Problem-based and project-based learning techniques are widely used in manufacturing engineering education. Project based learning uses an open-ended project statement provided by the instructor. Students, individually or in groups, are then required to solve the project by designing and developing an artifact over a defined period. Problem based learning offers generalization of solutions to open ended problems and is facilitated by an instructor [34]. Ullah et. al. states that engineering students can improve their engineering competencies through 3-D printing-based learning approaches [35]. Stolk et. al [34] presented a goals-activities-products-assessment (GAPA) framework that enables instructors to use project-based learning techniques to encourage broad competency development and reflection on the true achievement goals of a project. The framework emphasizes learning in the cognitive, affective, social, and psychomotor domains and describes broad competencies. This framework assists instructors to identify the learning activities that create intended products. Students are placed at the center of the course design since instructors create experiences that ensure alignment of the GAPA components and the connections between project experience and students' personal needs, values, and learning contexts. The GAPA framework was used in this doctoral study to assist with the organization of choices made in the creation of DfAM intervention goals, activities, products, and assessments. The GAPA framework is used as a design tool to expand the focus of the DfAM intervention workshop's goals, activities, products, and assessments.

2.6. DfAM Worksheets

A review of the literature shows that there are a variety of subjective techniques used to assess the designs from the training workshops. The assessments used as well as the assessment metrics typically used in DfAM education are reviewed. A summary of the review of the literature is detailed below.

Booth et al. [28] developed a visual DfAM worksheet that provides guidelines for novice and intermittent designers to address common design mistakes. Designers can assess the potential quality of a part made by AM technologies and have access to suggested options for redesign while using the worksheet. The worksheet is recommended for use in companies and by engineers as well as for use in courses that teach DfAM, hobbyists, maker clubs, and maker spaces. It is suggested that this worksheet can be embedded in a CAD environment. The use of the worksheet at a high-volume AM facility resulted in an 81% reduction in the rate of poorly designed parts. There was no difference between the control and experimental groups when the worksheet was used in a classroom setting.

The worksheet used generalized DfAM guidelines shown from the literature that includes the following areas: 1) part orientation, 2) removal of supports, 3) hollowing out parts, 4) manufacturing features, 5) interlocking features, 6) reduction of part counts, 7) identification marks, 8) avoid sharp edges, 9) round inner edges, 10) blunt extreme points, 11) short overhang, and 12) low island positions. These guidelines apply to most AM processes and must be considered in most designs. The worksheet provided by Booth simplified the DfAM guidelines previously mentioned which equipped novice users with DfAM knowledge. A checklist was provided to allow designers to validate a design before manufacturing a part. The top portion of the worksheet used categories that are most problematic to users such as part complexity, intended function, plans for material removal, and unsupported features. The lower portion of the worksheet included categories such as excessively thin features, part strength, part tolerances, and the effect of warping on geometric tolerances that address common mechanical design problems that affect the strength and the integrity of a part. Individuals were given a score based on the choice made in each category. The worksheet measures the reduction in the number of iterations to reach a successful print by using a list of considerations to evaluate the 3D printability of a part [28].

Similarly, Bracken et al. [36] developed and tested a Geometry for Additive Part Selection (GAPS) DfAM worksheet tool that assists engineers, drafters, and designers to select candidates for good parts without the need for prior knowledge of powder bed fusion (PBF) technology. The GAPS worksheet decreased bottlenecks during design to avoid the costs associated with lost time and material due to failed printed parts. In addition, the worksheet addressed the short supply of AM experts in companies where part screenings are required. The GAPS worksheet allows the user to answer questions while a dimensioned drawing is examined. The geometric feature limitations highlighted in the worksheet include the following categories: minimum tolerances, overhang distance, bridging distance, self-supporting angles, surface finish, pocket length, XY plane corners, height-to-width ratio and holes parallel to build plate. Users can identify parts that are not appropriate for PBF based on geometries of concern and limitations that are specified on the GAPS worksheet. A score range of 1 – 5 was given to the parts created. A score of 1 was given to parts with high AM appropriateness, and a score of 5 was given to parts with low AM appropriateness. A total score in the nine categories was used to determine the appropriateness of PBF. There are several limitations in the study, one of which is excluding the consideration of the dimensions for overall build volume of the PBF machine which must be considered when creating a part. Post processing such as support removal, accessibility of features for finish machining and reduction of surface roughness were not included in the worksheet.

2.7. DfAM Training Workshop Initiatives and Assessments

There have been several research initiatives by Prabhu et. al. [29], [37], [38], [39]–[41], [42]–[45], [46]–[48] and Bracken et al. [49] that have explored the effectiveness of training workshops on participant design outcomes as well as self-efficacy before and after training intervention workshops. Typically, the workshops include three stages which include pre-intervention surveys, short-duration DfAM lectures, AM design challenges pre and post workshops and a post intervention survey. The design outcomes are typically assessed in a subjective manner using expert raters. Prabhu et al. [29] – [48], investigated the impact of teaching DfAM on student design process. The results showed that the largest gains in student perceived utility in learning DfAM concepts and DfAM self-efficacy is achieved when DfAM concepts are introduced early in the semester. Additionally, previous AM experience has a positive influence on learning DfAM concepts. DfAM interventions have also been offered to industry professionals. In 2020, research was done to investigate the effect of workshop based DfAM training intervention on the creativity of industry professionals. The professionals were taught opportunistic and restrictive DfAM during short lectures and given design tasks with short idea generation sessions. The designs, DfAM and creative self-efficacy were compared before and after the training workshops. Results show that there is an opportunity to encourage creative idea generation due to the increase in design uniqueness and overall creativity of the participant's designs. DfAM training increased the participants' restrictive DfAM. Participants showed an increase in their self-efficacy with restrictive DfAM concepts but did not show an increase with opportunistic DfAM topics. There was a significant difference in the pre- and post-DfAM training scores for restrictive DfAM concepts of surface roughness, support material, and feature size at the $p < 0.05$ level. There was also a significant difference in the pre-and post-DfAM scores for free complexity at the $p < 0.1$

level. Results also showed that as the pre-intervention score increased, the change in DfAM self-efficacy decreased. The Wilcoxon signed-rank test was used to compare the participants' creative self-efficacy (CSE) pre- and post DfAM training. There was no statistically significant difference in the score distribution from before and after the training ($p > 0.5$). There was a positive influence on participant mean CSE score. A positive change was reported pre and post training in 7 out of 19 participants, 9 reported no change, and 3 participants reported a negative change which may be due to a high level of CSE prior to DfAM training. A Wilcoxon signed rank test was also used to compare the opportunistic and restrictive technical goodness scores of participants pre and post DfAM training to show the effects of training on the participants' integration of DfAM concepts in their designs. Results show that there is a significant increase in the opportunistic technical goodness of designs created after DfAM training ($z = 3.35$, $p < 0.001$ for opportunistic $z = 3.44$, $p<0.001$ for restrictive). Participants included complex geometries such as trusses and lattice structures as well as support minimization strategies in designs post-DfAM ideation sessions. These designs showed that DfAM training has a positive influence on participants' integration of opportunistic and restrictive DfAM in their designs. There was no effect on the usefulness of designs created post training. DfAM training encourages participants to be creative while using AM. Results show that DfAM training can increase creativity in industry professionals. There is a need to develop DfAM training that provides long term self-efficacy in using opportunistic DfAM which will result in a successful shift from a traditional limitation-based design for manufacturing approach to a dual design approach that emphasizes the limitations and opportunities of manufacturing processes. This leads to the generation of unique and creative ideas [47].

Prabhu et. al. [47] states that research should be done to explore if the skills attained in DfAM training is sustained over long periods of time. A limitation of the study is the use of one problem statement throughout the workshop which may create design fixation among participants. Rather, multiple problem statements should be used. Incubation effects must be tested by including a control group that do not receive DfAM training which can highlight the effects of a participant's prior experience in traditional design for manufacturing. This study uses a subjective measure, consensual assessment technique (CAT) to measure creativity and DfAM integration which relies on a rater's ability to provide unbiased scores and sufficient expertise. More objective assessment techniques should be used in the future such as the DfAM integration metric that separates creativity from technical execution.

The effectiveness of DfAM training in an educational setting was explored by Junk [50] through the use of a workshop entitled 'Workshop Rapid Prototyping'. The participants were master's level engineering and industrial engineering students that were required to optimize additive manufactured RC racing cars. The investigation explored the areas of product development that are improved following the workshop. Self-assessments were used to gauge student progress pre- and post-workshop. These surveys gathered information on participants' general skills, design skills, and AM skills. Participants were asked "How do you assess your practical knowledge in the field of rapid prototyping?". Participant's responses ranged from "very little knowledge" which was given 1 point to "very good knowledge" which equated to 6 points. Results showed that participants' skills and competencies increased moderately after the workshop, which was expected due to their prior knowledge in AM. This study was conducted to offer a different way of teaching students in higher education the practical skills needed for industry so that students can have a deep understanding of manufacturing technology and its capabilities in practical applications.

Efficient use of AM is important to industry professionals. Bracken et. al [49] examined the effects of AM education workshops combined with idea generation sessions on encouraging engineering professionals to use AM solutions to solve technical problems in their fields. Twenty-four project ideas from mechanical design engineers were collected from employees at a multinational commercial organization based in North America (Company X) before and after a training workshop focused on design for DfAM. The lecture was given with a 2:1 ratio of opportunistic to restrictive DfAM content to focus on inspiration and the positive aspects of AM that emphasizes design freedom. The experimental process followed include the following steps: 1) research team designed the AM workshop, 2) identified projects, participants, and reviewers, 3) conducted workshop, 4) generated ideas, 4) rated ideas, and 5) analyzed the results. The three-hour education workshops provided design instruction about design for two AM processes that are metal based. The training workshops included the following components: (1) an introduction and overview of the workshop events, (2) discussion of preconceptions about AM, (3) an introduction to AM, (4) an overview of powder bed fusion and binder jetting, (5) the initial breakout activity, (6) AM opportunistic success stories, (7) a second break out activity, and (8) a discussion of AM cost models and product identification. Participants were randomly divided into teams after the training workshop and given three project prompts to complete in 90 minutes. Ideas were recorded on idea sheet templates. Ideas collected during the workshop were assessed using the following four metrics: cost, time, completeness of solution and quality as a function of feasibility, usefulness, and novelty. The dimensions of quality (feasibility, usefulness, and novelty) were graphed on spider plots and averaged to compile an overall quality score for each idea. Data collected explored the workshop's effectiveness to inspire participants' use of AM methods and techniques from AM research in concept generation and AM solutions. AM solutions were assessed on improvement in the areas of implementation time, cost, and quality compared to non-AM designs created before the workshop. Statistical analysis was performed on the collected data.

Results showed that the training workshop was an effective intervention due to the increase in the teams' use of AM as part of their solution compared to the pre-workshop design where no AM was used as a solution to the given challenge. There were 11 out of the 24 participants that used AM after the workshop. Results also showed a positive result in the quality of AM designs produced after the intervention workshop; the 11 participants previously mentioned showed a higher statistical quality rating average than the pre-workshop where AM was not utilized for the same problem, showing that ideas produced used AM and added value to the business. There were improvements in the average scores of designs in the categories of novelty, usefulness, and quality after the workshop. The scores for the solutions that were produced did not improve in the cost to implement category. The scores were not statistically different pre- and post-workshop. The Time to Implement scores were statistically higher after the implementation of AM in the designs produced workshop which did not show the benefit of AM. The results imply that the expert raters believed the AM designs may take longer than the pre-workshop designs that did not use AM. Future work should require the expert raters to include explanations for the reasonings of longer time to implement scores to reduce rater bias against AM. Instead of the rating systems used in the study, descriptive quotes of time to implement ideas can be used in the future to investigate how time is affected by AM designs. There was no significant difference in the completeness of solution between the designs that utilized AM post-workshop and the pre-workshops where AM was not used. Overall, participants' designs showed an increase in novelty and usefulness which can be useful for the company's intellectual property. The limitations of the work include the use of a team of expert raters that may have swayed rating decisions as well as inhibit the provision of average scoring [49].

Another study conducted by Prabhu et al. [51] explored how DfAM intervention affected student AM design achievement of design task objectives. An experimental study in the fall and spring semesters with 301 undergraduate students was performed in a junior-level mechanical engineering course that focused on engineering design methods and product design. The students were divided into two educational groups (restrictive and dual DfAM) and were given a design challenge after being exposed to restrictive DfAM or dual DfAM (restrictive and opportunistic) concepts in an intervention workshop. DfAM considerations such as build time and build materials, various DfAM concepts used, and the features used to demonstrate the DfAM concepts were used to assess student design outcomes. The restrictive DfAM considerations used include support structure accommodation, warping due to thermal stresses, delamination and material anisotropy, stair-stepping and surface roughness, and minimum feature size. The opportunistic DfAM considerations used in the workshop include geometric and hierarchal complexity, material complexity and multi-material printing, part consolidation and printed assemblies, mass customization, and functional complexity and embedding. Participants' final designs were assessed with respect to minimizing build material and build time since these factors have a strong influence on the final cost of a part created via AM. Feature analysis was performed on the participant's design to investigate the manifestation of the various DfAM concepts as well as material removal and incorporation of different assemblies. A genealogical tree for part complexity, functional assembly complexity, support accommodation, and warping accommodation was developed to group these features. Each design was then assigned to a node in the feature tree. The frequency distribution was then obtained at each hierarchal level which includes design detail, embodiment, working principle and physical principle. Two raters independently rated 20% of the ideas which received a 0.75 inter-rater reliability (95% CI [0.59,0.84] that was measured by an average Intraclass Correlation Coefficient. One of the two raters then rated the remaining ideas.

Results show that varying DfAM education does not have a statistically significant effect on a participant's design achievement of design task objectives. The build material and build time consumed in manufacturing the designs were predicted by the participants' use of some DfAM considerations. Appropriate tolerances with easily accessible support material were incorporated in the designs of the restrictive DfAM group which also showed designs with higher build plate contact area compared with the designs made by the dual DfAM group. Results also showed that dual DfAM education promoted designs with more shape complexity along with less warping tendency. However, these designs tended to use more support material that was hard to remove. These results show that the use of DfAM influences the achievement of given design objective tasks and shows that DfAM improves engineering design outcomes.

There are limitations to the study conducted by Prabhu et al. [51]. The participants' designs were assessed for build material and build time. Results may vary if participants were assessed for part strength or creativity and if participants have different levels of experience. Other assessments should include assessing strength, ease of assembly, and creativity. Another limitation of the study is that the junior and senior level participants could have had high levels of engineering experience compared to freshmen or sophomore students. Future research must compare first year and second year students to graduate level students and professional students which will highlight the influence of CAD skills on students' ability to produce complex designs from concept to final product. The use of the participants' final design CAD designs to assess DfAM integration, participants' CAD skills, and the limited time available to generate CAD models was also a limiting factor in the study. Participants were also asked to choose one idea to represent the assigned group. Future research must explore the factors that affected the participants' selection of concepts when engaged in group design challenges which will highlight participants' emphasis on manufacturability, creativity, and any biases toward everyone's ideas. The time spent on prototyping has been shown to influence design performance. Therefore, future research must compare the effectiveness of a longer educational intervention module to a short lecture-based intervention. A longer educational intervention will allow students more time to apply DfAM concepts in created designs which will result in designs that show high manufacturability and leverage AM freedoms. The complexity of the problem statement was also limiting in this study which may have constrained the design space, ultimately limiting the participants' use of opportunistic DfAM. Open ended problems should be used in the future. In addition, future research must capture a participant's intent of integrating DfAM concepts in chosen designs since this study only captured the design features as they exist in the design while showing no information about the designer's intent for incorporating the DfAM concepts [51].

Prabhu et al. [29] explored the effects of 196 engineering students' motivation on the outcome of DfAM education in competitive environments after being taught restrictive or dual (restrictive and opportunistic) DfAM. The effects of dual DfAM intervention on student DfAM self-efficacy and creativity was investigated during a similar structure to the previous work where a pre-intervention survey was offered followed by a DfAM lecture, then a DfAM task and a post-intervention survey. One group of students showed the final designs in a performance a showcase at the end of the semester while the other performed in a competition. Designs were assessed for creativity using the metrics of usefulness, uniqueness, technical goodness, and overall creativity that were derived from a three-factor model of creativity assessment. Ideas were rated on a scale of 1 to 6 where a 1 meant least useful and a 6 meant most useful. An average mean for each metric was calculated from the scores of the two raters for each design. Results showed that there was a greater increase in participant self-efficacy in material anisotropy and part strength for participants that received the competitive-structured DfAM task. The show-case structured task encouraged participants to generate more useful ideas than the competitive task structured trained in restrictive DfAM. The participants trained in dual DfAM and who received competition-structured DfAM tasks generated ideas with higher technical goodness and overall creativity compared to participants that received a show-case structured task. More creative ideas were produced by students trained in dual DfAM compared to restrictive DfAM. This result urges educators to use design tasks that encourage the creative application of DfAM. Educators are also urged to use external rewards and motivation in conjunction with dual DfAM education to equip students with the ability to better design with AM capabilities and limitations as well as generate ideas with higher technical goodness. Students will then be motivated to integrate opportunistic DfAM in the design process.

There were limitations of the study that can be addressed in future research. The study used a subjective metric that relied on expert opinions of technical goodness to assess DfAM integration in designs produced. An objective assessment would better explain differences in self-efficacy. There were only two participant motivation structures used in the study, and future research must vary external motivation and note the effects on creativity and design performance. Other external motivation structures included the use of grades or extra credit. The effects of task motivation on designers with high levels of experience in DfAM and AM, such as professionals and graduate students, must be investigated to compare the outcomes of DfAM interventions to interventions that involve undergraduate students. Another limitation of the study was the short duration of the lecture portion of the DfAM intervention which possibly reduced lecture effectiveness. The use of dispersed educational interventions must be explored. The study was also skewed towards students that identified as male; therefore, future research must use a balanced sample since prior research shows that an individual's response to competitive environments is influenced by gender.

Chekurov et. al. [52] investigated how the creativity of DfAM assignments without functional requirements can be evaluated. The group also investigated the improvement in parts produced in the consecutive years in which the study was conducted and offered an explanation for improvement. The authors presented a DfAM assignment that was focused on quantifying DfAM creativity of students that were in the 4^{th} year of the mechanical engineering program as well as graduate students during a five-year period. The main goal of the assignment was to encourage students to learn from failure to achieve designs that can be manufactured. Designs created were assessed with numerical and jury methods of evaluation. The numerical evaluation method is objective and assigned a numerical value to each part based on definitions of complexity. A multi-point creativity assessment was performed by 10 jury members on a large sample of student created parts collected over five years. In the subjective jury method, manufactured parts are randomly grouped and graded based on (1) design, (2) execution, and (3) potential. An 18-point Likert scale was used to assess these three factors. The jury method of result assessment was recommended over the numerical method and must be used when resources are limited. The quality of student work improved significantly when the course assignment was performed for multiple years due to students gaining insight from an increasing number of high-quality parts from the previous years' assignments. One major limitation of the jury assessment is the long-drawn-out process that caused jurors fatigue which ultimately influenced their scores. Student learning was evaluated indirectly based on the quality of parts handed in for an assignment which did not provide enough information to evaluate the learning outcomes of groups of individuals. Future iterations of the study should evaluate the starting level of individuals and their learning outcomes [52].

Prabhu et. al. [53] investigated the effects of variations in DfAM education on students' creativity in an experimental study with 343 junior-level mechanical engineering students from a design course. DfAM education was varied in the following three groups: no DfAM instruction, restrictive DfAM, and opportunistic and restrictive (dual) DfAM education. The participants' self-reported use of DfAM in the design challenge and expert assessment was used to measure the differences in effects of the intervention. The self-reported scale was used to measure the participant's emphasis on the different DfAM techniques during the design challenge. Participants were asked to rate the importance of each technique using a 5-point Likert scale. The scores were averaged to achieve an opportunistic and restrictive emphasis score. The expert assessment used a subjective measure, the Consensual Assessment Technique (CAT), to assess the domain-specific nature of creativity assessment. Two expert raters used a 6-point scale to assess the designs using the following metrics: usefulness, uniqueness, technical goodness, and overall creativity. An average score was then assigned to the student designs. Results showed that teaching participants restrictive and opportunistic DfAM do not result in higher self-reported use of opportunistic and restrictive concepts. There was a higher emphasis on restrictive DfAM techniques compared to opportunistic techniques. Results show that there is a need to encourage the integration of opportunistic DfAM. In addition, results showed that teaching only opportunistic DfAM does not generate higher uniqueness and creativity in participant ideas. Ideas generated from the participants that received dual DfAM education showed better designs for AM. The limitations of the study were the simple design challenge used and the short duration of the lectures. Another limitation was the use of aggregate DfAM concepts to measure the participants' use of opportunistic and restrictive DfAM. Each DfAM concept should be used as a separate measure of participants' grasp of the concept. The final design was used to measure the creative outcome, but future work should investigate different stages of the design process. The authors suggest varying the participant sample to include students with a variety of prior experiences in AM and engineering from first year to senior level student populations, since this may vary the motivation of the participants toward learning about and using DfAM.

Prabhu et. al [41] investigated the importance of timing on the effectiveness of DfAM education on students' design process. Two DfAM educational interventions were conducted early (2^{nd} week) and late (10^{th} week) in the academic semester. The change in students' perceived utility, change in self-efficacy, and the use of DfAM concepts in the designs created was compared among the two educational timed intervention groups. The largest gains were shown when DfAM is introduced earlier in the semester when students have little to no experience in AM. Opportunistic DfAM concepts were applied at a greater rate in the early DfAM education group compared to the later introduction of DfAM. There was no difference in the application of restrictive DfAM concepts between the two intervention groups. The DfAM lectures and design challenges were most useful to students with low AM experience. This group also showed a greater learning of opportunistic and restrictive DfAM concepts and reported a greater application of opportunistic AM. This study supports the importance of introducing DfAM concepts early in the engineering curriculum to fully prepare students for design roles in the industry. Educators must have insight on students' prior AM experience to effectively teach DfAM. This allows educators to add to students' experiences and teach DfAM early in the semester when it is perceived to be most useful.

Educators must also encourage the use of opportunistic DfAM in the design process. A limitation of the study was the use of a 'guest lecturer' to perform the intervention as opposed to the DfAM educational intervention integrated in the course curriculum. The short duration of the educational intervention was also limiting since it may have limited the students' ability to apply various DfAM concepts.

In a further study performed by Prabhu et al. [44], the team stated that there is limited research that studies how DfAM educational interventions can be altered to encourage student learning and creativity. The group's recent work informed the development of educational interventions that were intended to train engineers in DfAM and encourage student creativity and learning. The group studied the effects of varying DfAM educational interventions which included presentations and DfAM tasks to draw conclusions on students' learning and design creativity. The objective of the studies included the effects of DfAM education on the following areas: opportunistic DfAM self-efficacy, restrictive DfAM self-efficacy, technical goodness of students' designs, and the effects on the creativity of students' designs. These areas are likely to be improved after DfAM education. Key findings from the study were used to provide recommendations that can be used in educational practice. An increase in restrictive DfAM self-efficacy can be accomplished with minimal education inputs especially when students have prior experience in DfAM. Dual DfAM educational content must be provided to encourage students to generate designs with high technical goodness; ideas generated showed higher uniqueness, usefulness, and overall creativity. Students' motivation, triggered by quality-based rewards and technical goodness of designs, was influenced by a task competitive structure. Prabhu recommended that educators use a simple or complex design task presented in a competitive structure when introducing dual DfAM concepts. Special emphasis must be placed on opportunistic DfAM in educational interventions if the goal is to increase student opportunistic DfAM self-efficacy. The research team also emphasized that thought must be given to the design tasks that are chosen in these interventions because the design task definition influences the uniqueness of participants' designs. Designs with high uniqueness were generated when participants were given complex tasks which was due to decreased motivation to use opportunistic DfAM when students are given simple design tasks without functional requirements. The students chose to increase feasibility through restrictive DfAM.

Prabhu et. al [29], [41]-[42], [43], [47], [54], provided key recommendations for the development of task-based DfAM educational interventions. There is still a need for future work in the following areas: 1) the investigation of the influence of DfAM educational interventions during different stages of the engineering design process, 2) the investigation of the influence of CAD expertise and engineering experience on students' learning and use of DfAM, 3) studying the effects of spaced educational interventions that are distributed over multiple design and information presentations compared to aggregate interventions used in the studies mentioned above, and 4) a full factorial 4 x 2 x 2 design of experiments to test interactions between DfAM education interventions and its effect on opportunistic DfAM self-efficacy, restrictive DfAM self-efficacy, technical goodness of students' designs, and the creativity of students' designs. The four factors in the factorial design include the variation of the DfAM content presented (restrictive, opportunistic, dual opportunistic followed by restrictive lectures, and dual restrictive followed by opportunistic lectures), simple or complex design task definition, and a competitive and noncompetitive task structure. The investigation of the four aforementioned areas will provide concrete recommendations for creating DfAM educational interventions.

Kong et al. [55] incorporated Virtual Reality (VR) technology of a customized media of advanced manufacturing technologies to offer an immersive, interactive, and engaging experience of real world manufacturing experiences to students in a higher educational institution. 360-media recordings are incorporated in the training to offer accurate representation of advanced technology used in the manufacturing industry. The investigation is being offered to bridge the skills gap in manufacturing education which allows university curricula to remain up to date with the technology used in the industry. Students learning is enhanced in AM.

The following sections discusses the gaps in the literature on AM training in educational institutions and the contributions of the current research that can be applied to all educational institutions' engineering curriculum.

2.8. Gaps in the literature on DfAM

The analysis of the literature shows that there are gaps in the literature on DfAM. There is a lack of research studies that address industry challenges and needs as it relates to AM and DfAM. A review of the literature shows that there is a great need for a list of barriers to AM [56].

In addition, a review of the literature also shows that industries need information on the limitations on the limitations of AM systems and materials such as property constraints, process availability, and costs. Other important areas of research that are lacking in literature are the challenges and needs for the industry include the following [56]:

1) Information on process dependency of product qualities such as anisotropic properties.
2) New quality control and management techniques.
3) AM training.
4) Integrate AM into design, manufacturing, and logistic processes.

5) AM designs methodologies and guidelines.

6) AM software limitations such as CAD lattice structures.

7) Limitations of AM systems and materials such as property constraints, availability and costs.

Future research must focus on conveying practical DfAM knowledge to students in Higher Education Institutions to increase student employability in the workforce. Additional research is also needed in identifying novel connections between design strategies and methods, AM parameters, and material development for each AM technology [57]. Table 2 shows the research gaps as it relates to DfAM.

Table 2. DfAM research gaps [56].

1. Need for new DfAM frameworks and methods to build AM expertise in industry and to transfer AM knowledge from academia to industry.
2. Need for improved AM materials and systems
3. Need for decision support on when to use AM
4. Need for new approaches to predict the life-cycle properties and costs of AM parts
5. Need for hybrid process chains combining additive and subtractive and formative processes
6. Need for managing interdisciplinary collaboration along and beyond supply chains
7. Need for organization- and process-spanning digitalization, including software support
8. Need for new AM-specific standards of systems, processes, and materials
9. Need for intellectual property and legal regulations for self-manufactured AM (spare) parts
10. Need for more empirical studies on industry challenges and needs with a specific focus on SMEs

2.9. Contribution of Current Research

Table 3 describes the contribution of the current research investigation. Many of the studies previously performed used subjective assessment tools to assess designs in intervention workshops. The participants used in previous studies were junior mechanical engineering students and experienced industry designers and practitioners with many years of engineering experience and CAD expertise.

Table 3. Comparison of previous studies and current research

Targets	**Literature**	**Current Research**
Objectively assess design outcomes		x
Used pre and post surveys	x	x
Impromptu pre and post test		x
Investigated first year students	x	x
Investigated gender differences		x
Investigated correlation between change in DfAM SE and year of study		x
Correlation between pre- and post AM tests, design outcome and year of study		x
Correlation between AM and DfAM experience and change in DfAM SE and design outcome	x	x
Effect of CAD experience on DfAM SE and design outcome after DfAM training	x	x
Used expert raters	x	x
Provided a detailed training framework with associated goals and activities		x
DfAM training framework that accounts for AM technology design guidelines.		x
DfAM training framework that considers business management aspects (quality, cost, etc.)		x

The participants in the current research were varied using samples of first year, sophomore, junior, and senior level engineering students from multiple disciplines with varying AM, DfAM, and CAD experience. The assessment tool that was created, provided information on each DfAM concept as opposed to an aggregate of DfAM grouped under restrictive and opportunistic DfAM. This project captured students' intentions for integrating DfAM concepts in chosen designs. A longer DfAM educational intervention was offered due to numerous recommendations of the benefits of a longer education intervention. The current research investigated the use of DfAM knowledge after concept generation when using a decision-making assessment tool. Students need early exposure to techniques that will assist them to fully utilize the capabilities of AM. Students were able to select appropriate AM designs with the use of an appropriate education design tool.

The DfAM educational intervention along with the assessment tool researched in the current study aimed to effectively increase student self-efficacy in both opportunistic and restrictive DfAM. The goal of the assessment tool was to enable educators to evaluate the use of DfAM concepts in student designs. Students can also use the assessment tool to ensure the implementation of DfAM concepts in designs created. There is a need to understand the effects of DfAM educational training and the use of an objective assessment tool on engineering students' DfAM self-efficacy and design outcomes. Therefore, the effects of workshop-based DfAM intervention on engineering students' use of DfAM concepts in design outcomes and DfAM self-efficacy were investigated. In addition, an AM technology design guideline provides recommendations for part orientation and geometric complexities when using material extrusion and vat polymerization processes. This will assist training participants to maximize their plan for manufacturing a part with vat polymerization or material extrusion processes.

Based on the recommendations in the literature, the results of a pilot study performed in the first-year engineering classes is described in the next chapter to offer preliminary results on the effects of DfAM educational training and the use of an objective assessment tool on student DfAM self-efficacy and design outcomes.

3. Preliminary Investigation of the effects of DfAM Training on First Year Engineering Students

3.1. Chapter Overview

The first phase of the investigation was conducted to investigate the effectiveness of DfAM training on first year engineering students' DfAM self-efficacy and design outcomes. The current chapter presents details on the participants in the study, the methodology used to collect data, self-efficacy changes and design outcomes pre- and post-DfAM training. The use of the objective assessment rubric is also detailed. The results provided in this chapter were used to inform the development of a DfAM training framework that will enable educators to prepare future designers to fill industry needs. The DfAM educational intervention along with the assessment tool provided in this work can increase student self-efficacy in both opportunistic and restrictive DfAM. The workshop was carefully designed to ensure that students can benefit from the workshop as well as the assessment tool to improve designs.

3.2. Methodology

During the intervention workshop, students were given a pre-intervention survey to gather information on their self-efficacy and prior experience with AM and DfAM. A pre-intervention assignment was then given. DfAM educational intervention is offered in the form of design workshops in conjunction with brief lectures. Each workshop includes a design challenge and the production of 3D printed designs. Ideas generated were collected and assessed using the created rubric shown in Appendix A that rates the use of DfAM concepts in students' designs. Design ideas are collected in hard copy format and SolidWorks. The student outcomes before and post intervention are collected and compared for improvement in total score. A post intervention survey is given to participants to gather information on their perceived utility of the intervention and DfAM self-efficacy. The change in students' AM and DfAM self-efficacy was analyzed.

The participants' learning and use of DfAM after the intervention was evaluated using the following metrics: 1) DfAM self-efficacy score and 2) Score from the rubric evaluating the incorporation of DfAM concepts in design outcomes.

Table 4. Validated tool used to measure change in opportunistic DfAM self-efficacy [41].

DfAM Self Efficacy Concepts	**Scale used for DfAM self-efficacy**				
	Never heard about it	**Have heard about it but not comfortable explaining it**	**Have heard about it but not comfortable applying it**	**Could apply it but not comfortable regularly integrating it within my design process**	**Could comfortably regularly integrating it with my design process**
Making products that can be customized for each different user					
Combining multiple parts into a single product or assembly					
Designing parts with complex shapes and geometries					
Embedding components such as circuits in parts					
Designing products that use multiple materials in a single part or component					

Table 5. Validated tool used to measure change in restrictive DfAM self-efficacy [41].

DfAM Self-Efficacy Concepts	Scale used for DfAM self-efficacy				
	Never heard about it	Have heard about it but not comfortable explaining it	Have heard about it but not comfortable applying it	Could apply it but not comfortable regularly integrating it within my design process	Could comfortably regularly integrating it with my design process
Using support structures for overhanging sections of a part					
Designing parts to prevent them from warping and losing shape					
Designing parts that have different material properties (i.e., strength) in different directions					
Accommodating desired surface roughness in parts					
Accommodating for min and max feature size permitted in a process					

The DfAM Self-efficacy table shown in Tables 4 and 5 was validated by Prabhu et al. [43] and was used to record changes in student DfAM self-efficacy. This information was collected in the pre and post survey that showed the change in opportunistic and restrictive DfAM self-efficacy. The 5-point Likert Scale and the DfAM concepts used to measure DfAM self-efficacy shown in Table 4 was used to assess student DfAM self-efficacy. The scale was developed from the cognitive domain of Bloom's taxonomy [28] to measure students' learning of the DfAM concepts. Opportunistic DfAM (O-DfAM) utilizes the capabilities of AM through design concepts such as 1) making products that can be customized for each user, 2) combining multiple parts into a single product or assembly, 3) designing parts with complex shapes and geometries, and 4) Embedding components such as circuits in parts. Restrictive DfAM (R-DfAM) reduces print failures and include the following constraints 1) using support structures for overhanging sections of a part, 2) designing parts to prevent them from warping and losing shape, 3) designing parts that have different material properties, 4) accommodating different surface roughness in parts, and 5) accommodating for minimum and maximum features sizes required by each AM process.

An average opportunistic and restrictive score was obtained by collecting scores in the opportunistic concepts and restrictive concepts. The difference in participant's pre and post scores is used to measure the change in self-efficacy. Information on participant SE was collected during the pre- and post-surveys. The surveys collected student ratings of their knowledge and comfort with opportunistic and restrictive DfAM concepts. This scale highlights the concepts of remembering, comprehending, and applying based on Bloom's Taxonomy. A 5-point Likert scale was used to rate their knowledge and comfort with each DfAM concept. The following points were given to each response:

1- Never heard about it.
2- Have heard about it but not comfortable explaining it.
3- Could explain it but not comfortable applying it.
4- Could apply it but not comfortable regularly integrating it with my design process.
5- Could feel comfortable regularly integrating it with my design process.

A total score was calculated in each category based on the number of responses multiplied by the corresponding points from each response. An aggregated score of opportunistic concepts (O1-O5) and restrictive concepts (R1- R5) was used to obtain a mean opportunistic and restrictive score pre- and post-intervention. The experimental group's changes in DfAM self-efficacy and design outcomes were compared to that of the control group's DfAM self-efficacy.

The overview of the steps taken in the experiment is shown in Figure 3.

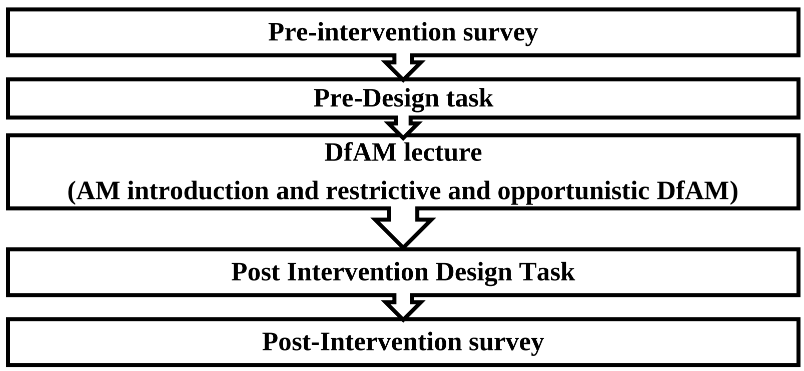


Figure 3. Summary of experimental procedure used in preliminary study

The pre-survey asked students to share demographic information, previous experience in AM and DfAM, duration and source of AM experience, work experience, intended major and profession. Students were also asked to rate their interest in AM. The survey included a section that evaluated the students' self-efficacy in opportunistic and restrictive DfAM techniques as well as a section that allowed the students to rate their motivation and interest in learning AM which was used in Prabhu et al. [29],[41] study on timing on the effectiveness of DfAM education on DfAM self-efficacy and perceived utility. Students were then asked to complete a 20-minute pre-design task that required a sketch of a toy that was to be presented as a gift. An introduction to AM technologies as well as restrictive and opportunistic DfAM was offered to students in the form of a lecture. The 10-minute AM introductory lectures gave a brief history of AM and an overview of the seven categories of AM. The differences in AM or 3D printing versus traditional manufacturing practices were also explained. The students were taught that AM or 3D printing processes build objects by adding material layer by layer until a part is complete versus subtractive manufacturing processes such as computer numerical control (CNC) machining (turning, drilling, boring, and milling) and laser cutting that remove material to achieve a final product.

The DfAM lecture included opportunistic examples and topics such as geometric complexities, mass customization, printed assemblies, part consolidation, multi-material structures, and functional component embedding. Restrictive topics covered in the lecture included build time, minimum feature size, support material use, material anisotropy, surface finish and warping. Students were shown examples of successful and failed prints. DfAM considerations for each metric used in the rubric were reviewed during the lecture. The DfAM scoring rubric was reviewed and can be seen in Appendix A. The rubric shown in Appendix A was used to assess student designs using the following metrics: part complexity, assembly complexity, number of separate parts, functionality, thin/smallest feature size, smallest tolerance, unsupported features, support material removal, and the largest build plate contact. Students were given a score of 4 in each category for the most ideal feature of a part and was given a 1 for poor design choices that may lead to part failure. The scores from each metric were totaled for a total score out of 36 possible points.

The pre and post designs were assessed using the DfAM rubric. The choice in metrics and choice suggestion was inspired by work from Booth et al. [28] and Prabhu et al. [29], [41]-[42], [43]-[54]. The design task was chosen to assist the students in creating value through the connection of developing a toy for a friend or loved one. The students were allowed to use the DfAM rubric during the pre and post design tasks. The students were given 30 minutes to an hour to complete the design task. The same design task was used in the post design challenge. The same design task was used in the post design challenge. During the pre and post design tasks, students are encouraged to use the rubric to design with the limitations and opportunities of AM in mind.

3.3. First year engineering participants

The participants in phase 1 of the research investigation were first year engineering students from six sections of engineering classes at Western New England University. The participants were recruited based on their enrollment in a semester long first-year undergraduate engineering class, Introduction to Engineering (ENGR103), that teaches design principles.

3.3.1. Participants Demographics

The DfAM intervention was offered to 178 students but a sample size of 67 was used in the study due to unavailable post intervention scores and surveys. The sample included first-year students pursuing undergraduate degrees in biomedical (15%), mechanical (39%), electrical and computer engineering (13%), and civil and environmental engineering (25%). 8% of the participants are undecided in a major field of study.

Figure 4 shows that 76% of the participants were male while 24% were females. 76 % of the sample participants are male (N=51) and 84% of the participants used in the study can be described as “White or Caucasian”. Information was provided orally about the research study and the benefits prior to the workshop. The study was approved by the Institutional Review Board (IRB) and implied consent was given by all participating students.

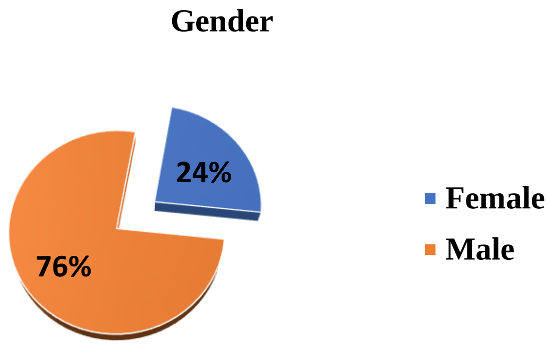


Figure 4. Gender representation in the first-year participant sample

3.3.2. Participant AM Experience

Information on the participants' previous experience in AM and DfAM can be seen in Figure 5 which shows that approximately 52% of students that participated in the workshop had informal experience in AM. Students with informal experience can be described as individuals that have used 3D printers but was not formally trained. 19% of the participants had no AM experience. 2 % of the participants reported being experts in AM.

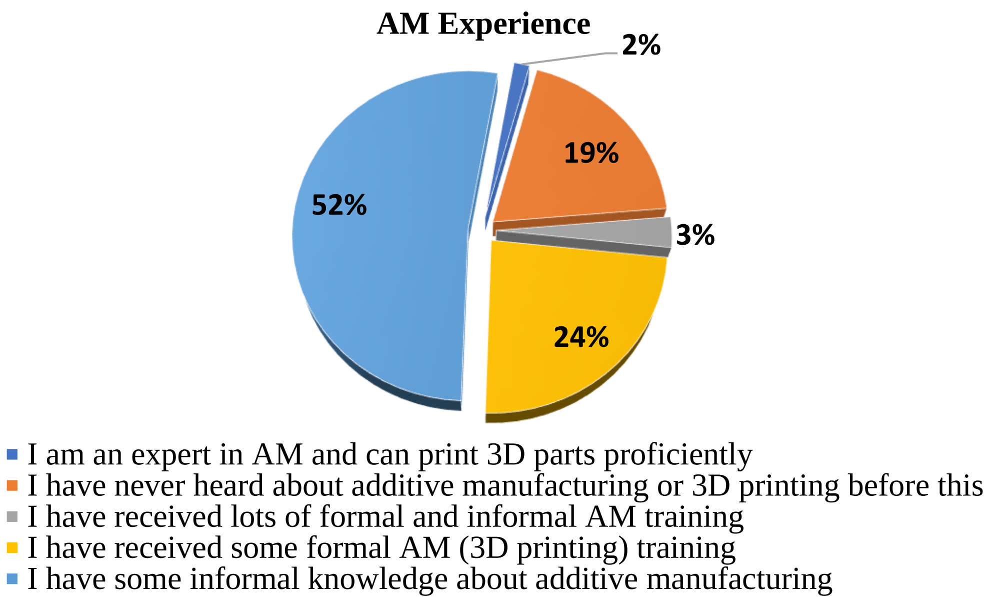


Figure 5. Participants' AM experience.

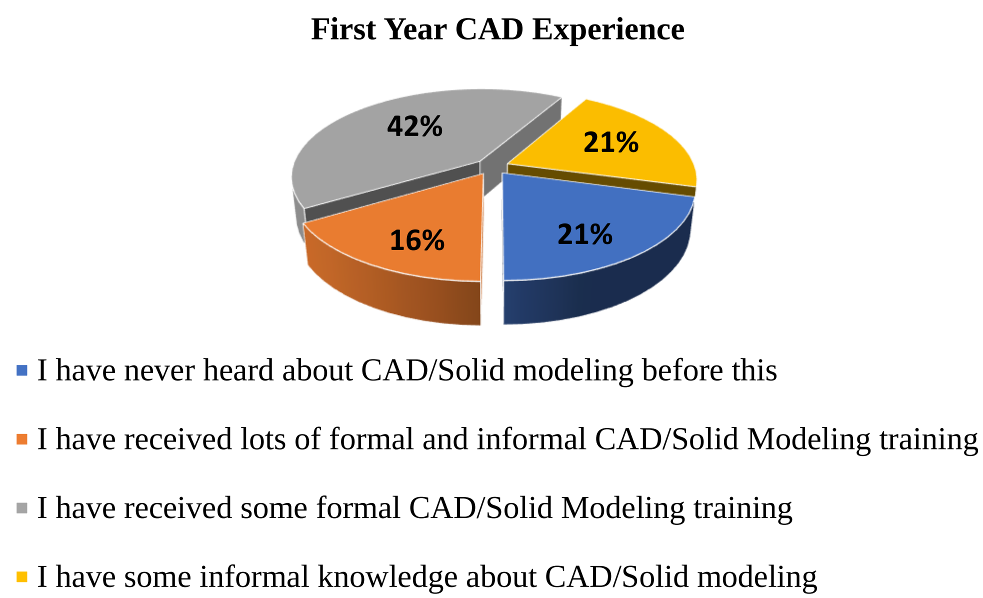


Figure 6. CAD experience in the first-year participants.

3.3.3. Gender and AM Experience

Figure 7 shows the breakdown of participants' gender and AM experience. The figure shows that males are more experienced in AM than females.

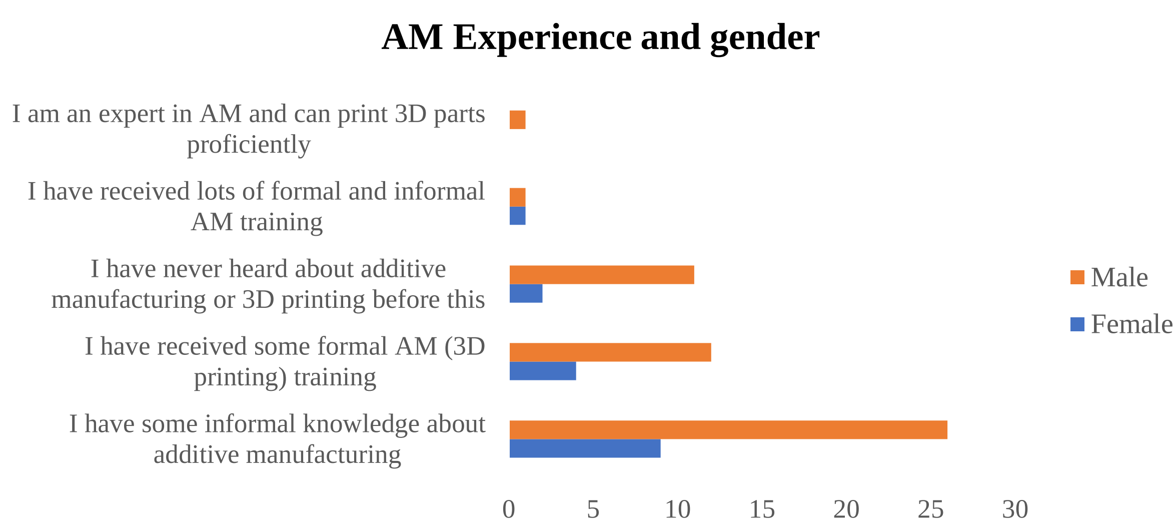


Figure 7. Participants' gender and AM experience.

3.4. Data Analysis and Results: First Year Students

3.4.1. Change in DfAM self-efficacy in First Year students

The pre and post surveys were used to collect information on students' DfAM self-efficacy. The participants showed an increase in DfAM self-efficacy after the intervention workshops. Figure 8 highlights the changes in each of the DfAM SE categories. Students in the first year showed the lowest DfAM SE in the O4 category of obtaining the desired surface quality. First year participants are more confident in the opportunistic aspects of DfAM.

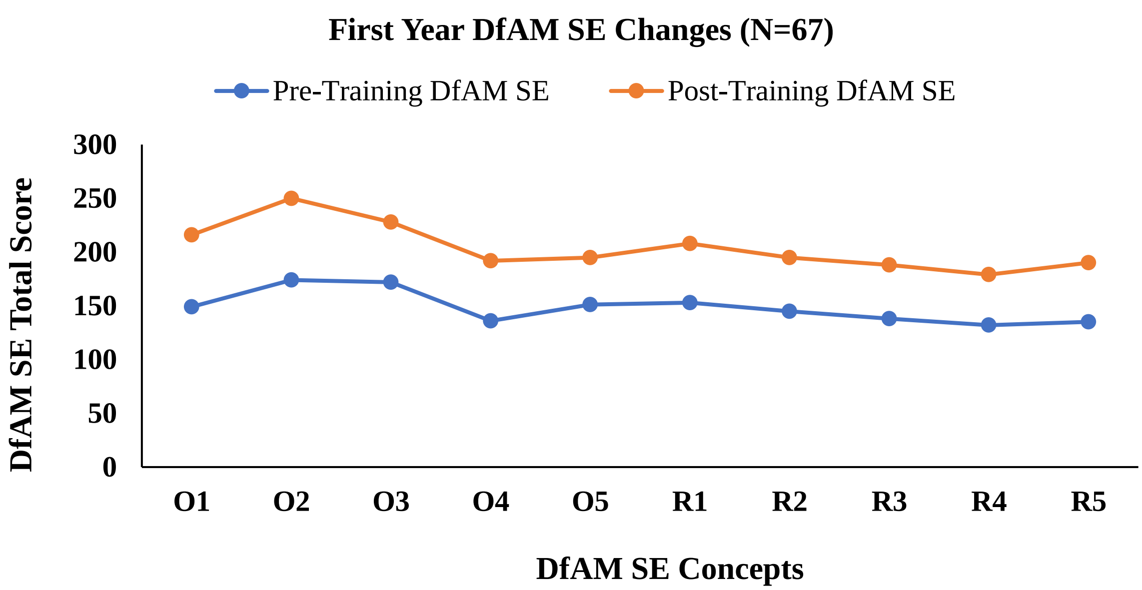


Figure 8. Participants' gender and AM experience.

Figures 9 and 10 show the total opportunistic and restrictive scores in each DfAM self-efficacy concept. The average self-efficacy score pre-workshop for opportunistic DfAM concepts was 156.4 +/- 16.23 pre-workshop compared to an average post workshop of 216.2 +/- 24.1. This showed a 38% increase in opportunistic DfAM self-efficacy.

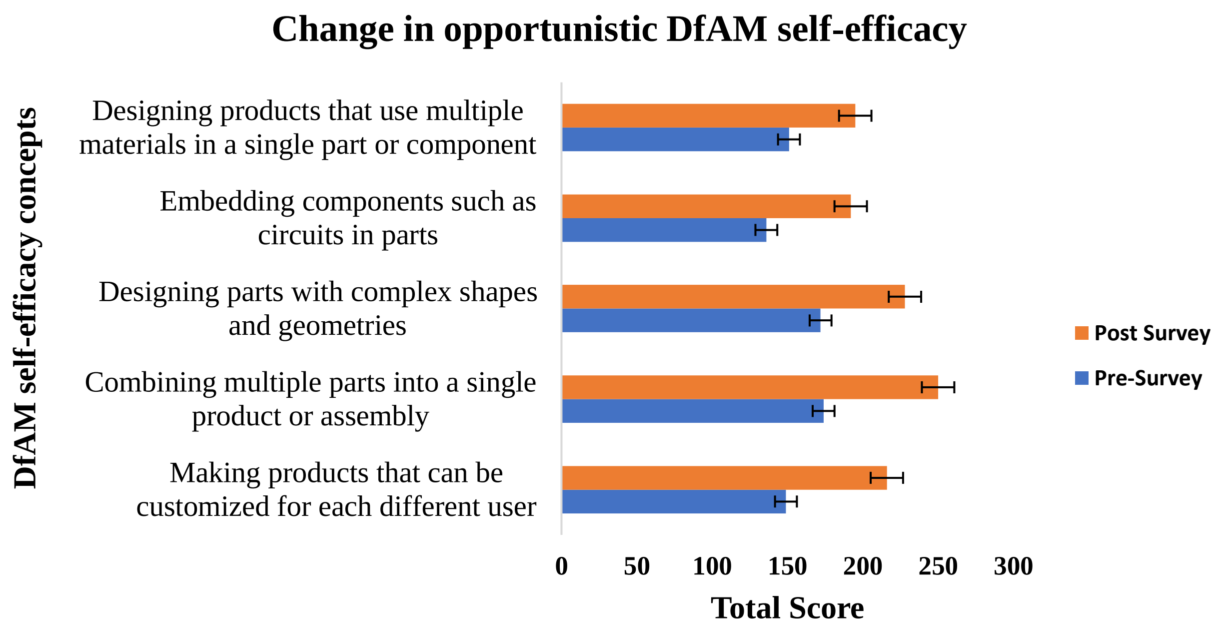


Figure 9. Participants' change in opportunistic DfAM self-efficacy ($p<0.05$)

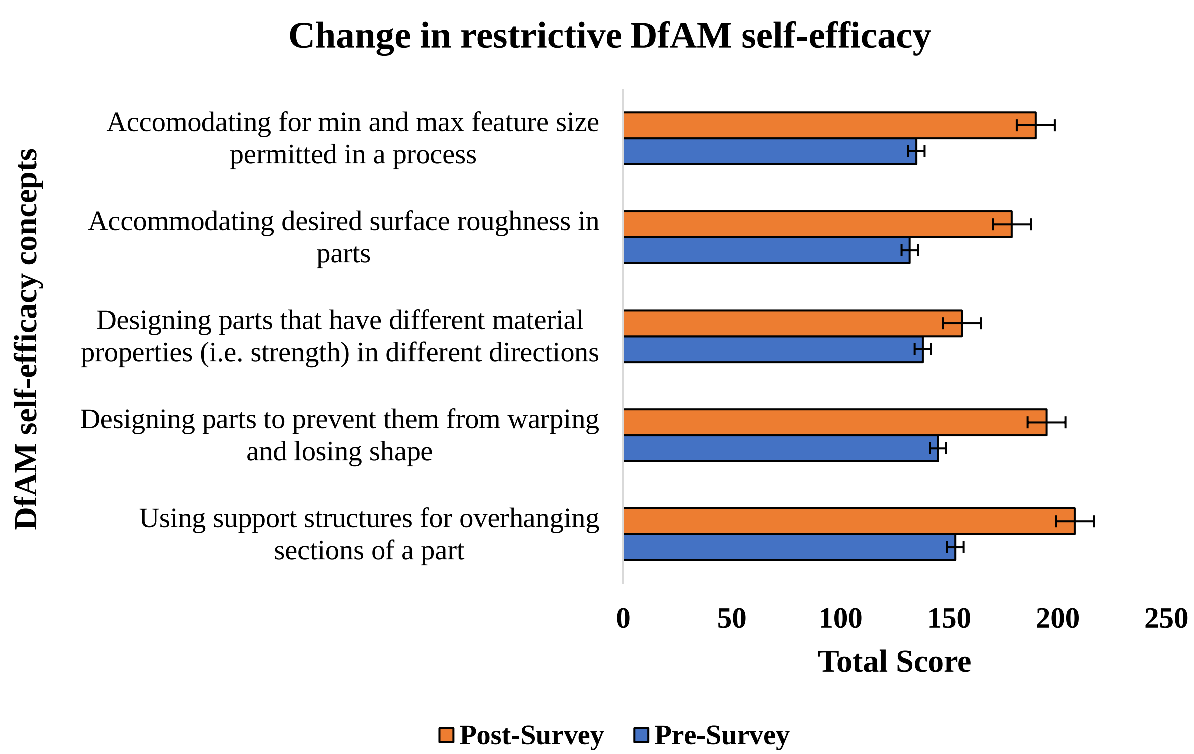


Figure 10. Restrictive DfAM self-efficacy changes pre- and post-intervention

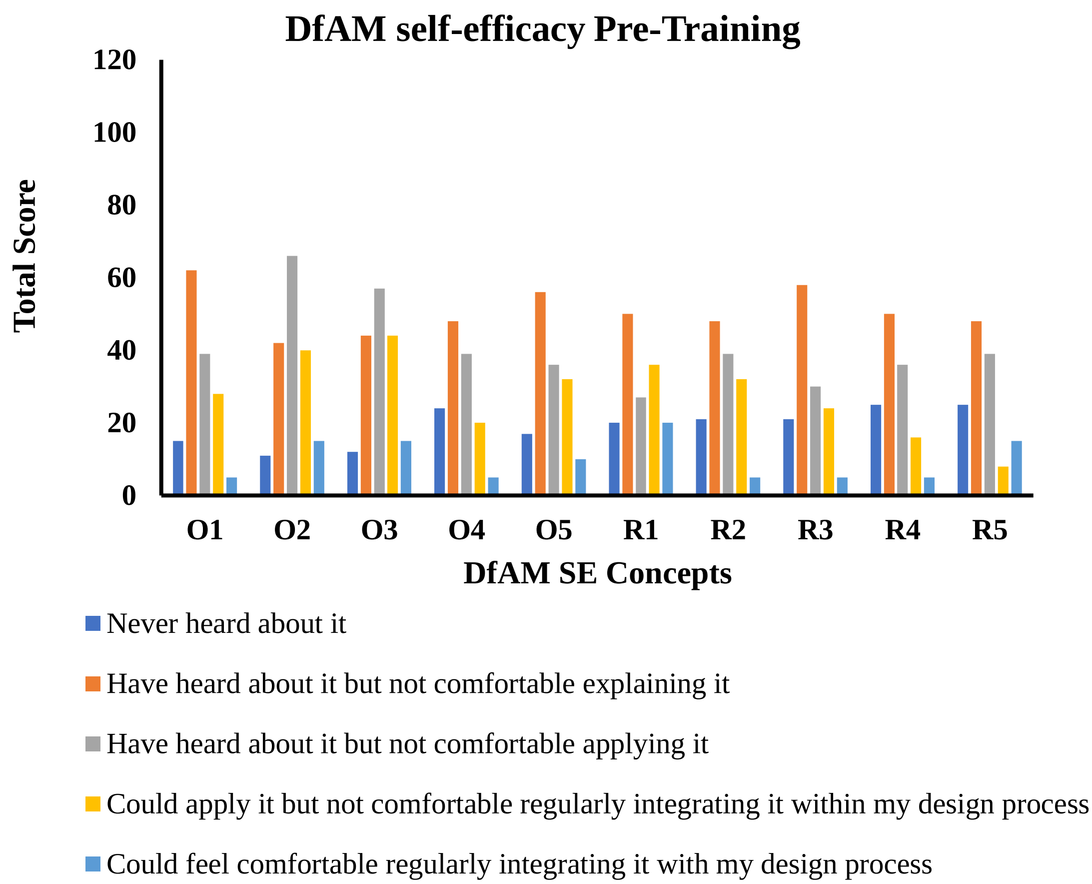


Figure 11. DfAM self-efficacy before DfAM training

Figures 11 and 12 shows the number of responses in each DfAM SE category. In figure 11, the participants' have heard about most of the DfAM concepts but were not comfortable explaining it or applying it. There were a small number of participants that felt comfortable regularly integrating DfAM concepts into the design process. In Figure 12 which shows the students' DfAM SE after training, the students showed more confidence in each DfAM SE concept area. Most students felt confident in the O2 DfAM concept area which requires combining multiple parts in a single product or assembly. The students reported being able to confidently regularly integrate the O2 concept area in the design process.

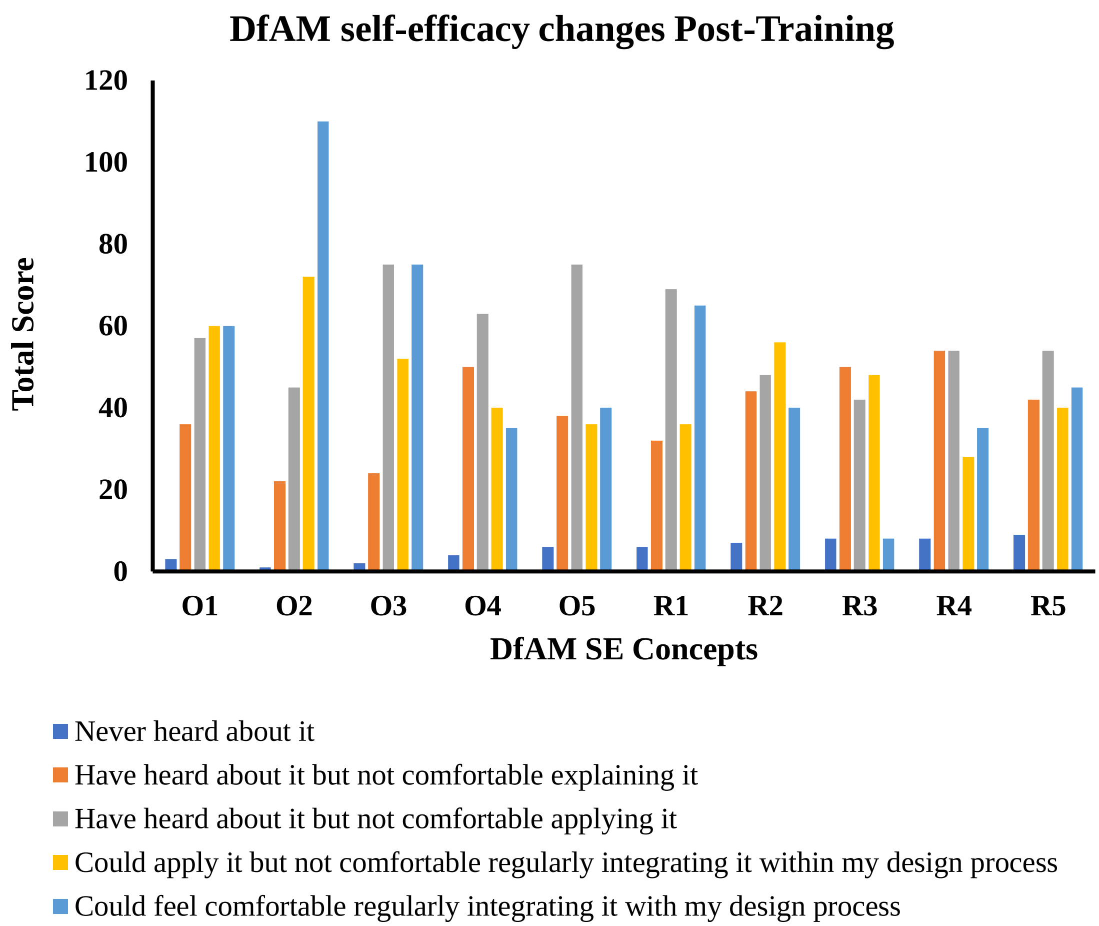


Figure 12. Changes in DfAM self-efficacy after DfAM training

The DfAM self-efficacy improved in the first-year participants after DfAM training. Table 6 highlights the changes in the participants' opportunistic and restrictive DfAM before and after the training. Table 6 shows that the highest percent increase can be see in the opportunistic category of O1 which assessed their confidence in making products that can be customized for different users. The lowest DfAM SE percent increase was seen in the O5 category which requires confidence in designing products that use multiple materials in a single part or component.

Table 6. DfAM self-efficacy improvement in first year students after training

DfAM Self Efficacy Concepts	Pre-Training DfAM SE Total Score	Post-Training DfAM SE Total Score	% Increase
O1	149	216	**45%**
O2	174	250	**44%**
O3	172	228	**33%**
O4	136	192	**41%**
O5	151	195	**29%**
R1	153	208	**36%**
R2	145	195	**34%**
R3	138	156	**36%**
R4	132	179	**36%**
R5	135	190	**41%**

The average DfAM self-efficacy score pre-workshop for restrictive DfAM concepts was 140.6 +/- 8.44 pre-workshop compared to an average post workshop of 185.6 +/-19.55. This showed a 32% increase in restrictive DfAM self-efficacy. The greatest change was noted in the opportunistic DfAM self-efficacy concept category of 'combining multiple parts into a single product or assembly' (O1) where the difference in average score was 76 points. The lowest percentage increase was seen in the O5 category which covers designing parts with multiple materials in a single component. This finding was expected since the participants were not given a task that emphasizes this concept. The first-year participants were least confident in the DfAM concept areas R4 (achieving the desired surface quality), R5 (accommodating for minimum and maximum feature size permitted in a process), and O4 (embedding components such as circuits) prior to DfAM training.

Results showed that there was a difference in DfAM self-efficacy change between males and females which is detailed in figures 13 and 14.

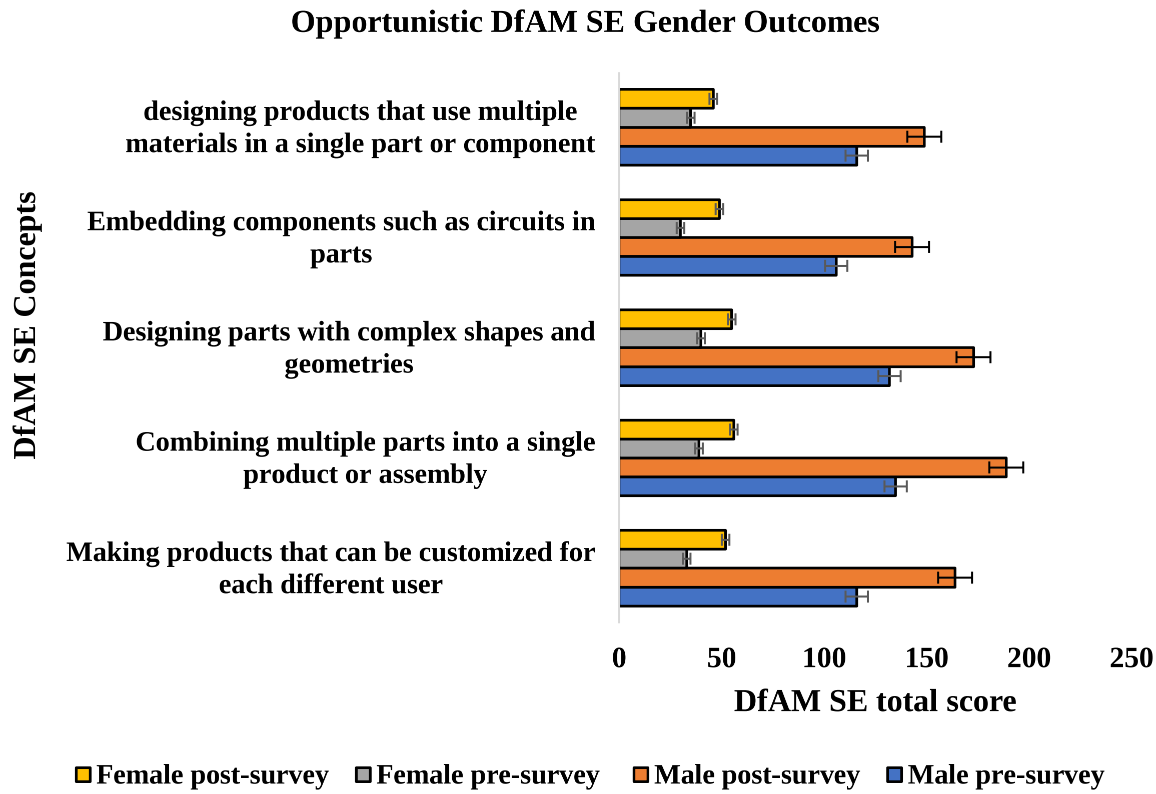


Figure 13. Differences of total opportunistic DfAM Scores and gender ($p<0.05$).

The percent difference in DfAM self-efficacy scores were greater for female participants that showed a 31.4% difference in pre and post opportunistic DfAM self-efficacy score compared to males that showed a 26% difference in pre and post opportunistic DfAM self-efficacy.

There was a greater percent difference in restrictive DfAM self-efficacy scores for males compared to females. Males showed a 28% difference in restrictive DfAM self-efficacy scores compared to a percent difference of 23% shown in the results for females. Overall, both groups showed a positive improvement in DfAM self-efficacy.

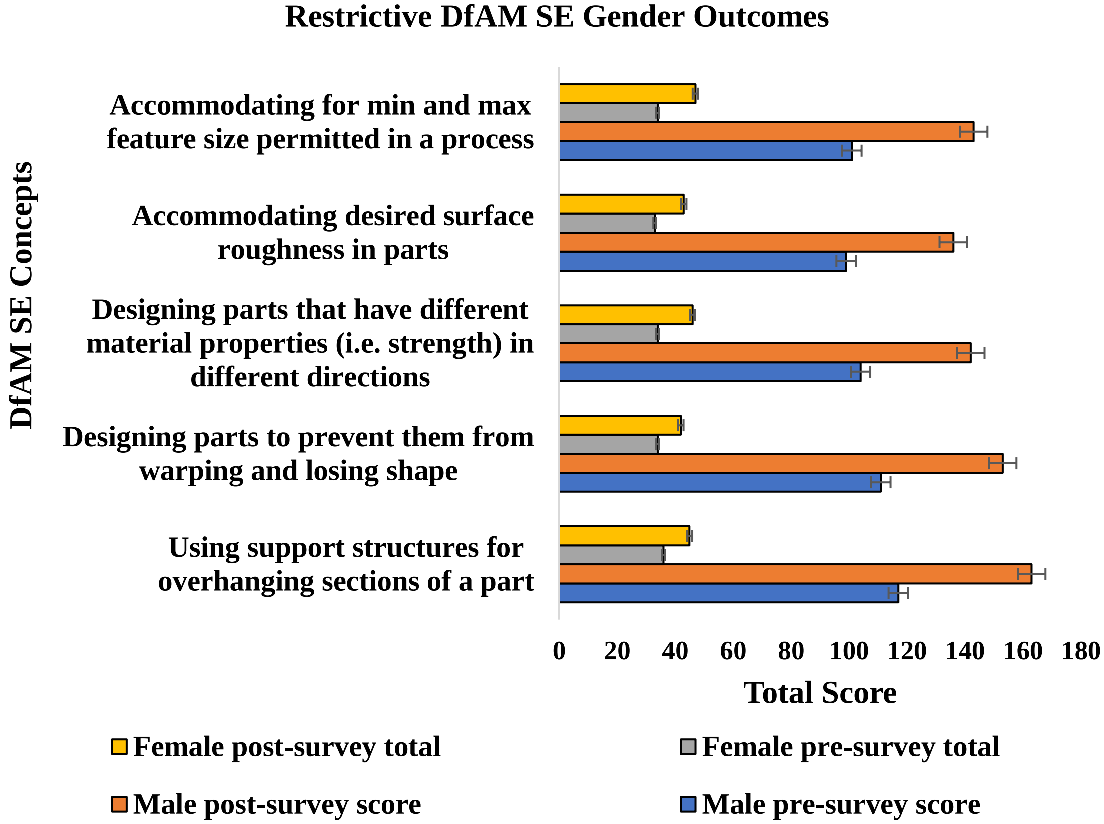


Figure 14. Differences in total restrictive DfAM scores and gender ($p<0.05$)

These results can be used to plan educational activities that improve female DfAM SE in and out of the classroom setting.

3.4.2. Design Outcomes Scoring: First Year Students

This work offers an objective method of assessing student designs in engineering curriculum and encourages the use of DfAM concepts in the design process. A Student's paired t-test with a significance level of $\alpha=0.05$ was used to statistically compare pre and post intervention design scores. Table 7 shows the improvement in average scores post DfAM intervention.

Table 7. Average participant scores pre- and post-DfAM intervention

Sample	Pre-Intervention Average Score	Post-Intervention Average Score	Median Pre-Intervention Score	Median Post-Intervention Score
All Participants	67.3%	79.2%	66.67%	80.56%
Participants with no AM Experience	66.54 %	78.54%	63.88% /	81.94%
Participants with 1 – 3 years AM experience	67.59 %	77.31 %	68.05 %	77.77%
Participants with > 3 years AM experience	75 %	92.36 %	75%	93%
Females (N=16)	62.5 %	77.3 %	65.28 %	80.56 %
Males (N=51)	68.8 %	79.8 %	69.44 %	80.56 %

Results using the assessment rubric showed that the average scores from the participants pre-design task was 67.3%. After the intervention, participants' average score was 79.2% on design outcomes. There is statistical difference in scores after the intervention workshop (Student's t-test, t (66) = -8.18 p=0). The participants with no AM experience averaged 67.5% on the predesign challenge score and averaged 80.1% on the post design challenge. Participants with many years of AM experience had a predesign average score of 72.2% and averaged 94.4% on the post design challenge. Participants with some informal AM experience had a predesign average score of 67% and averaged 78.1% on the post design challenge. Participants' that identify as females had an average pre intervention score of 62.5% +/- 0.1338 and a post design average score of 77.25% +/- 0.7726 (Student's t-test, t (15) = -4.1, p=0.001) compared to students that identify as males with a pre-design task average score of 68.8% +/- 0.1148 and an average post design score of 79.8% +/- 0.1032 (Student's t-test, t (50) =-7.13, p=0).

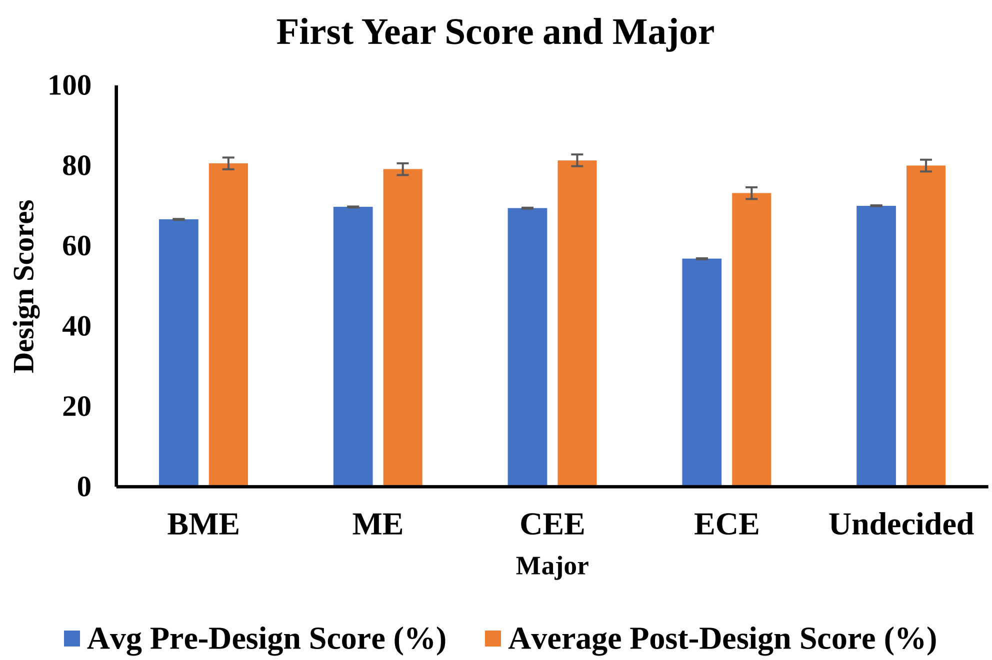


Figure 15. Pre- and Post-DfAM score and chosen field of study.

Figure 15 shows that the average design score pre and post DfAM intervention increased regardless of the chosen major.

3.4.2.1. Mann-Whitney Test Results

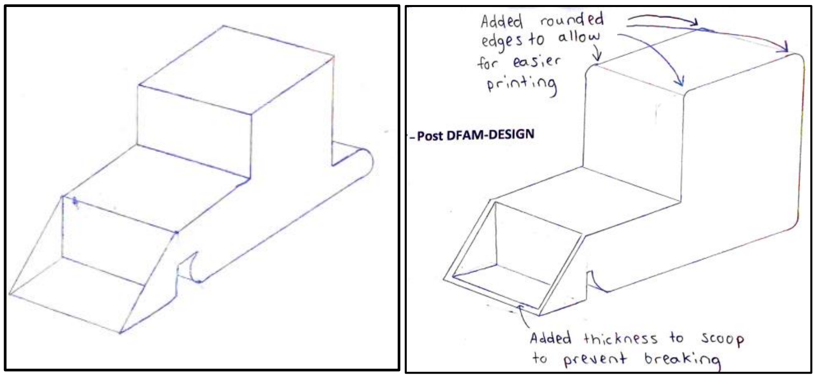
A Mann-Whitney test also showed that the medians of the pre-intervention design scores and the post intervention design scores are significantly different (p=0, 95% CI for η1-η2 = (-16.67, -8.33, W=3313). The predesign median score is 66.67% compared to the median post intervention design median score of 80.55%.

A Mann-Whitney test was used to determine the differences between median DfAM self-efficacy scores pre and post intervention. The median opportunistic DfAM self-efficacy score pre-intervention was 151 compared to a median of 216 in the post DfAM self-efficacy opportunistic score ($p<0.012$, 95% CI for $\eta1-\eta2$ = (-99, -21, W=15). Since the p-value is 0.012 which is less than the significance level of 0.05, the null hypothesis is rejected, and the conclusion can be made that the median pre and post intervention DfAM self-efficacy opportunistic scores are significantly different.

The median restrictive DfAM self-efficacy score pre-intervention was 138 compared to a median of 190 in the post opportunistic score ($p<0.012$, 95% CI for $\eta1-\eta2$ = (-70, -18, W= 15). The results also show that there is a significant difference between the medians of the pre and post intervention DfAM self-efficacy scores.

3.4.2.2. Sample Student Design Scoring

Students are also able to self-assess designs produced by using the assessment tool. A sample of student work from the workshop is shown in Figure 16. The designs shown were scored using the assessment rubric during the pre and post design task. The post designs show the implementation of DfAM concepts. A copy of the sheet used to record the students' ideas can be found in Appendix B.



METRIC	Part Complexity	Assembly Complexity	Number of separate parts	Functionality	Thin/smallest feature size	Smallest Tolerance	Unsupported Features	Support Material Removal	Largest Build plate contact	TOTAL SCORE
PRE DESIGN SCORE	2	0	4	1	1	4	4	1	1	50%
POST DESIGN SCORE	2	0	4	1	4	4	4	3	2	67%

Figure 16. Student toy scoop design pre- and post-intervention workshop.

The student work shown in Figure 16 received a predesign score of 50% and a post design score of 67%. The students' design showed improvement in accounting for the smallest feature size, support material removal, and the largest build plate contact. The design shows the student's choice to prevent the breaking of the scoop by increasing the thickness of the part which showed the consideration of the smallest feature size of the available extrusion 3D printer and the possibility of the part being damaged while support material is removed during post processing. The plate contact area was also reduced with rounded edges to decrease the warping of the edges.

Figure 17 shows samples of parts designed by student participants. Additional samples of student designs pre and post intervention can be seen in Appendix C. Each design created after the intervention workshop showed evidence of DfAM concept implementation in each design outcome.

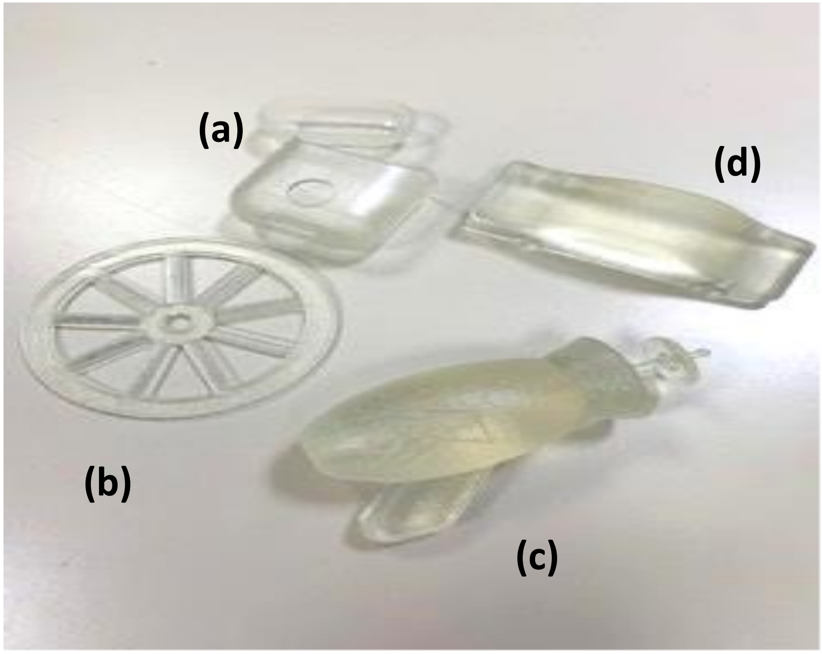


Figure 17. Selection of parts designed by students: a) iPhone ear pod case, b) toy wheel, c) toy gun, d) toy car.

In Figure 17, the participants created the following toys during the training workshop: a) an iPhone ear pod case, b) wheel, c) toy gun, d) toy car. The parts shown in Figure 17 were printed on the Form 3 vat polymerization printer.

4. DfAM Training of Upper-Level Engineering Students

4.1. Chapter Overview

A DfAM training framework was created to increase designers' DfAM self-efficacy and improve designing for additive manufacturing. A rubric that enables designers to implement DfAM considerations for material extrusion and vat polymerization processes was developed and was incorporated in the training workshop during design tasks. An impromptu pre and post AM and DfAM test was created to measure the change in AM and DfAM knowledge pre and post DfAM training. The impromptu pre-test was included in the training of the upper-level engineering students.

The training framework also included business management considerations when designing parts for additive manufacturing. The training workshop was offered to an experimental group and included a pre-intervention survey followed by a pre-intervention design task and DfAM lecture. A post-intervention design task was then completed with the conclusion of a post-survey at the end of the workshop. The control group did not complete the DfAM training workshop but was required to complete the pre-and post-design tasks as well as the impromptu DfAM pre and post-tests. The control group and the experimental group were compared to investigate whether there are improvements in designers' design outcomes and DfAM self-efficacy after DfAM training.

The effect of prior experience in AM, DfAM, engineering, and CAD on design outcomes and DfAM self-efficacy after training was also investigated. The design outcomes were evaluated using the DfAM assessment rubric that was developed. The study was approved by the Institutional Review Board (IRB) and implied consent was given by all participating students.

The current chapter describes the methods and procedures used to answer research questions 1 and 2.

- Research question # 1: Does DfAM training improve designers' design outcomes and DfAM self-efficacy?
- Research question #2: What effect does prior experience in AM, engineering, and CAD have on DfAM training?

In the upcoming sections, the participants' demographics, AM, CAD, and DfAM experience are described along with the experimental procedures used to offer DfAM training. The learning goals for DfAM training, an outline of the training workshop, and the design project used is described in detail. Information on the evaluators of the design outcomes is also provided.

4.2. Methodology

The participants in the control group completed the pre- and post-intervention survey as well as the pre- and post-intervention test. Participants in this group also completed the pre- and post-design task where a sketch of the cup ideas was made on the idea sheet shown in Appendix B.

The control group did not undergo DfAM intervention training. The experimental group was exposed to all the steps shown in Figure 18 which shows the experimental procedure used with the experimental group participants from the manufacturing processes undergraduate class. The main focus for training the upper-level engineering students was to incorporate industrial applications as well as DfAM training. Cost, time, and quality was emphasized in order to prepare the students for the manufacturing industry.

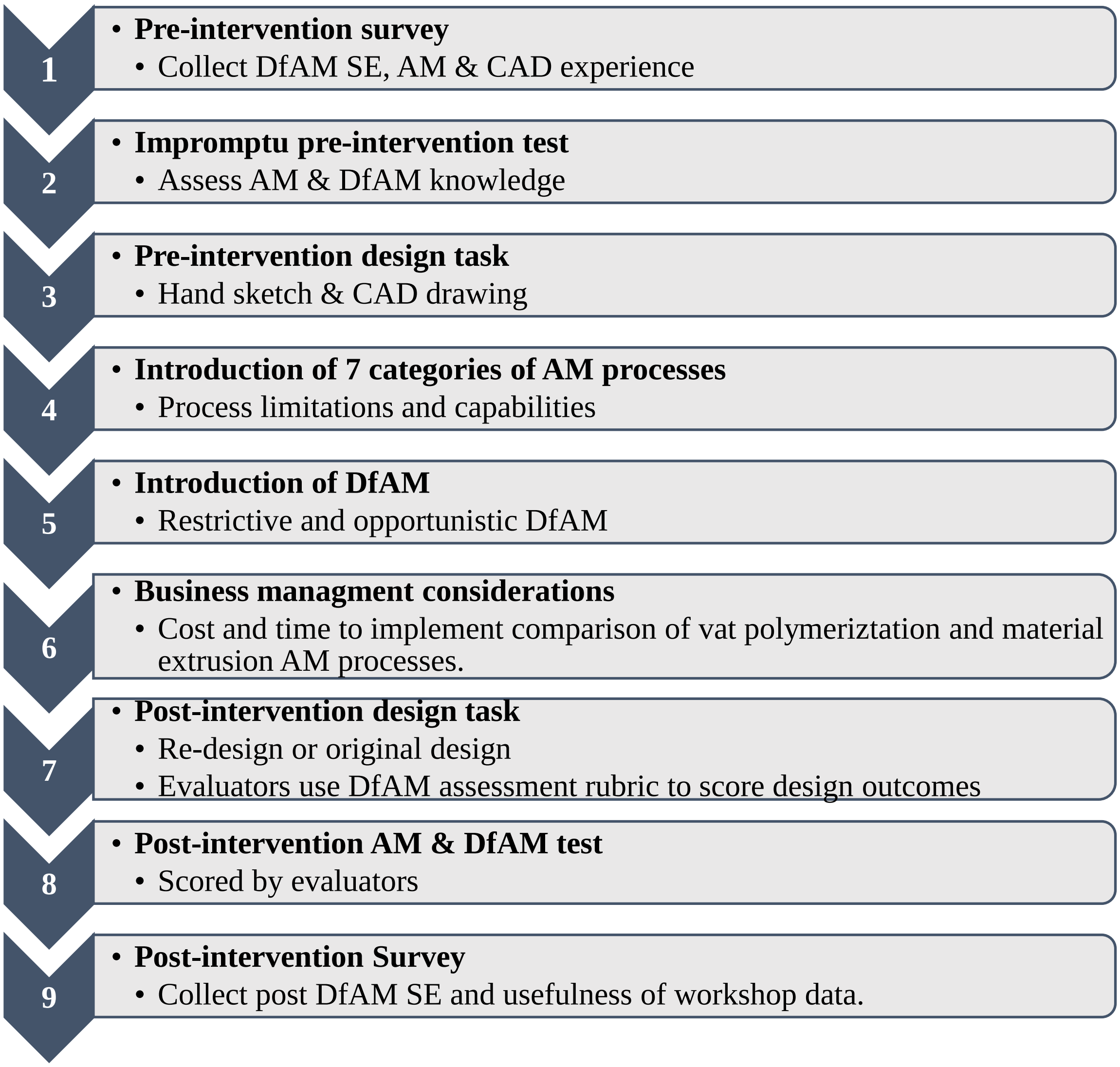


Figure 18. Experimental procedure used in the investigation with upper-level engineering students.

This experimental procedure included the same steps as the one used in the preliminary study with the first-year students as well as additional tasks. The additional tasks that were added to the experimental setup included an impromptu pre- and post-AM and DfAM knowledge test, hands-on experience with a vat polymerization process, and cost analysis comparison of the AM processes, vat polymerization and material extrusion. The training of the upper-level students included hands-on lab experience with 3D printers. Students were able to alter the DfAM considerations to obtain an intended design. A sample of student work can be seen in Appendix F.

4.2.1. Learning Goals for DfAM Training

The overall goal of the DfAM training intervention was to increase participant DfAM self-efficacy and design outcomes. The utilization of DfAM considerations in designs are compared pre- and post-intervention. The main learning goals for the DfAM intervention training included the following objectives:

1. Explain the capabilities, limitations, and basic principles of AM technologies.
2. Explain the fundamental causes of errors and irregularities in AM parts.
3. Evaluate and select appropriate AM technologies for specific design-manufacturing applications.
4. Apply DfAM techniques to challenging design and manufacturing applications.
5. Generate ideas of high AM technical goodness.
6. Incorporate business management considerations in design solutions.
7. Apply/incorporate rubric metrics to design outcomes parameters such as part complexity, assembly complexity, smallest tolerance, functionality, unsupported features, number of separate parts, support material removal, and largest build plate contact.

4.2.2. Activities: Outline of DfAM intervention workshop

The workshop included the following steps that were completed over a 3-week period:

I. Pre-intervention survey that collected information on DfAM self-efficacy, CAD, AM, and DfAM experience. Demographics information was also collected as well as year of study, career field interests, and motivation to learn AM and DfAM. (10 - 15 minutes)

II. DfAM and AM Pre-test which is shown in Appendix E assessed the participants' knowledge of AM and DfAM concepts. (10 – 15 minutes)

III. A pre-intervention design task was given to participants. The design task required a hand sketch and a CAD model of a cup and a cup holder. Participants used the assessment rubric (Appendix A) with DfAM considerations to assist with creating a sketch or CAD model. (Given as a homework assignment – 3 days)

IV. AM Introduction (50 minutes)

   a. Introduction of the seven categories of AM according to the American Society for Testing and Materials (ASTM) F2792 Standards: Material extrusion, vat polymerization, material jetting, binder jetting, powder bed fusion, directed energy deposition, and sheet lamination. The limitations and capabilities of these processes were reviewed in detail. Students were given a worksheet to follow along with the lecture and class activities.

   b. Compare and contrast traditional and subtractive AM.

   c. Discussion of potential benefits of AM.

   d. Discussion of AM applications.

   e. Discussion of the general AM process.

      i. Create CAD model

      ii. Convert file to a .stl format

      iii. Transfer file to 3D printer

      iv. Set up 3D printer

      v. Build model

      vi. Remove from 3D printer plate

vii. Post-processing

viii. Application

V. DfAM introduction (50 minutes)

a. Discussed and demonstrated restrictive and opportunistic DfAM considerations

i. Restrictive DfAM considerations

1. Build time, minimum feature size, support material angle limits, anisotropy, surface finish (stair stepping and point defects), warping.

2. Learning goals:

a. Use support structures for overhang sections of a part

b. Design parts to prevent them from warping and losing shape.

c. Design parts that have different material properties in each direction.

d. Accommodate desired surface roughness in parts.

e. Accommodate for minimum and maximum feature size permitted in a process.

ii. Opportunistic DfAM considerations

1. Mass customization, functional component embedding, printed assemblies and part consolidation, multi-material structures, and geometric complexity.

2. Learning goals:

a. Make products that can be customized for different users.

b. Combine multiple parts into a single product or assembly.

c. Design parts with complex shapes and geometries.

d. Embed components such as circuits in parts.

e. Design products that use multiple materials in a single part or component.

iii. Activity: Create a model of a cup and a holder out of Playdoh. Figure 19 shows an example product from the activity.

Figure 19. Student sample of Playdoh cup holder.

VI. DfAM lab and business management (30 minutes)

a. Activity: DfAM lab that compares the cost of vat polymerization and material extrusion.

i. Students utilized the Form Lab 3D printer and alter the orientation, layer thickness, and resolution of the designs to compare vat polymerization and material extrusion processes for the following areas:

1. Cost analysis
2. Quality considerations
3. Time to implement considerations

ii. Students were provided with 30-minute time slots to use the 3D printer and gather information to compare material extrusion and vat polymerization.

VII. Post Design: Design project (2 weeks)

a. Activity: Students worked individually initially and then in groups to complete the final design project. A technical memo was assigned which required an explanation of the design choices that were made as well as cost considerations for the chosen design

4.2.3. Products: Manufacturing Processes Project

The details of the design project given to the manufacturing processes class is provided below.

Individually:

- Students identified, designed, and fabricated products that is suitable for AM.
  - Design a cup and cup holder.
  - Submit hand sketches and SolidWorks files of the 3D model.

In groups of 2 or 3 students:

- Clarify the task and develop concepts: Each group generated a formal problem statement and a requirements list (or specifications sheet). The target market was considered.
- Refine and select a leading concept and a detailed design. Perform detailed technical and economic analysis of the chosen concept.
  - Design and implement a procedure for customer needs analysis and concept generation, leading to a set of preliminary concepts (often in the form of hand sketches).
- Iteratively refine the design as necessary, culminating in a CAD model and .stl file of the final design. The instructional team fabricates the part with in-house AM machines. After receiving the fabricated parts, design and implement a testing and evaluation procedure for

assessing the technical performance of the fabricated product (as well as its usability, if applicable).

- For each iteration:
  - Vary the number of parts used. Note the cost of each design.
  - Vary the weight – change geometry.
  - What orientation is the best – alter surface finish.

- Participants identified technical and/or economic reasons for additively manufacturing the product, rather than utilizing more conventional manufacturing techniques.
  - For example, AM is often driven by the need for customization, rapid cycle times, and/or small lot sizes.
- Students noted challenges in manufacturability. (warping, small features, dimensional accuracy, surface finish, and stiffness/flexibility, etc.)
- Finally, students critically evaluated their results and documented their projects in the form of a report.
- Assessment:
  - Students used the rubric to assess other students' parts/designs.
  - The parts were assessed using the DfAM rubric shown in Appendix A.
    i. Activity: Post designs: CAD model and sketch of the cup and holder showing DfAM considerations on the Idea Sheet shown in Appendix B.

VIII. Post DfAM and AM tests (Appendix E)

a. The control group and the experimental group completed the post-DfAM test during a class session.

b. The following rubric shown in Figure 20 was created to evaluate the pre- and post-DfAM tests

• **0 – Student responds "I don't know or I'm not sure". There is no part of the response that is correct.**
• **1 – Student's response matches ¼ of the problem correct. A small portion of the response matches the correct answer.**
• **2 – Student's response matches ½ of the correct answer. Some of the response matches the correct answer**
• **3 – Student's response matches ¾ of the correct answer. Most of the question is answered correctly**
• **4 – All parts of the question are answered correctly. Answer is complete and clearly answers the questions.**

Figure 20. Rubric to assess pre- and post - AM tests.

IX. Post Intervention Survey

a. The experimental and control groups completed the post-survey which included student feedback on the usefulness of the DfAM training.

4.2.4. Assessment of DfAM Self-Efficacy

Performance ability in engineering design can be measured by self-efficacy. To measure the effectiveness of the educational intervention, the self-efficacy (SE) scale was used to analyze changes in DfAM-SE pre- and post-intervention. The SE scale used in the preliminary study was used to assess and record the DfAM SE changes in the upper-class engineering experimental and control group. Information from the pre- and post-surveys was gathered and analyzed for changes in DfAM self-efficacy. The change in DfAM self-efficacy was calculated for 67 first-year students in the preliminary study. The change in DfAM self-efficacy was also calculated for 21 participants from the experimental group and 17 participants from the control group. The juniors from the control group and experimental groups were further analyzed where the changes in DfAM self-efficacy and changes in design outcomes were compared pre- and post-DfAM training.

4.2.5. Assessment of DfAM Design Outcomes

The design outcomes of the experimental group and the control group's pre- and post-designs were evaluated and compared. The assessment rubric shown in Appendix A was used to assess the design outcomes based on the metrics, part complexity, assembly complexity, number of separate parts, functionality, thin/smallest feature size, smallest tolerance, unsupported features, support material removal, and largest build plate contact. The pre-and post-DfAM tests and designs from the control and the experimental groups were evaluated by four evaluators which included a mechanical engineering industry professional, a full-time biomedical engineering faculty member, a retired biomedical engineering faculty member and current adjunct professor, and an undergraduate engineering student. The results are presented in the next chapter. In addition, the next chapter describes the results of the control group and the experimental group's change in DfAM self-efficacy and the design outcomes pre- and post-DfAM training.

4.3. Upper-level engineering student participants

The DfAM intervention was offered to 178 first year students at Western New England University in the preliminary study but a sample size of 67 was used due to unavailable post-intervention scores and surveys. The participants in the current research included an experimental group of 21 engineering students (sophomore, junior, and senior) and a control group of 17 junior engineering students at Western New England University. The experimental participants were recruited based on their enrollment in a semester-long elective undergraduate engineering class, Manufacturing Processes (ME-322), that teaches manufacturing processes and systems. The control group participants were recruited based on their enrollment in a semester-long junior level undergraduate engineering class, Biomechanics I (BME-351), that introduces statics and strength of materials related to the human body.

4.3.1. Participant Demographics

Demographic information was collected in the pre-survey and can be seen in Figure 21-24.

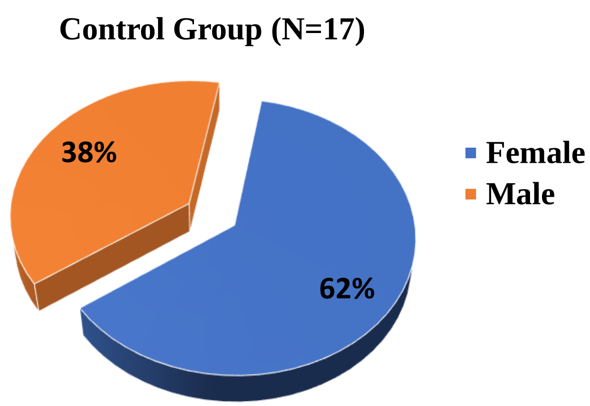


Figure 21. Control group gender grouping

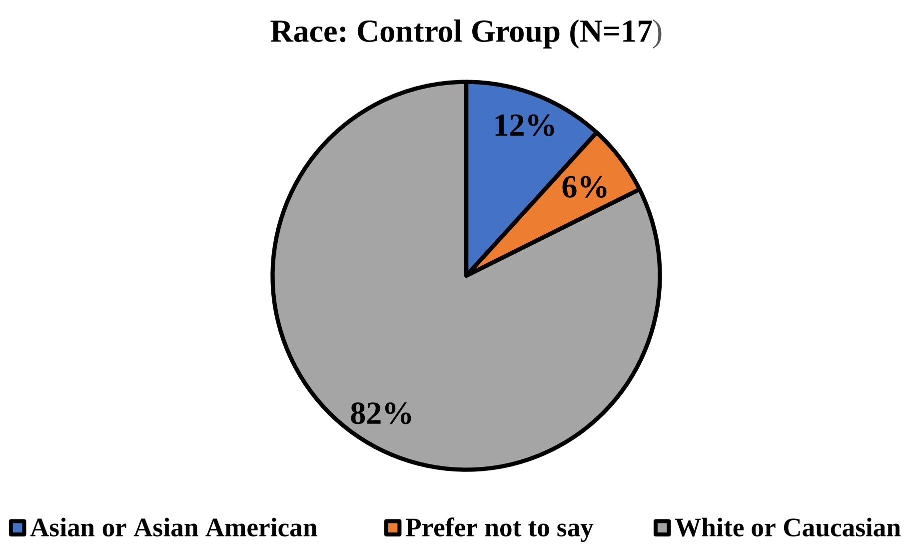


Figure 22. Race categories in the control group

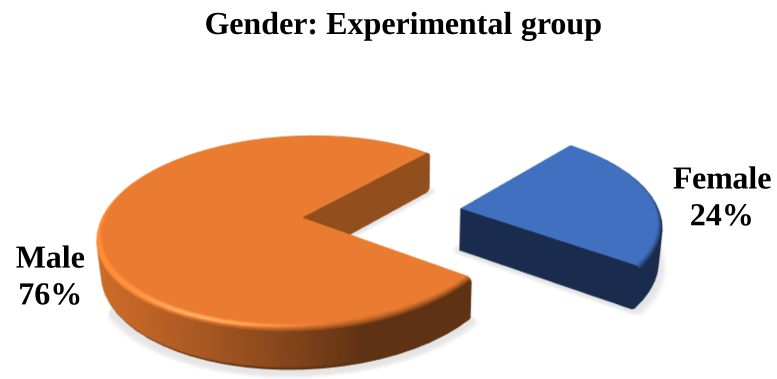


Figure 23. Experimental group gender breakdown.

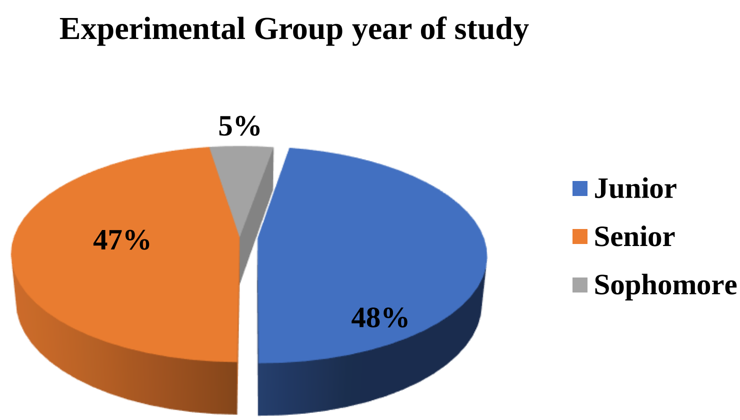


Figure 24. Year of study in the experimental group.

Figures 22 and 23 shows that the study was skewed towards participants in the 'White or Caucasian' group. 59% of the control group's participants were females while 76% of the experimental group were males.

4.3.2. Participant year of study

The participants in the control group consisted of all biomedical engineering students in the junior year of study. The experimental group consisted of 5% of the participants in the sophomore year of study, 48% in the junior year of study, and 47% of participants in the senior year of study.

4.3.3. Participant CAD Experience

The participants from the control group and the experimental group were compared based on their CAD experience. Figure 25 shows the CAD experience differences in the control group.

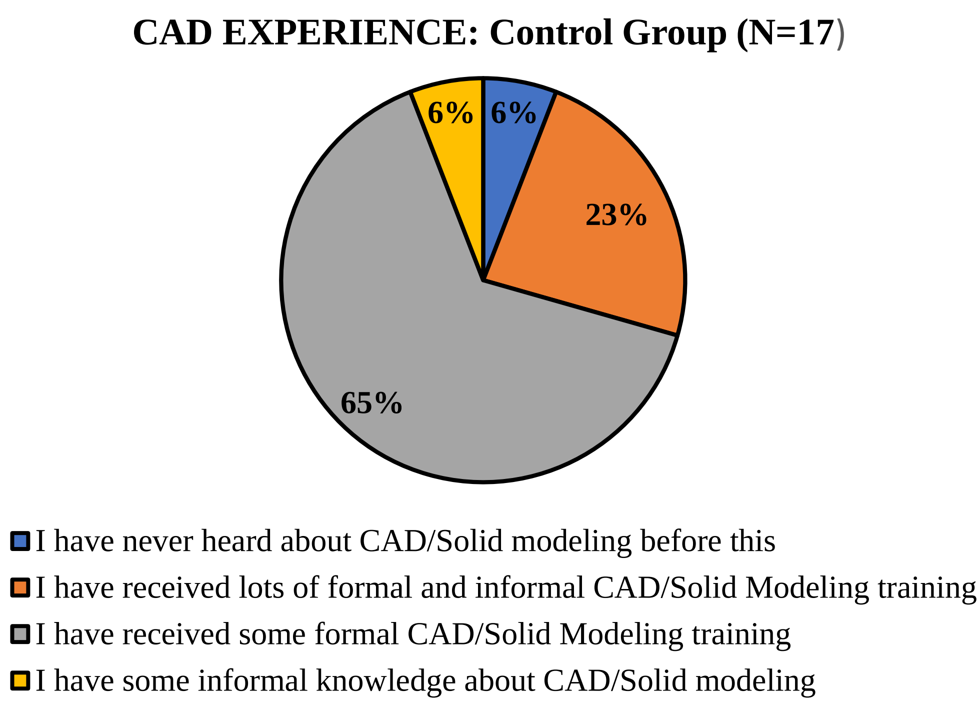


Figure 25. Control group's CAD experience.

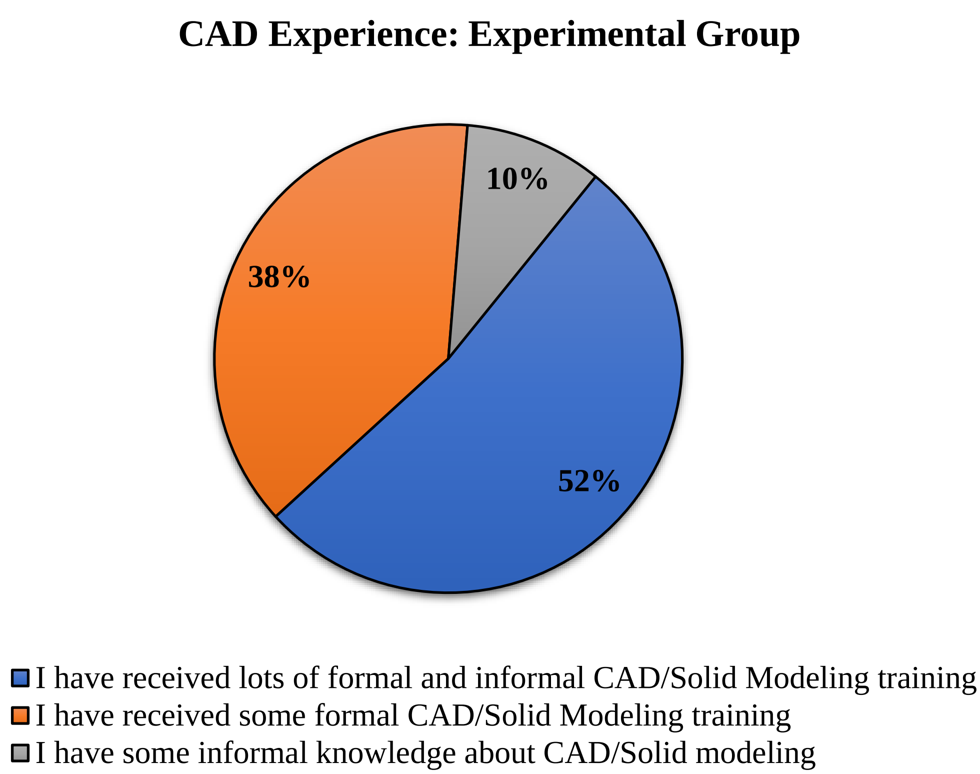


Figure 26. Experimental group's CAD experience (N=21)

The experimental group's CAD experience is shown in figure 26 which shows that 38% of the participants in the experimental group received some formal CAD/solid modeling training compared to 64% of the participants in the control group with similar CAD/solid modeling experience which is highlighted in figure 25. 52% of the participants in the experimental group have received many years of formal and informal CAD/solid modeling training compared to the control group that included 23.5% of participants with many years of formal and informal CAD/ solid modeling training. Figure 27 shows the year of study and the associated CAD experience of the students in the experimental group. The seniors in the experimental group claimed to have received a lot of formal and informal CAD training.

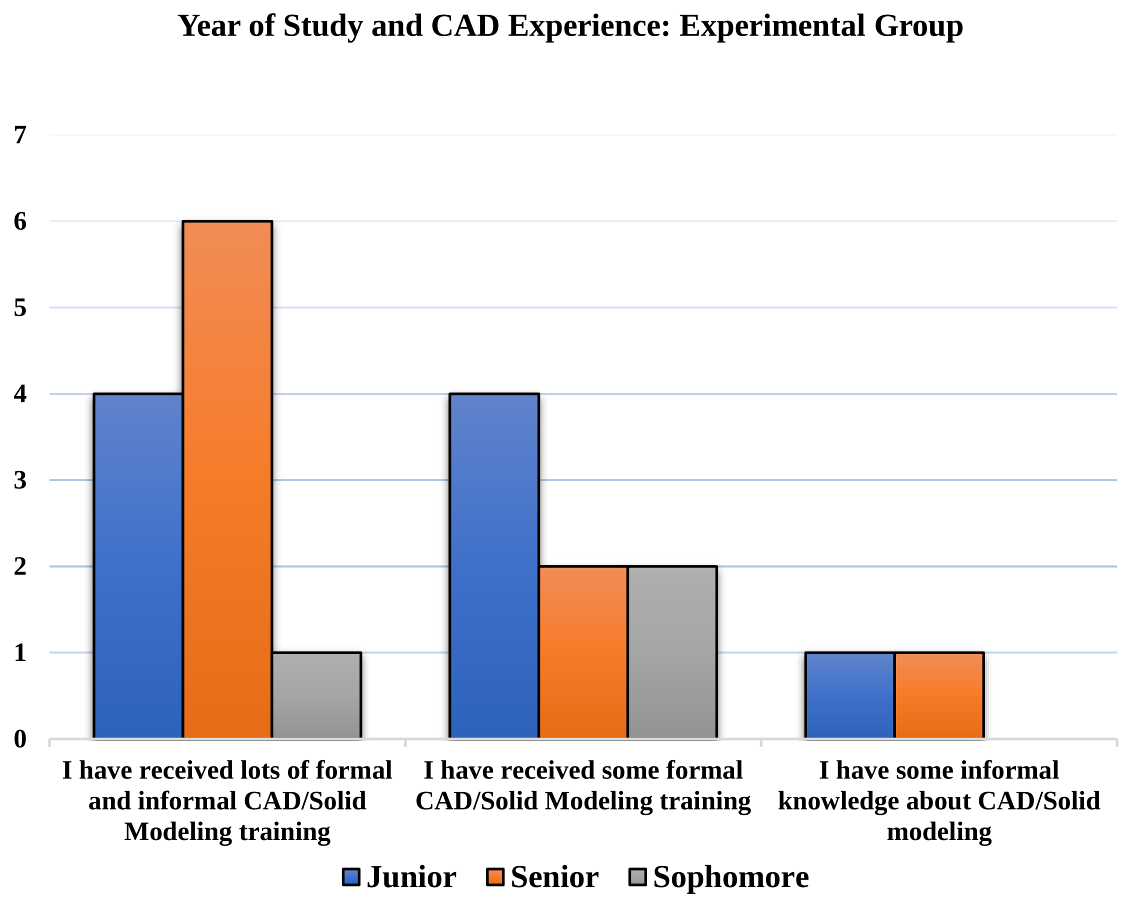


Figure 27. Experimental group CAD experience and year of study

The junior students in the experimental group claimed to have received lots of formal and informal CAD/solid modeling training as well as some formal CAD/solid modeling training. A comparison of the DfAM self-efficacy and the design outcomes of the junior students in the control and experimental groups are compared and discussed in the upcoming section.

4.3.4. Gender and CAD experience

The gender differences and CAD experience among the participants in the study was investigated to gather information on the association between gender and CAD experience on DfAM training outcomes.

Figure 28 shows that females in the control group represented the highest percentage of participants that claimed to have received some formal CAD/solid modeling training. There was 1 individual in the control group that have never heard about CAD or solid modeling. The males in the control group received CAD or solid modeling training before the intervention.

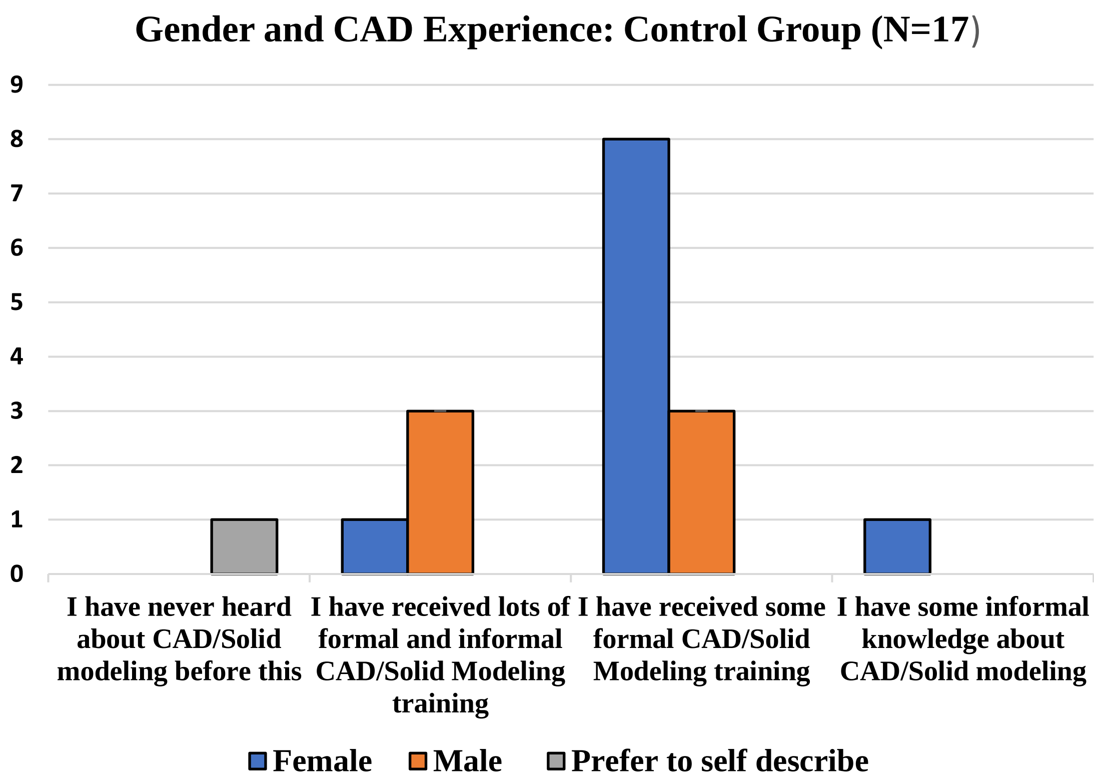


Figure 28. Control group CAD experience based on gender

Figure 29 shows that the males in the experimental group had more CAD/solid modeling experience than the females in the group. Overall, the participants in the control and experimental group had prior experience in CAD/solid modeling.

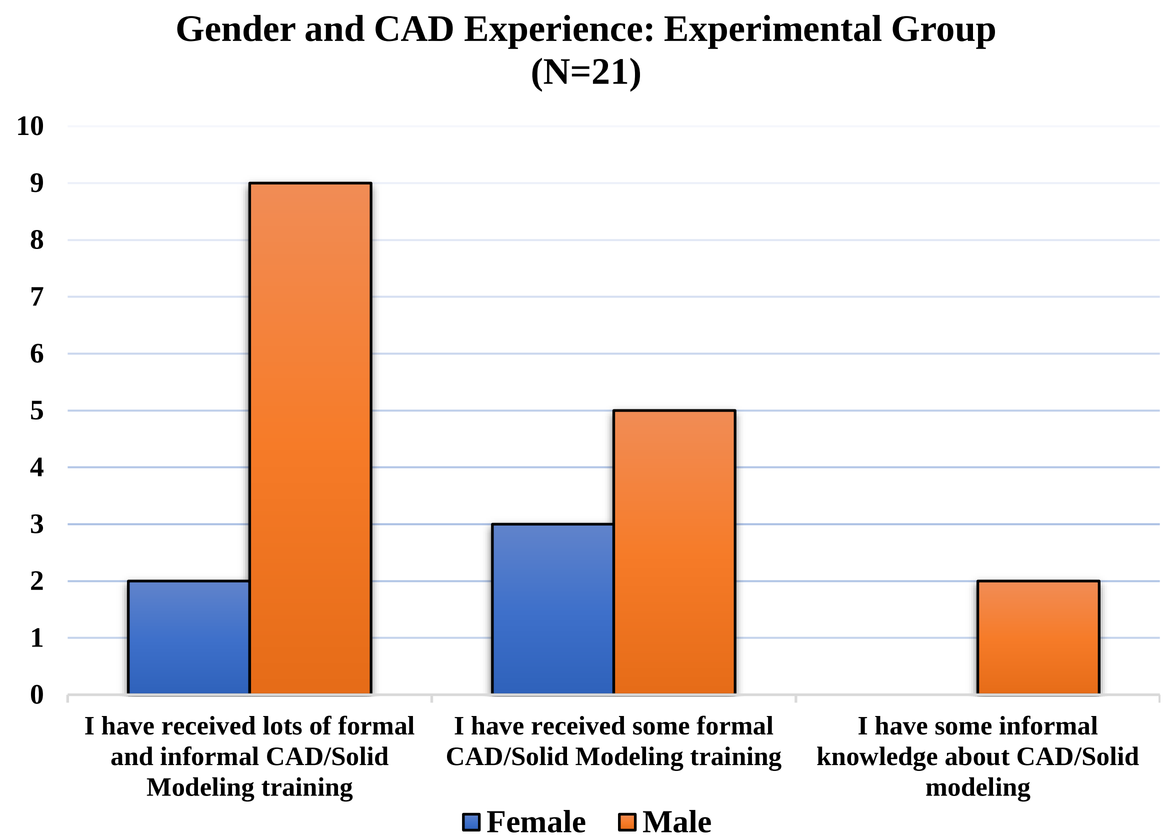


Figure 29. Experimental group CAD experience based on gender

4.3.5. Junior Year Student Participants

The control group consisted of undergraduate students in their junior year of study which prompted the need to compare the junior students from experimental group with the students from the control group. The experimental junior group consisted of nine students (Females: N=4 and Males: N=5). The control group consisted of seventeen students (Females: N=10, Males: N=6, Prefer not to self-describe=1). Figures 30 and 31 show the AM experience of the experimental and the control group.

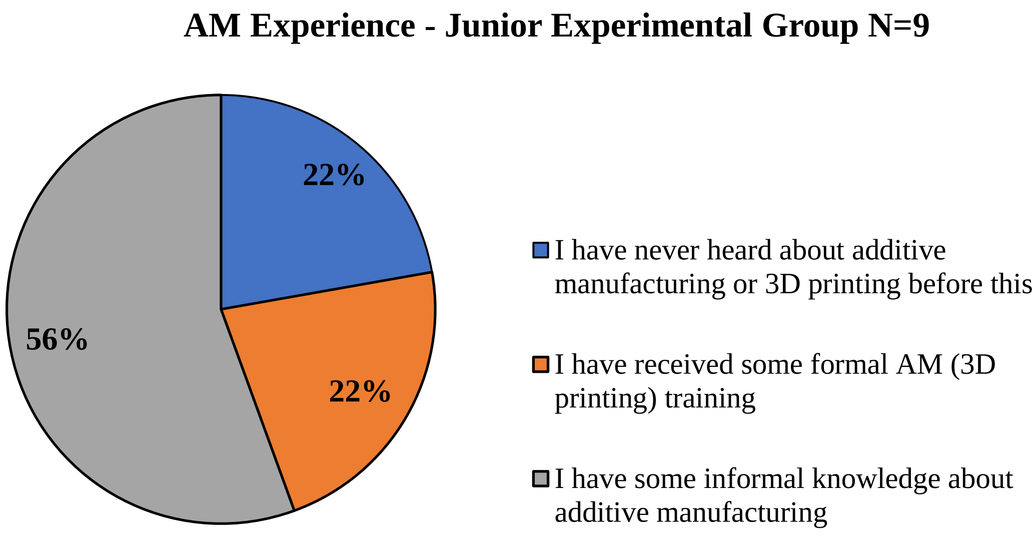


Figure 30. AM experience of experimental junior group.

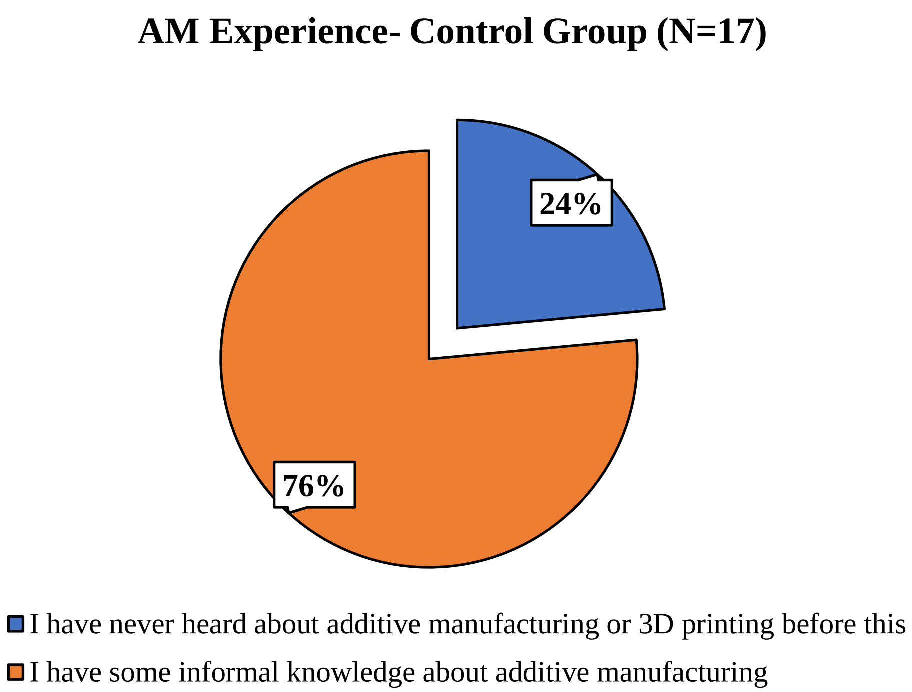


Figure 31. AM experience of the junior control group

Figure 30 and 31 shows that the participants in each group have a similar background in additive manufacturing.

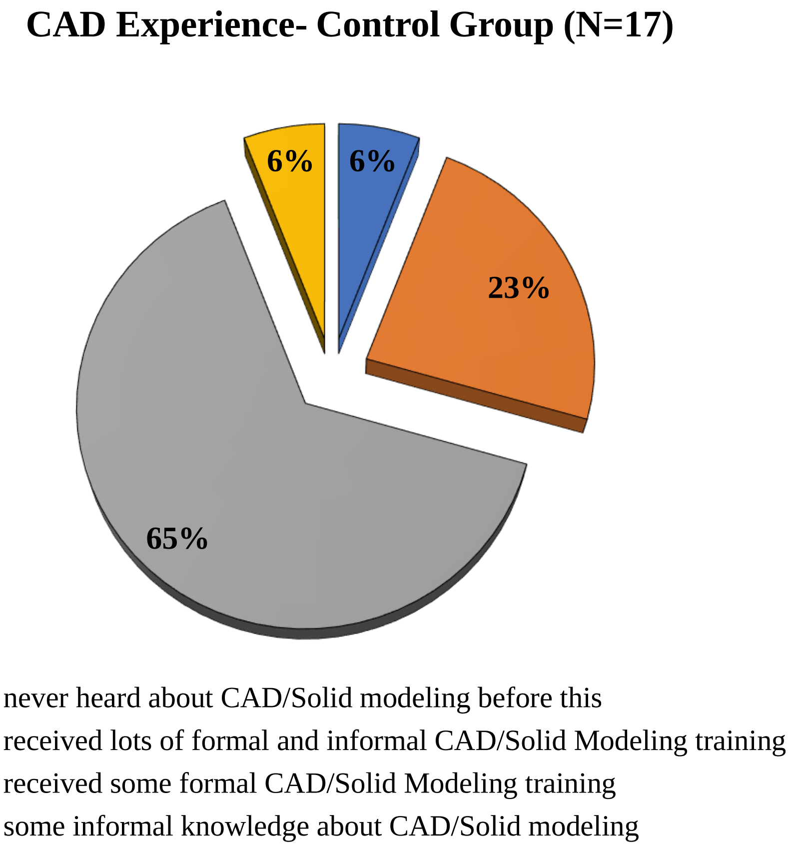


Figure 32. CAD experience of the control group.

Figure 32 shows that 65% of the participants in the control group claim to have received some formal CAD/solid modeling training.

Figure 33 shows that 56% of the participants in the experimental junior group claimed to have received many years of formal and informal CAD/solid modeling compared to the control group, with 23% of the participants with formal and informal CAD/solid modeling experience.

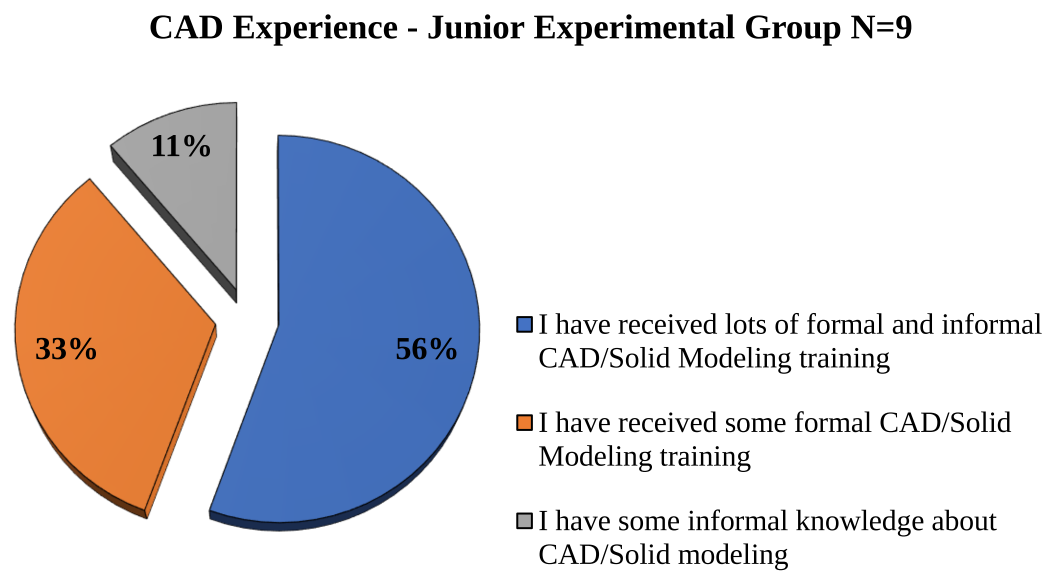


Figure 33. CAD experience of the experimental junior group participants.

Figures 34 and 35 show the differences in the groups' DfAM experience. Figure 34 shows that 11% of the junior experimental group participants received some formal DfAM training. Majority of the students in the experimental junior group had no experience in DfAM.

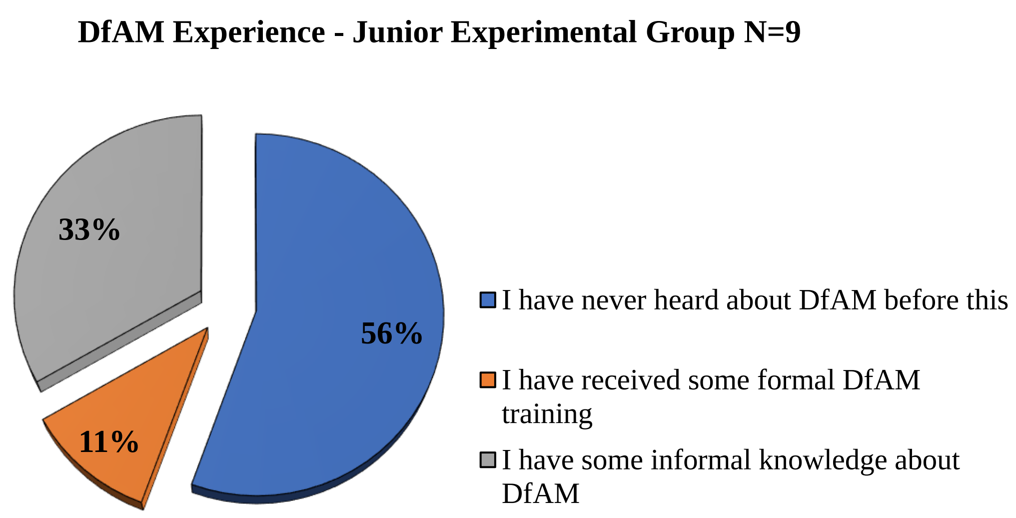


Figure 34. DfAM experience in the junior experimental group.

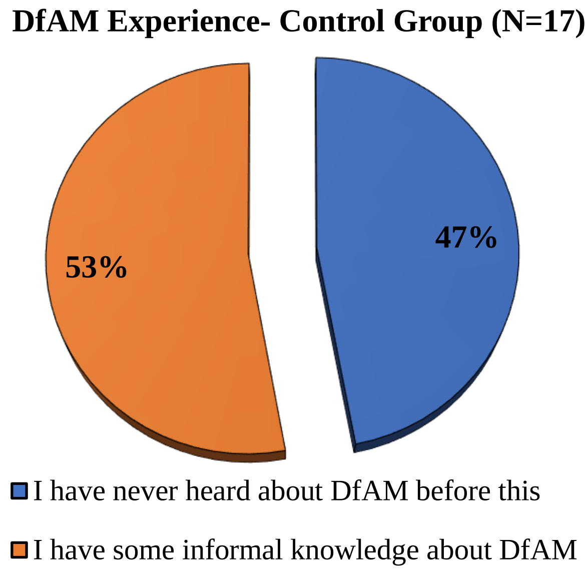


Figure 35. DfAM experience of the junior participants in the control group.

Figure 35 shows that 47% of the participants in the control group had never heard about DfAM compared to 56% of the experimental group participants that fell within the same category.

4.4. Results and Analysis

The results from the pre- and post-DfAM tests, pre- and post-design tasks, and the DfAM self-efficacy pre and post surveys were compiled, evaluated, and analyzed to note changes pre- and post-DfAM training. Research question #1 investigated whether DfAM training improved designers' design outcomes and DfAM self-efficacy. DfAM training improved DfAM self-efficacy and increased the implementation of DfAM considerations in design outcomes. The following sections answer research question #1 and provide details on changes in DfAM self-efficacy, pre- and post-knowledge tests, and design outcomes for the control and experimental groups. The design outcome and DfAM test results from each evaluator were also compared.

4.4.1. DfAM Self-Efficacy: Upper-Level Participants Control versus Experimental Group

Table 8. DfAM self-efficacy scores in the experimental group

PRE SURVEY - Experimental Group (N=21)							
	Scale used for DfAM self-efficacy						
DfAM Self Efficacy Concepts	Never heard about it	Have heard about it but not comfortable explaining it	Have heard about it but not comfortable applying it	Could apply it but not comfortable regularly integrating it within my design process	Could feel comfortable regularly integrating it with my design process	Pre Intervention DfAM SE Total Score	Average DfAM SE Score
O1	2	12	18	24	5	61	61.4
O2	1	8	21	16	25	71	
O3	2	12	9	16	30	69	
O4	6	16	12	4	10	48	
O5	4	14	12	8	20	58	
R1	4	14	12	12	15	57	56.2
R2	6	8	15	8	20	57	
R3	6	12	6	8	25	57	
R4	7	10	9	20	5	51	
R5	8	6	6	4	35	59	

Table 8 shows the results the DfAM SE calculations from the pre-survey information of the experimental group. The O1 concepts received a total score of 61 which is a result of an aggregate score from each participant's response. For example, in the O1 DfAM SE concept category, there were 2 responses of 'Never heard about it' which was calculated by multiplying 2*1 = 2. There were 6 responses of 'Have heard about it but not comfortable explaining it' (6*2 = 12). There were 6 responses of 'Have heard about it but not comfortable applying it' (6*3=18). There were 6 responses of 'Could apply it but not comfortable regularly integrating it in my design' (6*4=24), and there was 1 response of 'Could feel comfortable regularly integrating it within my design process' (1*5=5). The pre-intervention DfAM SE total score was calculated in O1 by adding

2+12+18+24+5 totaling 61. This was repeated for the remaining DfAM SE concepts. An average of the opportunistic and restrictive scores were recorded pre- and post-intervention.

The total DfAM SE scores for the experimental group and the control group can be seen in Table 9.

Table 9. Control and experimental group total DfAM self-efficacy scores

DfAM Self Efficacy Concepts	Experimental			Control		
	Pre-Training DfAM SE Total Score	Post-Training DfAM SE Total Score	% Increase DfAM SE Total Score	Pre-Training DfAM SE Total Score	Post-Training DfAM SE Total Score	% Increase DfAM SE Total Score
O1	61	95	**56 %**	45	46	**2 %**
O2	71	91	**28 %**	49	46	**6 %**
O3	69	91	**32 %**	44	45	**2 %**
O4	48	79	**65 %**	41	38	**7 %**
O5	58	84	**45 %**	37	40	**8 %**
R1	57	91	**60 %**	39	39	**0 %**
R2	57	87	**53 %**	36	39	**8 %**
R3	57	83	**46 %**	37	40	**8 %**
R4	51	86	**69 %**	32	34	**6 %**
R5	59	89	**51 %**	37	34	**8 %**

Table 9 shows that there was an increase in the participants' restrictive and opportunistic DfAM SE scores post-intervention. The highest percent difference of 69 % between pre- and post-DfAM SE in the experimental group is noted in the R4 category which addressed obtaining the required surface quality. The lowest percent difference of 28% in the experimental group was seen in the O2 category which addressed combining multiple parts into a single product or assembly.

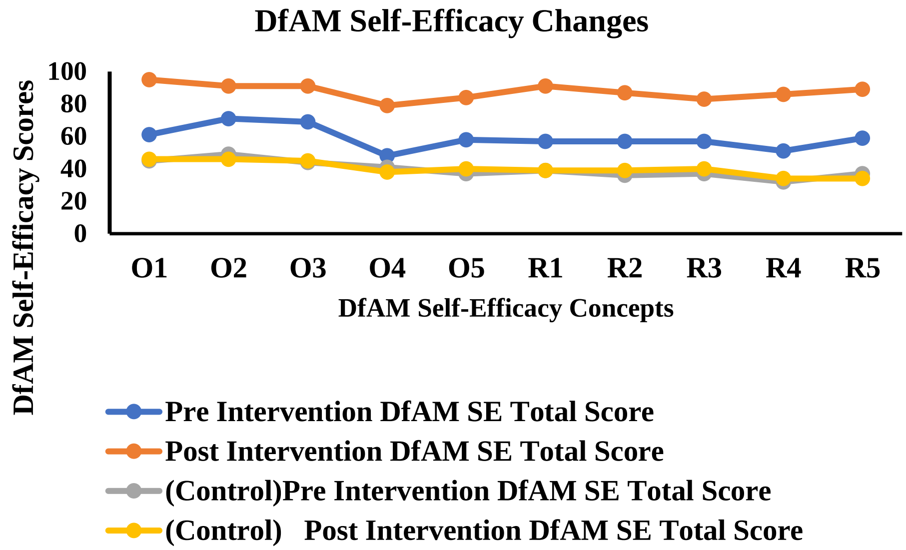


Figure 36. Comparison of the DfAM SE changes between the control group and experimental groups.

Figure 36 highlights that categories O4 (embedding components such as circuits in parts) and R4 (obtaining the required surface quality) were the lowest scoring areas that need to be addressed in training individuals for DfAM. There was also no significant change in DfAM SE in the control group as anticipated. It can be observed from figure 36 that both the control group and the experimental group have a higher DfAM self-efficacy in opportunistic concepts than in restrictive DfAM self-efficacy concepts. Also noteworthy is the fact that the students in the experimental group had a low DfAM SE in O4 categories just like the student in the control group. The greatest change was seen in the O1 and R4 categories in the experimental group. Overall, there was an increase in all categories of opportunistic and restrictive DfAM concepts post-DfAM training which can be seen in Figure 37.

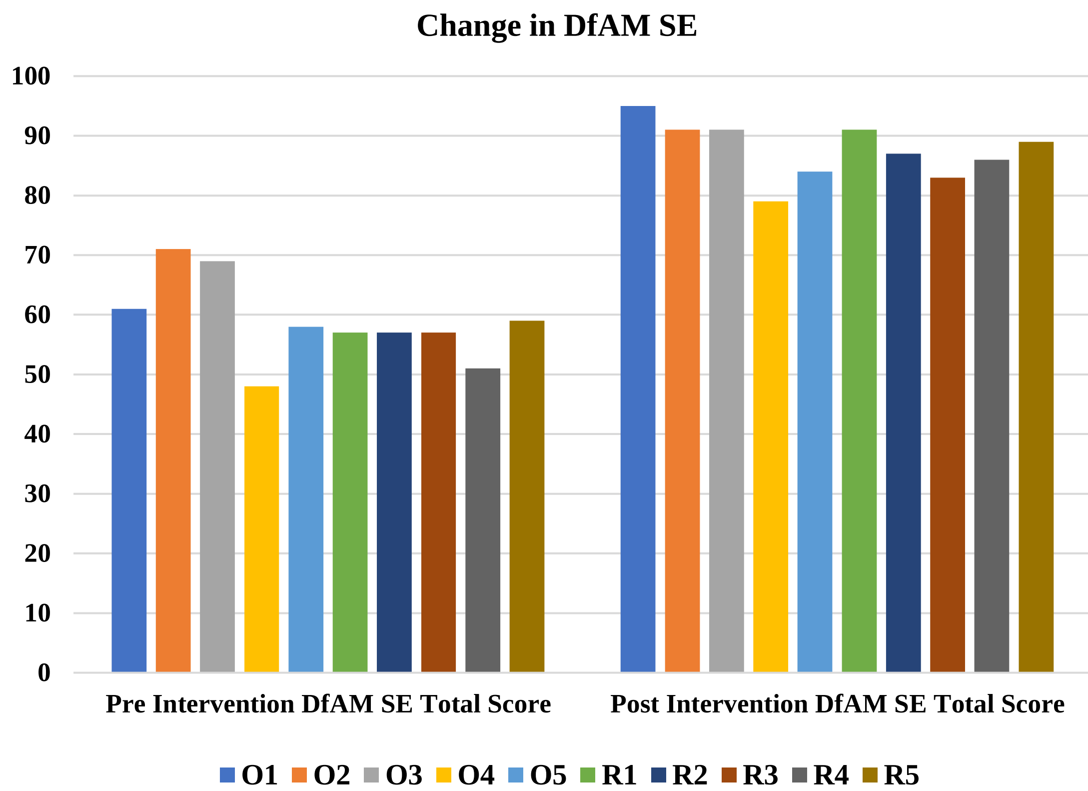


Figure 37. Experimental group DfAM SE changes.

Figures 38 and 39 highlights the change in the experimental groups' DfAM SE before and after DfAM training. The students DfAM SE increased in each category and showed the highest number of participants that have the highest SE in O1 which shows confidence in making products that can be customized for different users. There was an increase in the participants that reported being able to comfortably integrate DfAM concepts in each concept area.

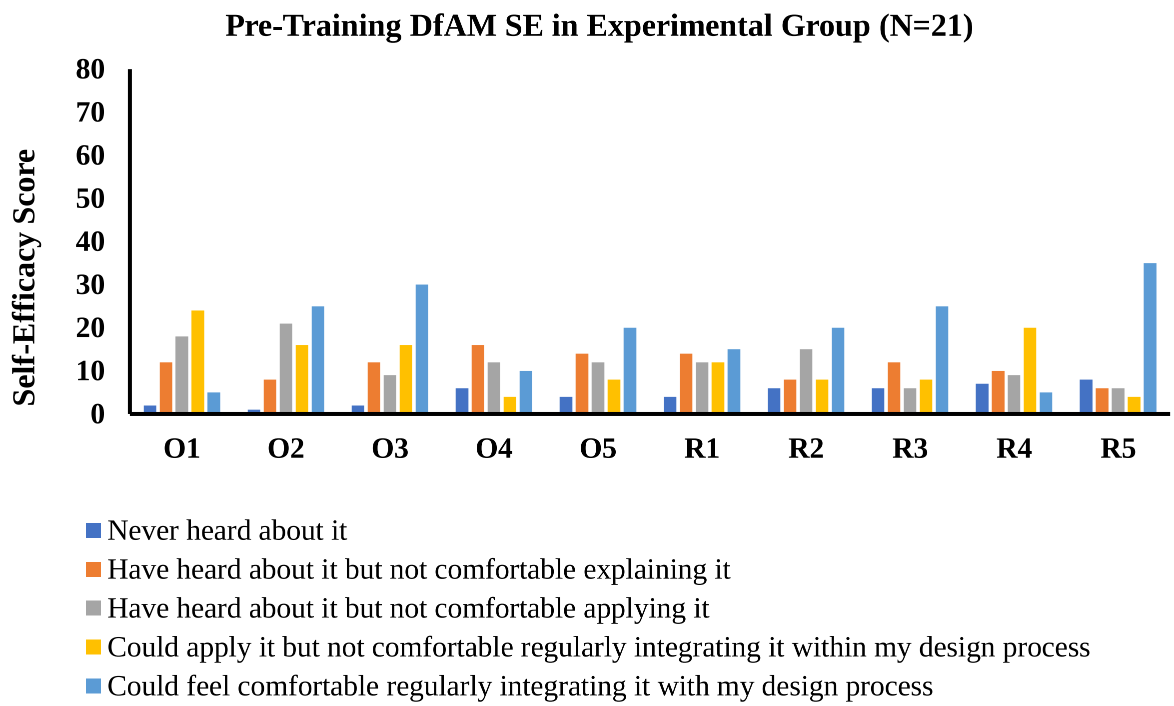


Figure 38. Experimental group DfAM SE changes

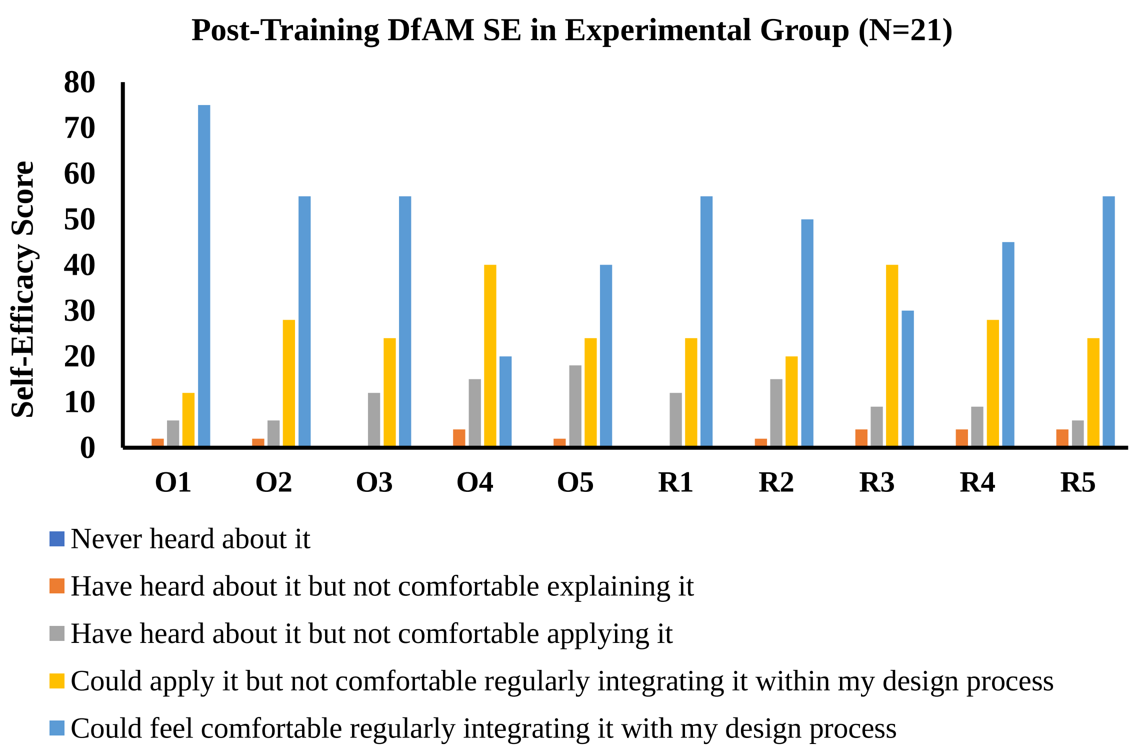


Figure 39. Experimental group DfAM SE changes

4.4.1.1. Analysis of Variance

An analysis of variance (ANOVA) statistical test was completed to analyze the differences between the means of the experimental and control group pre- and post-intervention. The effect of the DfAM training on DfAM SE scores was analyzed. The null hypothesis of the ANOVA is that there is no difference in the mean DfAM SE scores pre-and post-DfAM training. The results shown in Table 10 demonstrate that the experimental group's mean DfAM SE score differed significantly between pre- and post-DfAM training as compared to the control group's DfAM SE that was not significantly different pre and post DfAM training. Since $p<0.5$, the null hypothesis was rejected. It is likely that DfAM intervention training had a significant effect on DfAM self-efficacy ($f(4) = 173.64$, $p=0$). ($S= 5.408$, R-squared (adj)=93% R-squared (predicted) 92.02%). The high R-squared value showed that the model fit the data well. In summary, the statistical test demonstrated that DfAM training had a significant effect on improving students' perception of skills.

Table 10. Results from ANOVA test of DfAM self-efficacy pre and post intervention in control vs. experimental groups

Factors	Mean	Standard Deviation	95% CI
Pre-intervention DfAM SE total	58.80	7.04	(55.33,62.27)
Post – Intervention DfAM SE total	87.60	4.74	(84.13,91.07)
Control Pre DfAM-SE total	39.70	5.06	(36.23, 43.17)
Control Post DfAM SE total	40.10	4.41	(36.63,43.57)

4.4.1.2. Tukey post-hoc test

A Tukey post-hoc test that runs pairwise comparison among each of the groups shows that there was a significant difference between the pre- and post-DfAM SE scores. The test revealed significant pairwise differences between the experimental and control groups' DfAM SE scores pre- and post-DfAM training. The Tukey test showed that the means of the pre and post DfAM SE scores from the control group were not significantly different. Figure 40 shows the differences in means between the pre- and post-control and experimental groups.

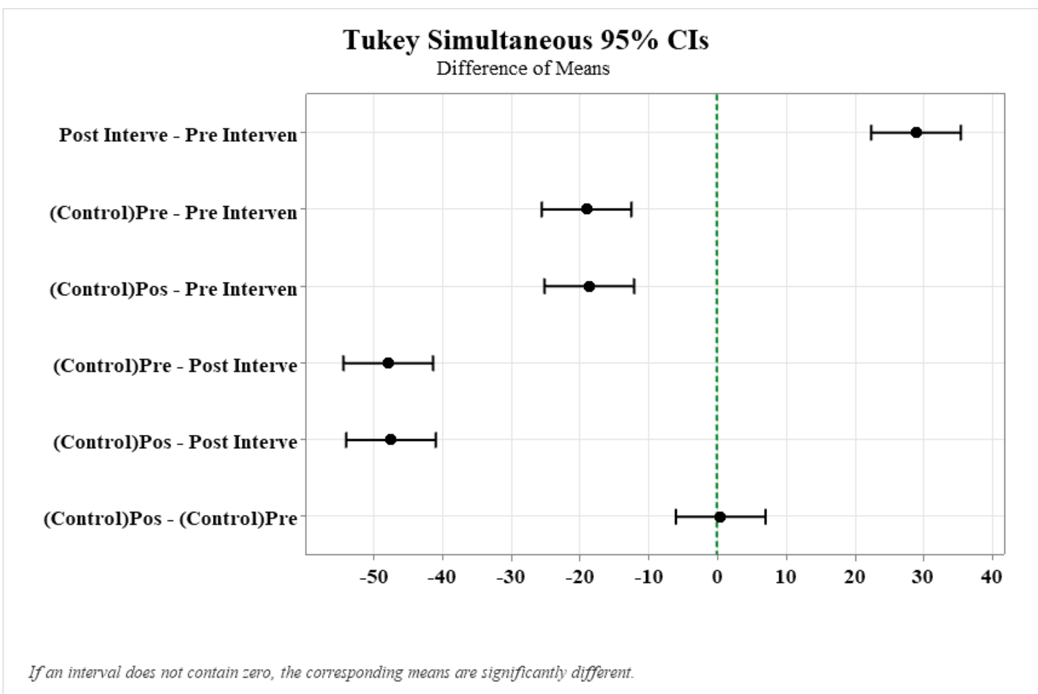


Figure 40. Tukey simulation test results for differences in control and experimental groups.

The difference in mean between the pre- and post-intervention in the experimental group is 28.80 (p=0) compared to a difference in mean of 0.40 (p=0) for the control group. Figure 40 also shows that the confidence intervals of the experimental group and the control group are significantly different.

4.4.1.3. Two Sample T-test

A two sample T-test (α=0.05) was performed to check if the population means were equal between the pre- and post-DfAM SE scores in the control and the experimental groups. Results showed the population differences in SE DfAM scores in the experimental group (t (10) = 10.73, p=0) and in the control group (t (10) = 0.19, p=0.853). The T-tests showed that there was a significant difference between the pre- and the post-DfAM SE concepts in the experimental group. The difference between the pre- and post-DfAM self-efficacy was not significant in the control group. Figure 41 and 42 show the difference between the outcomes of DfAM SE in both groups.

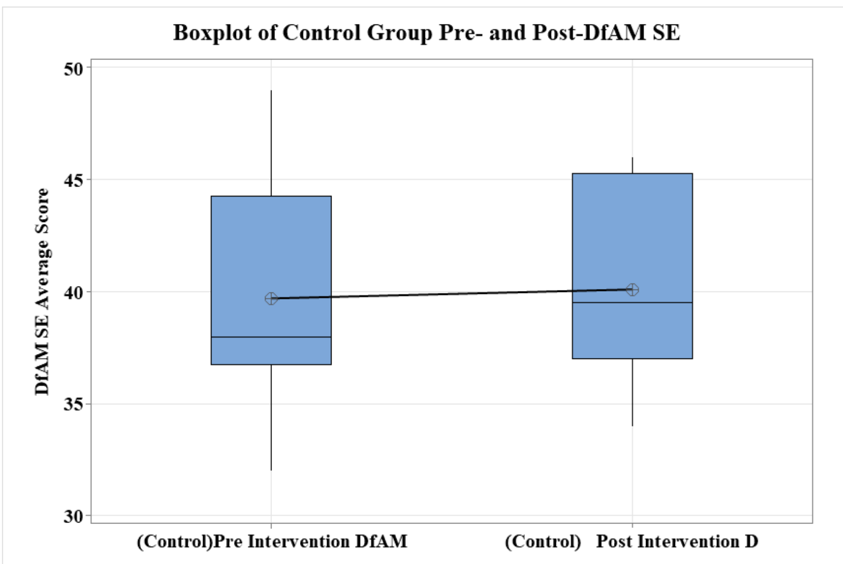


Figure 41. Pre- and post-DfAM self-efficacy comparison in the control group.

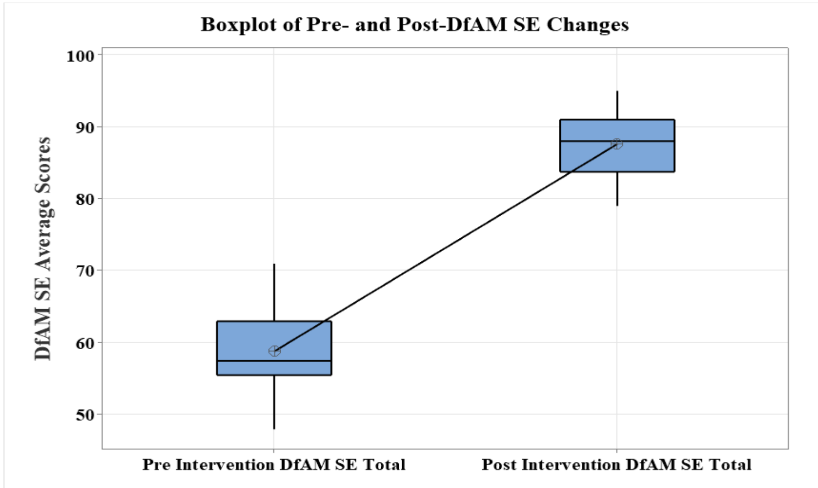


Figure 42. Pre- and post-DfAM self-efficacy in the experimental group.

4.4.1.4. Mann-Whitney Tests

A Mann-Whitney test was used to determine the differences between median DfAM self-efficacy scores pre- and post-intervention to compare the control and experimental groups' DfAM SE changes. The median DfAM self-efficacy score pre-intervention was 57.5 compared to a median of 88.0 in the post-DfAM self-efficacy ($p=0$, 95% CI for $\eta 1-\eta 2 = (-34, -22)$, $W=55$). Since the p-value was 0 which is less than the significance level of 0.05, the null hypothesis was rejected. The conclusion can be made that the median pre and post intervention DfAM self-efficacy were significantly different in the experimental group. In the control group, the median DfAM self-efficacy score pre-intervention was 38.0 compared to a median of 39.5 in the post DfAM self-efficacy ($p=0.65$, 95% CI for $\eta 1-\eta 2 = (-5, -4)$, $W=98.5$). A p-value of 0.65 shows that the null hypothesis was accepted. The conclusion can be made that the median pre- and post-intervention DfAM self-efficacy were not significantly different in the control group.

The median opportunistic DfAM self-efficacy score pre-intervention in the experimental group was 61 compared to a median score of 91 in the post-opportunistic assessment ($p<0.012$, 95% CI for $\eta 1-\eta 2 = (-43, -13)$, W= 15). The results also show that there was a significant difference between the medians of the pre- and post-intervention opportunistic DfAM self-efficacy scores. The median restrictive DfAM self-efficacy score pre-intervention in the experimental group was 57 compared to a median of 87 in the post-restrictive score ($p<0.012$, 95% CI for $\eta 1-\eta 2 = (-36, -26)$, W= 15). The results also show that there is a significant difference between the medians of the pre- and post- intervention restrictive DfAM self-efficacy scores. These results highlight that there was an overall increase in DfAM self-efficacy after DfAM training. There was a greater change in restrictive DfAM self-efficacy in the experimental group after DfAM training compared to opportunistic DfAM self-efficacy.

Analysis of the control group's average DfAM self-efficacy scores showed that there is no significant difference between the DfAM SE scores pre- and post-DfAM training. The median opportunistic DfAM self-efficacy score pre-intervention in the control group was 44 compared to a median of 45 in the post-opportunistic score ($p<0.917$, 95% CI for $\eta 1-\eta 2 = (-8, -7$, W= 26.50). The median restrictive DfAM self-efficacy score pre-intervention in the control group was 37 compared to a median score of 39 in the post-restrictive group ($p<0.531$, 95% CI for $\eta 1-\eta 2 = (-7, -3)$, W= 24).

4.4.1.5. Junior Students DfAM SE Changes

The data detailed in the previous section required taking a closer look at the junior participants' DfAM SE changes since the control group consisted mostly of students in the junior year of study. There were 16 participants (female – N=10, males – N=6) in the control group and 9 junior students in the experimental group. 33 % of the participants in the experimental group were female (N=4) and 67% are males (N=5). In the control group, 59% of the participants were females and 35% of the participants were males.

Figures 43 and 44 show that there was a significant increase in the DfAM SE in the junior experimental group compared to the control group that showed no significant change in DfAM SE after training.

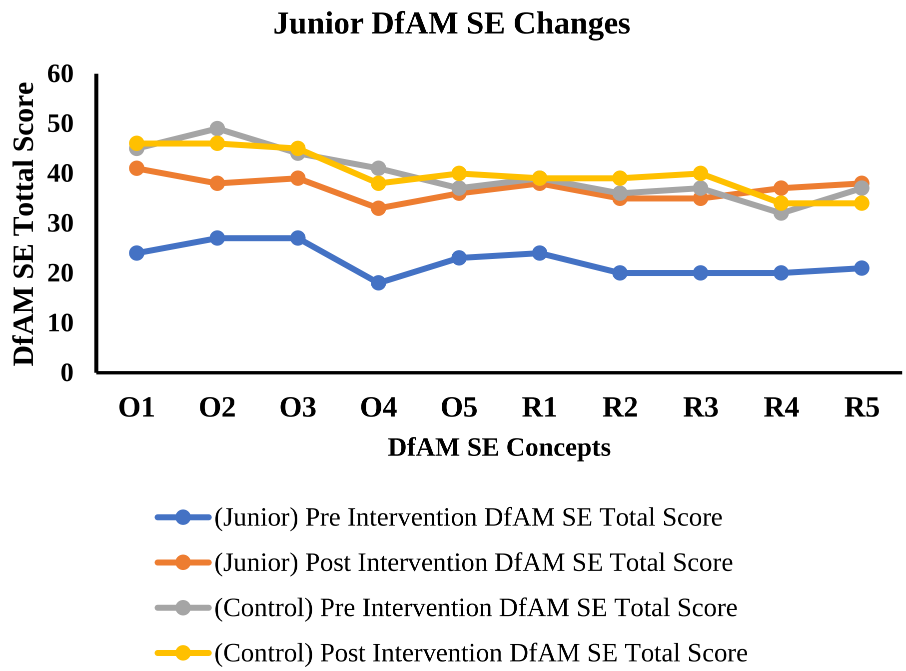


Figure 43. DfAM SE changes in the junior experimental group.

The average DfAM SE score prior to training in the experimental group was 22.4+/-3.10 compared to an average score of 37.0+/-2.31 (t (10) = 11.95, p=0, α=0.05) after training. The control group's average DfAM SE total score was 39.70+/-5.06 compared to an average DfAM SE total score of 40.10+/-4.41 (t (10) = -0.19, p=0.853, α=0.05) that was collected from the information in the post-survey that each participant filled out.

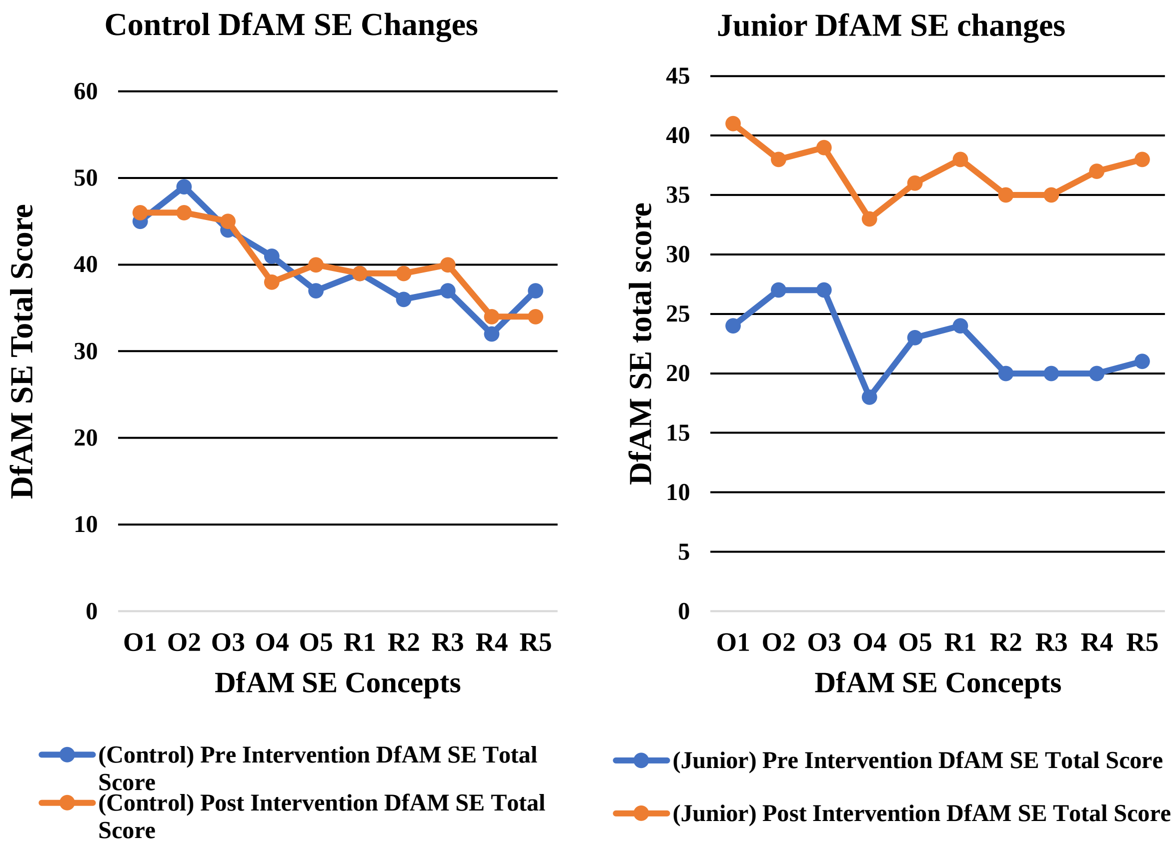


Figure 44. Pre- and post-DfAM SE after DfAM training in the junior group

Table 11. DfAM SE Changes in Junior experimental versus control group.

	Experimental			Control		
DfAM Self Efficacy Concepts	(Junior) Pre Intervention DfAM SE Total Score	(Junior) Post Intervention DfAM SE Total Score	(% Change) Junior Experimental DfAM SE Total Score	(Control) Pre Intervention DfAM SE Total Score	(Control) Post Intervention DfAM SE Total Score	(% Change) Control DfAM SE Total Score
O1	24	41	**70%**	45	46	**2%**
O2	27	38	**40%**	49	46	**6%**
O3	27	39	**44%**	44	45	**2%**
O4	18	33	**83%**	41	38	**7%**
O5	23	36	**56%**	37	40	**8%**
R1	24	38	**58%**	39	39	**0%**
R2	20	35	**75%**	36	39	**8%**
R3	20	35	**75%**	37	40	**8%**
R4	20	37	**85%**	32	34	**6%**
R5	21	38	**80%**	37	34	**8%**

Table 11 shows that differences in DfAM SE changes in the control versus the experimental group. The highest percent change in DfAM SE after training was seen in the R4 category which requires confidence in obtaining the desired surface quality. The lowest percent change was seen in the O2 and O3 categories which required confidence in combining multiple parts into a single product or assembly and designing parts with complex shapes and geometries. There was no change in the DfAM SE of the control group which did not receive DfAM training.

4.4.1.5.1. Mann-Whitney tests

Mann-Whitney tests were used to compare the medians of the experimental and control DfAM SE changes from the Juniors in the sample. The control group's median pre-DfAM SE total score was 38 compared to a post- DfAM SE score of 39 ($p=0.65$, 95% CI for $\eta 1-\eta 2 = (-5, 4)$, $W=98.5$) showing that there was no significant difference in DfAM SE pre-and post-scores. The experimental group's median pre- DfAM SE total score was 22.0 compared to a post-score of 37.5 ($p=0$, 95% CI for $\eta 1-\eta 2 = (-18, -12)$, $W=55$). These results show that the junior participants in the control group had a slightly higher DfAM SE than the junior students in the experimental group. The control group believed in their DfAM abilities more than the experimental group showing a possibility of over-confidence.

4.5. DfAM Self-Efficacy Changes and Gender in Upper-Level Engineering Students

DfAM SE changes were investigated to single out areas of low DfAM SE pre and post DfAM training in male and female participants. Educational activities can be planned based on the information gathered on DfAM student self-efficacy.

4.5.1. Experimental Group

Figure 45 shows the increase in DfAM self-efficacy for male and female participants. Female participants in the experimental group (N=5) showed a greater percent change in DfAM self-efficacy after DfAM training compared to male participants (N=16). The larger percent change is due to the lower starting values for females. The females in the experimental group showed an initial lower DfAM self-efficacy than the males. After DfAM training, the females' DfAM SE increased but was not higher than the DfAM self-efficacy shown in males after training. The average pre-DfAM SE for females was 8.5+/-2.45 compared to an average of 18.6+/-1.5 post-DfAM SE.

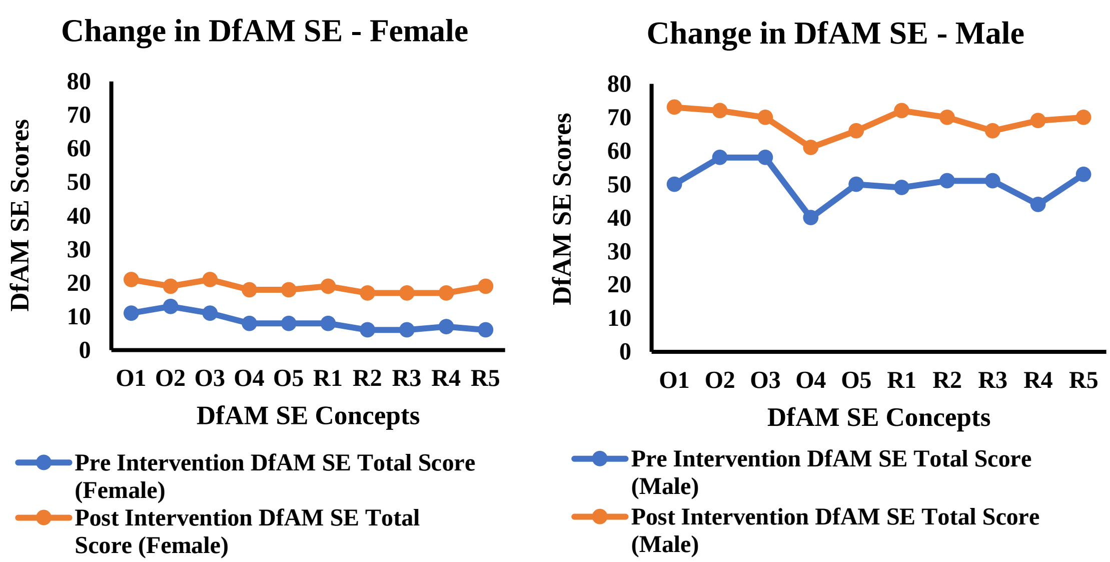


Figure 45. Changes in DfAM SE and gender in the experimental group.

Table 12 highlights the differences between male and female DfAM self-efficacy changes after DfAM training.

Table 12. Changes in DfAM self-efficacy (Experimental group)

DfAM SE Concepts	Pre-DfAM SE Total (Female N=5)	Post-DfAM SE Total (Female N=5)	Pre-DfAM SE Total (Male, N=16)	Post-DfAM SE Total (Male, N=16)	% Change (Female)	% Change (Male)
O1	11	21	50	73	90.91	46.00
O2	13	19	58	72	46.15	24.14
O3	11	21	58	70	90.91	20.69
O4	8	18	40	61	125	52.50
O5	8	18	50	66	125	32.00
R1	8	19	49	72	137.50	46.94
R2	6	17	51	70	183.33	37.25
R3	6	17	51	66	183.33	29.41
R4	7	17	44	69	142.86	56.82
R5	6	19	53	70	216.67	32.08

Females showed the highest percent change in the R5 category which required accommodating for minimum and maximum feature size permitted in a process. Males showed the highest percent change in the R4 category of accommodating desired surface roughness in parts. The greatest change in DfAM self-efficacy for the females was shown in the restrictive DfAM SE concept areas. The lowest percent change in DfAM self-efficacy for males was shown in the opportunistic O3 DfAM SE concept area of designing parts with complex shapes and geometries which illustrated their confidence in this area. Males had a greater DfAM self-efficacy pre-DfAM training in the O2 and O3 categories which are combining multiple parts into single products for assembly and designing parts with complex shapes and geometries. Similarly, females demonstrated the highest DfAM SE in the O2 category before DfAM training. In addition, females showed the highest DfAM SE average score in the O3 category post DfAM training compared to the male participants that demonstrated the highest post-DfAM SE in O1 (making products that can be customized for each user) post-intervention. All participants in the experimental group showed a higher DfAM SE in the opportunistic DfAM SE concept areas.

4.5.2. Control Group

Figure 46 shows that there is no significant difference between the control group's pre-and post-DfAM SE. Female participants in the control group (N=10) showed a greater percent change in DfAM self-efficacy after taking the post-intervention survey compared to male participants (N=6). Students in the control group did not receive DfAM training.

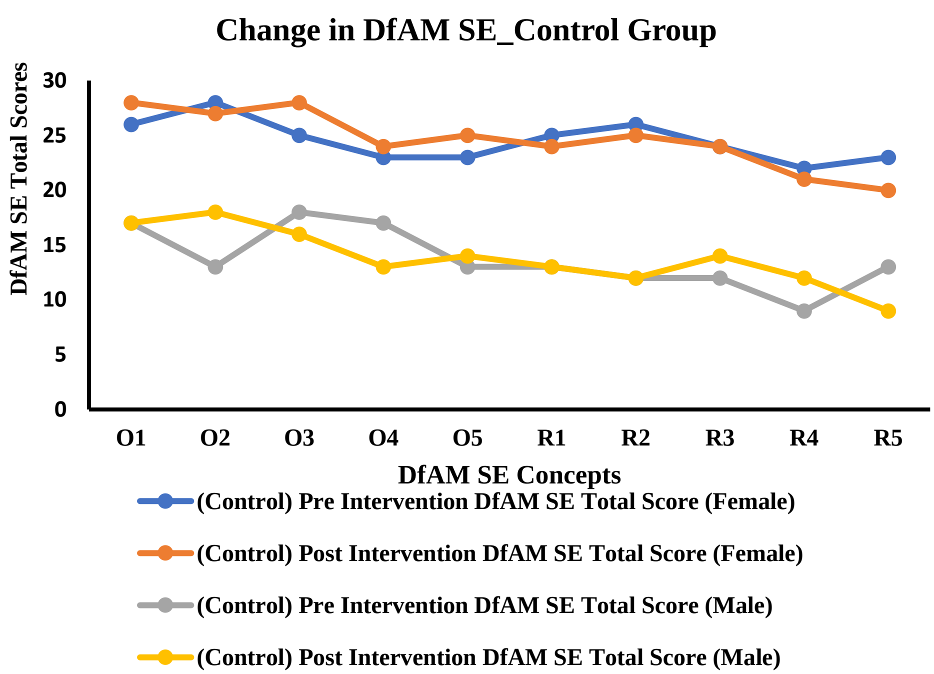


Figure 46. Changes in DfAM SE and gender in the control group.

Figures 47 and 48 shows that there was no significant change in all the DfAM self-efficacy concept areas for the control group.

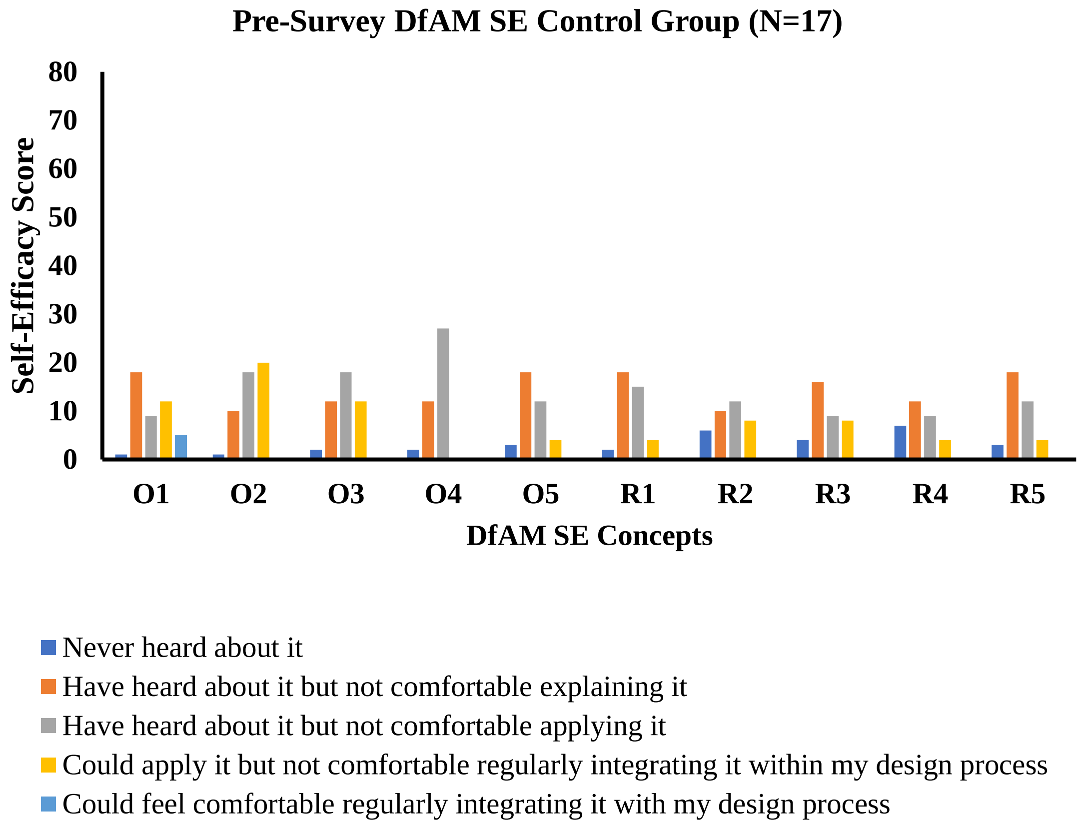


Figure 47. Changes in DfAM SE and gender in the control group.

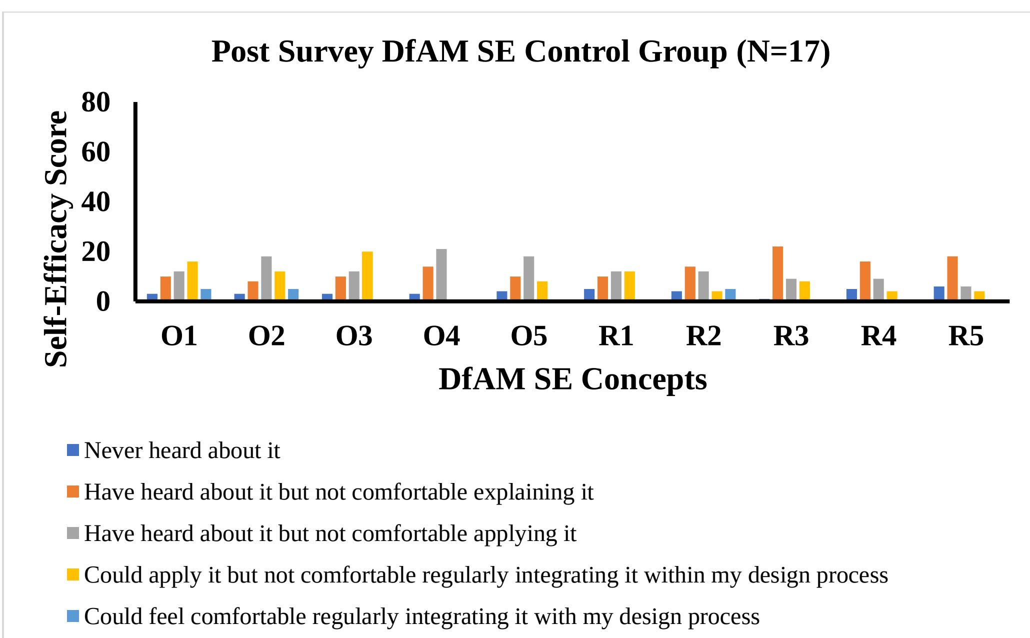


Figure 48. Changes in DfAM SE and gender in the control group.

Table 13 reinforces that there was no significant difference between the pre-and post-DfAM SE scores in males and females in the control group pre-and post-DfAM training.

Table 13. Changes in DfAM self-efficacy (Control group)

DfAM SE Concepts	Pre-DfAM SE Total (Female) (N=10)	Post-DfAM SE Total (Female) (N=10)	Pre-DfAM SE Total (Male) (N=6)	Post-DfAM SE Total (Male) (N=6)	% Change (Female)	% Change (Male)
O1	26	28	17	17	7.69	0
O2	28	27	13	18	-3.57	38.46
O3	25	28	18	16	12	-11.11
O4	23	24	17	13	4.34	-23.52
O5	23	25	13	14	8.69	7.69
R1	25	24	13	13	-4	0
R2	26	25	12	12	-3.84	0
R3	24	24	12	14	0	16.66
R4	22	21	9	12	-4.54	33.33
R5	23	20	13	9	-13.04	-30.76

The female students from the control group reported the highest DfAM SE in the category O2 before DfAM training which was the same for the females in the experimental group. The male students in the control group showed the highest DfAM SE prior to DfAM training in the O3 category which again was the same case in the males in the experimental group. Female students had the lowest DfAM self-efficacy prior to DfAM training in the R4 category.

4.5.3. Junior Students DfAM Changes in the Experimental Group

The changes in DfAM SE pre-and post-DfAM training were noted in the male and female junior students from the experimental group. Figure 49 clearly illustrates that both junior females and males from the experimental group showed an increase in DfAM SE post-DfAM training.

Figure 49 highlights the DfAM SE concepts areas of concern in the students in the junior experimental group.

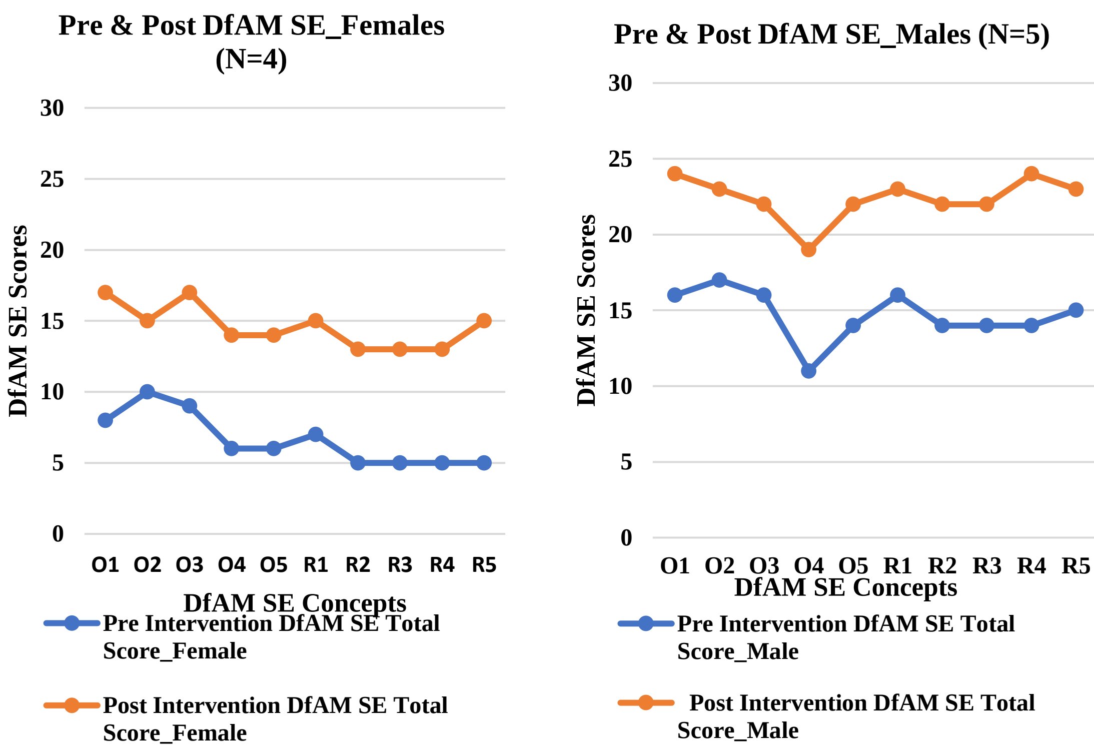


Figure 49. DfAM SE changes in junior males and females from the experimental group.

Both males and females in the experimental group showed an increase in their DfAM self-efficacy after training. The females in the group showed a lower DfAM self-efficacy after DfAM training than males. Both males and female groups show a higher opportunistic DfAM self-efficacy than restrictive DfAM concepts. The O4 DfAM concept area is the lowest scoring DfAM category for the male group. The female students showed the greatest increase in DfAM SE in all the concepts areas (O1-O5 and R1-R5) which can be seen in Table 14.

Table 14. Changes in DfAM self-efficacy (Junior experimental group)

DfAM SE Concepts	Pre-DfAM SE Total (Female) (N=4)	Post DfAM SE Total (Female) (N=4)	Pre-DfAM SE Total (Male) (N=5)	Post DfAM SE Total (Male) (N=5)	% Increase (Female)	% Increase (Male)
O1	8	17	16	24	**1.13**	**0.50**
O2	10	15	17	23	**0.50**	**0.35**
O3	9	17	16	22	**0.89**	**0.38**
O4	6	14	11	19	**1.33**	**0.73**
O5	6	14	14	22	**1.33**	**0.57**
R1	7	15	16	23	**1.14**	**0.44**
R2	5	13	14	22	**1.60**	**0.57**
R3	5	13	14	22	**1.60**	**0.57**
R4	5	13	14	24	**1.60**	**0.71**
R5	5	15	15	23	**2.00**	**0.53**

In addition, Table 14 shows that both males and females had the highest DfAM SE in the O2 category pre DfAM training. Females showed the lowest DfAM SE in the restrictive DfAM categories (R1-R5) prior to DfAM training. Females demonstrated the highest DfAM SE total score in in the categories O1 & O3 post-DfAM training. Males showed the highest DfAM SE total score in the O1 and R4 categories post-DfAM training. The highest percent increase was seen in the O4 category in the male group compared to the female group which showed the highest percent increase in the R5 category. Both groups showed the lowest percent increase in the O2 category pre-and post-DfAM training.

4.5.3.1. Mann-Whitney Test: Experimental group junior males and females

Mann-Whitney tests were used to compare the medians of the male and female junior year students in the experimental group DfAM SE changes. The junior female students' median pre-DfAM SE total score was 6 compared to a post-DfAM SE score of 14.5 ($p=0$, 95% CI for $\eta1-\eta2 = (-10, -6)$, $W=55$) showing that there was a significant difference in the DfAM SE pre-and post-scores. The junior male students' median pre-DfAM SE total score was 14.5 compared to a post DfAM SE score of 22.5 (p=0, 95% CI for $\eta 1-\eta 2$ = (-9, -6), W=55) showing that there was again a significant difference in DfAM SE pre-and post-DfAM training.

4.5.3.2. Analysis of Variance: Experimental group junior males and females

Table 15 shows that the mean DfAM SE scores were significantly different after DfAM training in both males and females.

Table 15. Results from ANOVA test (Male and Female DfAM self-efficacy)

Factors	Mean	Standard Deviation	95% CI
Female Pre-intervention DfAM SE total	6.6	1.84	(5.56, 7.64)
Female Post – Intervention DfAM SE total	14.6	1.51	(13.55, 15.64)
Male Pre DfAM-SE total	14.7	1.70	(13.66, 15.74)
Male Post DfAM SE total	22.4	1.43	(21.36, 23.44)

Figure 50 shows that there was an increase in both groups' DfAM SE pre-and post-DfAM training. The box plot graphs show that female participants' DfAM SE total score was like the male participants' pre-intervention DfAM SE. Since $p<0.05$, the null hypothesis was rejected. The results demonstrated that DfAM intervention training has a significant effect on DfAM self-efficacy (f (4) = 157.21, p=0). (S= 1.63, R-sq(adj)=92.32% R-sqd (pred) 91.24%). The high R-squared value showed that the model fit the data well.

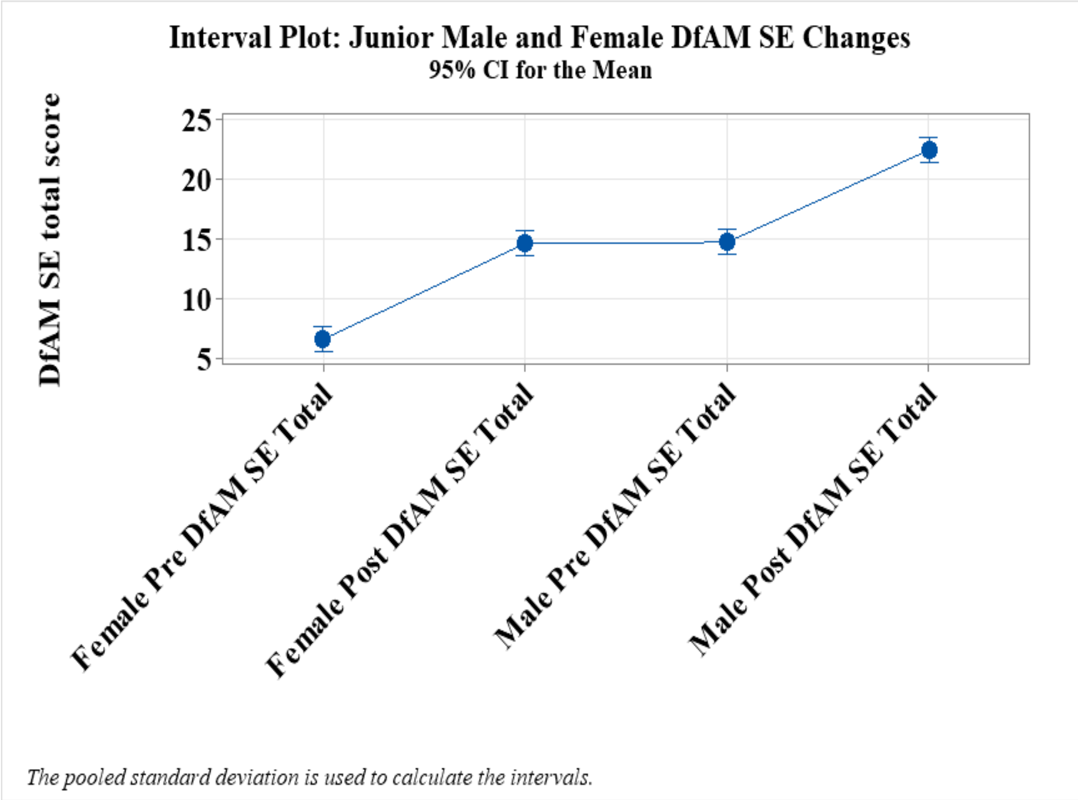


Figure 50. DfAM SE changes in junior males and females.

4.6. Pre and Post DfAM Tests: Control versus Experimental Group

The pre- and post-DfAM tests were assessed before and after DfAM training intervention to investigate whether participants' knowledge of AM and DfAM principles improved after DfAM training. The scores of 16 participants from the control group and 21 participants from the experimental group were compared pre- and post-DfAM training. The scores from four evaluators show that there was a significant increase in AM and DfAM knowledge post-DfAM training.

Table 16 shows the results from all the evaluators which highlights that there was a significant change in test scores-and post-DfAM training.

Table 16. Pre- and post-DfAM test results.

	Control (N=16)			Experimental (N=21)		
	Average Pre-Test Score	**Average Post-Test Score**	**P-value (α=0.05)**	**Average Pre-Test Score**	**Average Post-Test Score**	**P-value (α=0.05)**
Evaluator 1	14 +/-0.08	13+/-0.05	0.621	31+/-0.18	65+/-0.23	0
Evaluator 2	15+/-0.07	17+/-0.06	0.355	30+/-0.16	51+/-0.18	0
Evaluator 3	8+/-0.05	7+/-0.03	0.38	25+/-0.17	44+/-0.21	0.004
Evaluator 4	18+/-0.08	17+/-0.07	0.91	37+/-0.22	63+/-0.21	0

Figures 51 to 55 show a comparison of the scores the 4 evaluators assigned to the participant's pre- and post-tests in the control and experimental group. Figures 51 and 55 show that the evaluators scores of the experimental tests from the control group did not change significantly on the post-DfAM tests. Figures 51-55 show that the evaluators' ratings of experimental group's post-DfAM test scores increased.

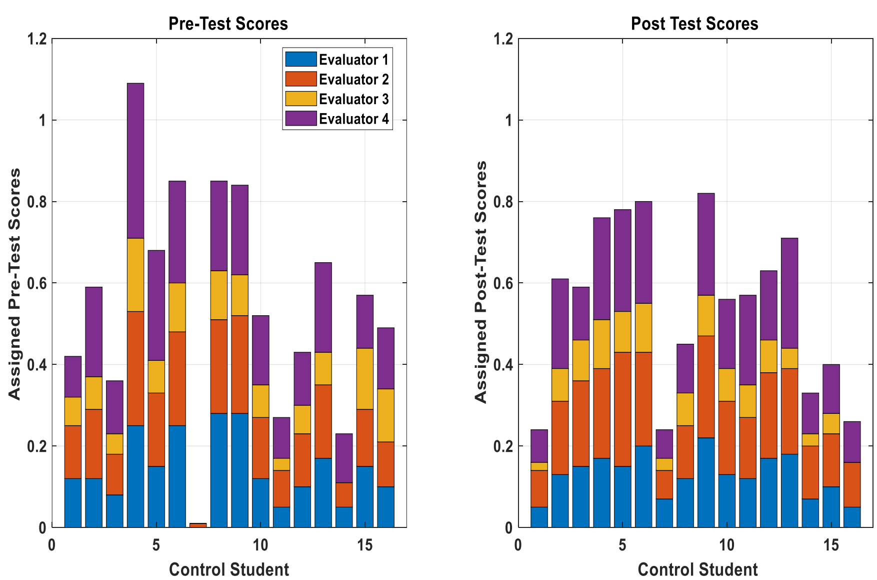


Figure 51. Evaluator scoring of control pre- and post-DfAM tests.

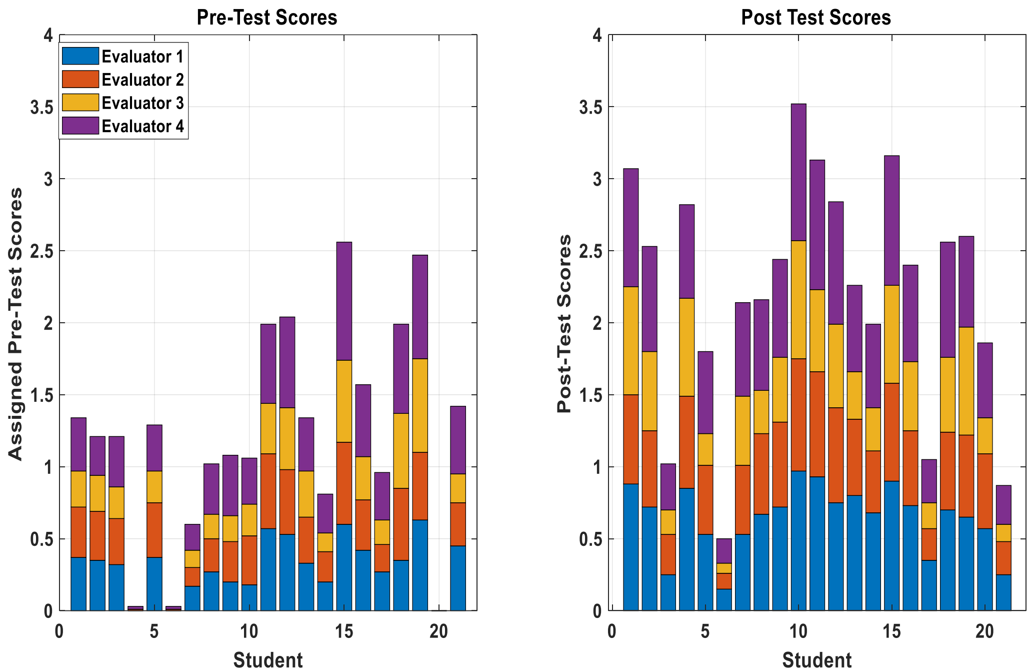


Figure 52. Evaluator scores of the experimental group pre- and post-DfAM test scores.

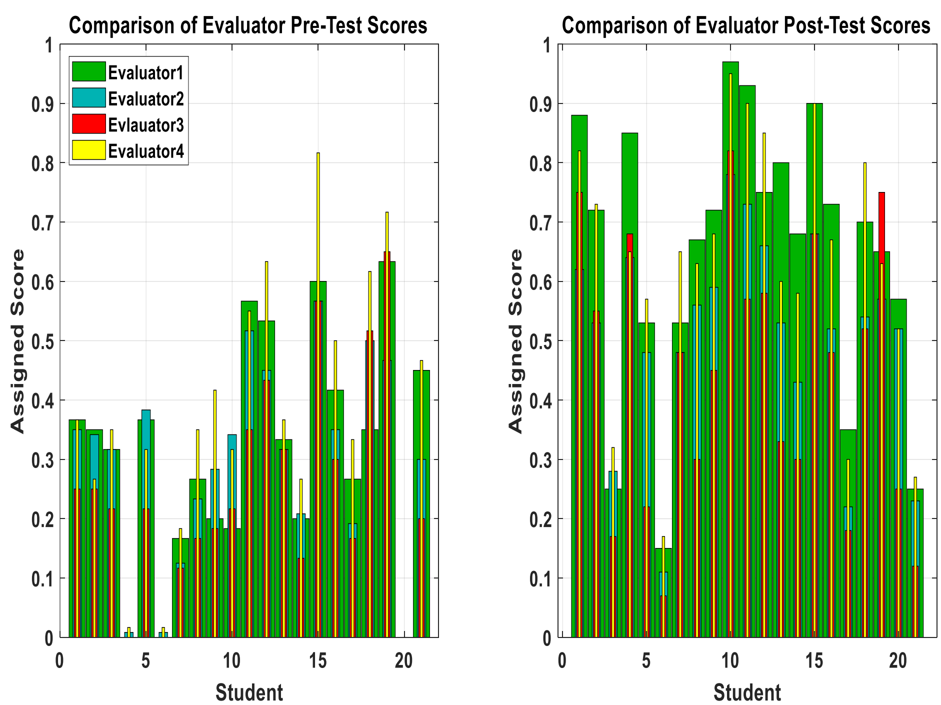


Figure 53. Comparison of evaluator scoring of the experimental group's pre- and post-test.

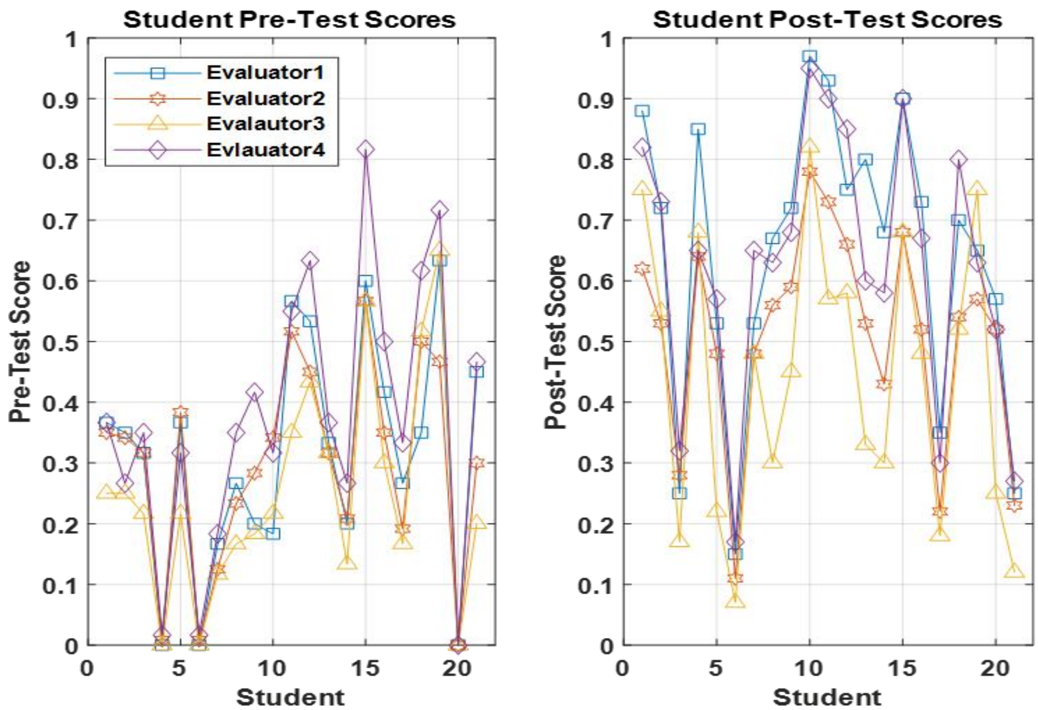


Figure 54. Experimental group pre- and post-test scoring.

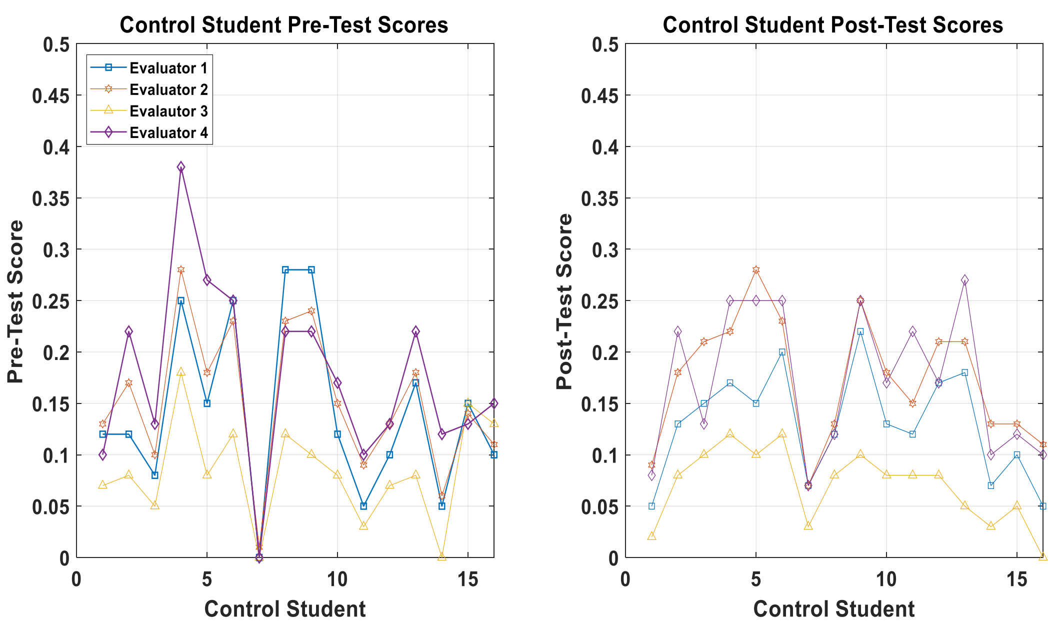


Figure 55. Evaluator scoring of the control group pre- and post-test.

Figure 56 reinforces the hypothesis that DfAM training increases participant's DfAM test scores after DfAM training. Students' scores increased after the training workshop. The experimental group's tests scores increased significantly after DfAM training compared to the control group's test scores that did not increase the second time the DfAM test was taken without training.

4.6.1. Item Analysis of Evaluator Scores

An item analysis was performed on the evaluators' scores to ensure that the evaluations consistently measured participant performance pre-and post-DfAM test.

Pre-DfAM Scoring			
	Evaluator 1	**Evaluator 2**	**Evaluator 3**
Evaluator 2	0.907		
Evaluator 3	0.877	0.900	
Evaluator 4	0.918	0.921	0.936
Post-DfAM Scoring			
	Evaluator 1	**Evaluator 2**	**Evaluator 3**
Evaluator 2	0.949		
Evaluator 3	0.835	0.842	
Evaluator 4	0.933	0.951	0.858

Figure 56. Correlation matrix of evaluator's pre- and post-DfAM scores.

The correlation matrices in Figure 56 show that there are high positive values which indicate that evaluators 1, 2, and 3 scores were highly correlated with each other. Each evaluator gave a higher rating to the pre- and post- AM test and DfAM design scores after training

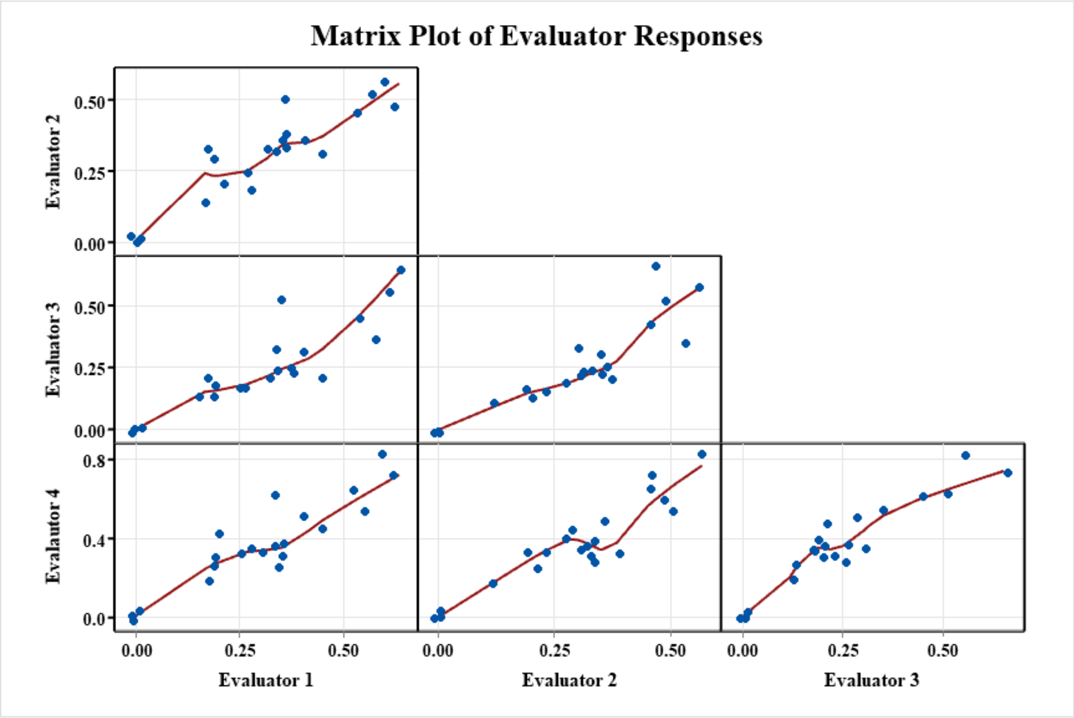


Figure 57. Matrix plot for evaluators' responses pre- and post-DfAM training.

Figure 57 shows that all the evaluators' responses had a positive linear relationship. The overall Cronbach's alpha was 0.972 for the pre-test scores and 0.966 for the post-test scores which indicates that the evaluator responses measured the same characteristics. There was a high level of internal consistency among the evaluators' ratings of the pre-and post-DfAM and AM tests.

The evaluators' responses were checked for inter-rater reliability. It was found that there was 14% agreement between each evaluator's ratings of the pre- and post-tests. This can be attributed to improper use of the pre- and post-test rubric since no rating training was offered. Evaluators' feedback on the test items mentioned the rigor of the test as well as the length and number of parts in the test. The pre- and post-DfAM tests must be altered in future iterations of the study to include multiple choice elements and questions that ask for one target versus multi-part questions.

4.6.2. Junior Group AM & DfAM Pre & Post Test Score Comparison

A closer look at the junior students in the experimental group shows that there was an improvement in scores on the DfAM test after DfAM training. The experimental group's pre-test scores improved after DfAM training. A comparison can be made between the experimental group and the control group showing that there was no significant change in DfAM test scores in the control group. This is highlighted in Figure 58.

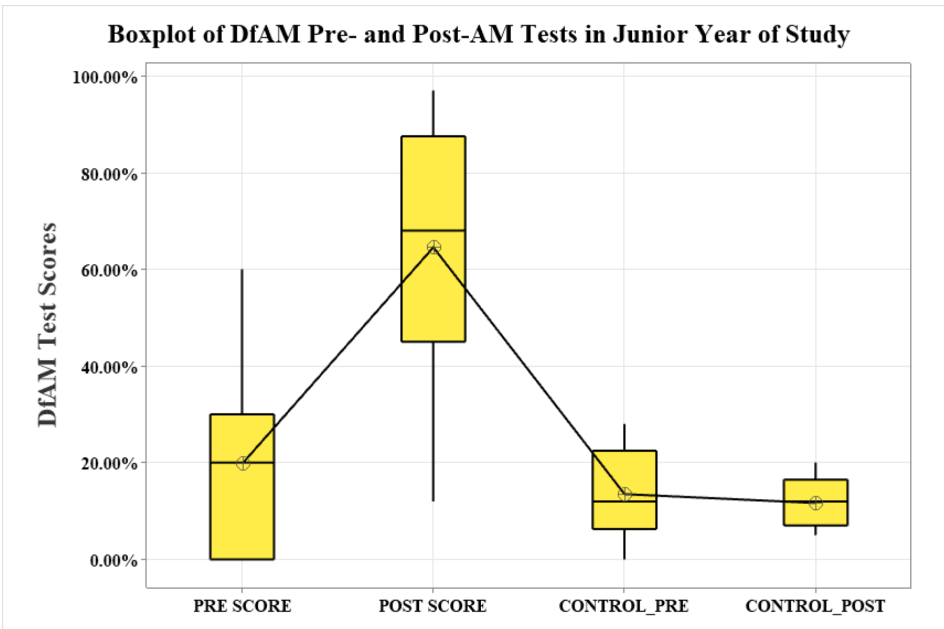


Figure 58. Boxplot of DfAM pre- and post-test scores in the control and experimental group.

The experimental group and the control group's pre-tests scores were significantly similar while the post-test scores of the experimental group were significantly higher than the starting pre-test scores. This is highlighted by the results of the one-way ANOVA that was performed on the four factors: 1) pre-test scores from the experimental group, 2) post-test scores of the experimental group, 3) pre-test scores of the control group, and 4) the post-test of the control group.

4.6.2.1. Analysis of Variance – Junior DfAM Pre & Post Test

Table 17. ANOVA results of Junior DfAM pre- and post-tests

Factor	N	Mean	Standard Deviation	95% CI
EXP_PRE-SCORE	9	0.1978	0.1943	(0.0876, 0.3080)
EXP_POST-SCORE	9	0.6456	0.2740	(0.5353, 0.7558)
CONTROL_PRE	12	0.1350	0.0871	(0.0395, 0.2305)
CONTROL_POST	12	0.1167	0.0500	(0.0212, 0.2121)

The null hypothesis of the ANOVA is that there is no difference in the mean DfAM pre- and post-test scores after DfAM training. The results in Table 17 show that the experimental group's mean DfAM post-test score differed significantly to the pretest scores. The control group's pre- and post-test scores were not significantly different before and after DfAM training. Since p=0, the null hypothesis was rejected. In summary, DfAM intervention training had a significant effect on DfAM pre- and post-tests in the junior test group (f (4) = 22.55, p=0). (S= 0.163, R-sq (adj)=61.19% R-sqd (pred) 54.77%).

4.6.2.2. Tukey Simultaneous Tests for Differences of Means

The Tukey pairwise comparison results described in Table 18, show that the means of the post-test scores of the experimental group were significantly different than that of the pretest and post-test of the control group of junior students as well as the experimental pre-test scores. The junior experimental group's pre-test score were not significantly different than that of the junior control group's pre- and post-test scores. This shows that both groups started at the same content knowledge level prior to the DfAM training.

Table 18. Difference in means of control vs. experimental pre- and post-test

Difference of Levels	**Difference of Means**	**SE of Difference**	**95% CI**	**T-Value**	**Adjusted P-Value**
POST SCORE – PRE-SCORE	0.4478	0.0770	(0.2409, 0.6547)	5.82	0.000
CONTROL_PRE – PRE-SCORE	-0.0628	0.0720	(-0.2563, 0.1307)	-0.87	0.819
CONTROL_POST – PRE-SCORE	-0.0811	0.0720	(-0.2746, 0.1124)	-1.13	0.676
CONTROL_PRE – POST-SCORE	-0.5106	0.0720	(-0.7041, -0.3170)	-7.09	0.000
CONTROL_POST – POST-SCORE	-0.5289	0.0720	(-0.7224, -0.3354)	-7.34	0.000
CONTROL_POST - CONTROL_PRE	-0.0183	0.0667	(-0.1975, 0.1608)	-0.27	0.993

4.6.2.3. Paired t-test and Confidence Interval of Junior Experimental Group

Paired t-tests (α=0.05) were performed to compare the DfAM pre- and post-test scores for the junior year experimental group and the control group. Results also show that there was a significant difference in pre- and post-DfAM/AM mean test scores (M=0.447, SD=0.2811, t (8) = -4.78, p=0.001) of the experimental group compared to the control group's pre- and post- DfAM/AM mean test scores (M=0.018, SD=0.0711); t (11) = 0.89, p=0.391) which showed no significant difference in the pre- and post-test scores.

The results suggest that the students that were exposed to DfAM training gained a higher AM and DfAM content knowledge than students that did not experience DfAM training. In summary, DfAM training improves student's DfAM and AM knowledge.

4.7. Pre- and Post-DfAM Design Task Outcome: Control versus Experimental Group

The experimental group and the control group were given a pre- and post-DfAM design task of creating a sketch of a cup and a holder. The experimental group was also asked to create a CAD model pre- and post-DfAM training of the same cup and holder. Three evaluators rated the pre- and post-designs. Two evaluators used the assessment rubric shown in Appendix A. A sample of a student's sketch can be seen in Appendix F.

4.5.1. Control Group

The evaluation of the pre- and post-designs for the control group showed no significant difference based on the pre- and the post-design scores of the evaluators. Evaluator 2 reported the pre-design average score of the control group (N=16) to be 41%+/-0.048 and a post-design score of 38% +/- 0.067. (Student's t-test, t (15) = -1.09, p = 0.286). The average pre-design score for the control group (N=15) evaluated by evaluator 3 was 56.07%+/-9.5 compared to a post-design score average of 59 % +/- 6.2. The estimate of the difference in population means between pre- and post- design scores was 2.93%, Student's t-test, (t (14) = -2.43, p = 0.307).

4.5.2. Experimental Group

Pre- and post-designs from the participants in the experimental group were evaluated by two evaluators. The results from both evaluators showed that there was a significant difference between the pre- and post-design scores after DfAM training.

The results from Evaluator 2 showed an average pre-design score of 51% +/- 7.8 compared to a post-design score average of 63.2% +/- 10.3. (Student t-tests, t (11) = -3.16, p=0.005). The results from Evaluator 3 showed an average pre-design score of 66.2% +/-0.11 and a post-design score of 85.4+/-0.06. (Student t-tests, t (11) = -5, p=0). These results reinforce that design scores increased after DfAM training.

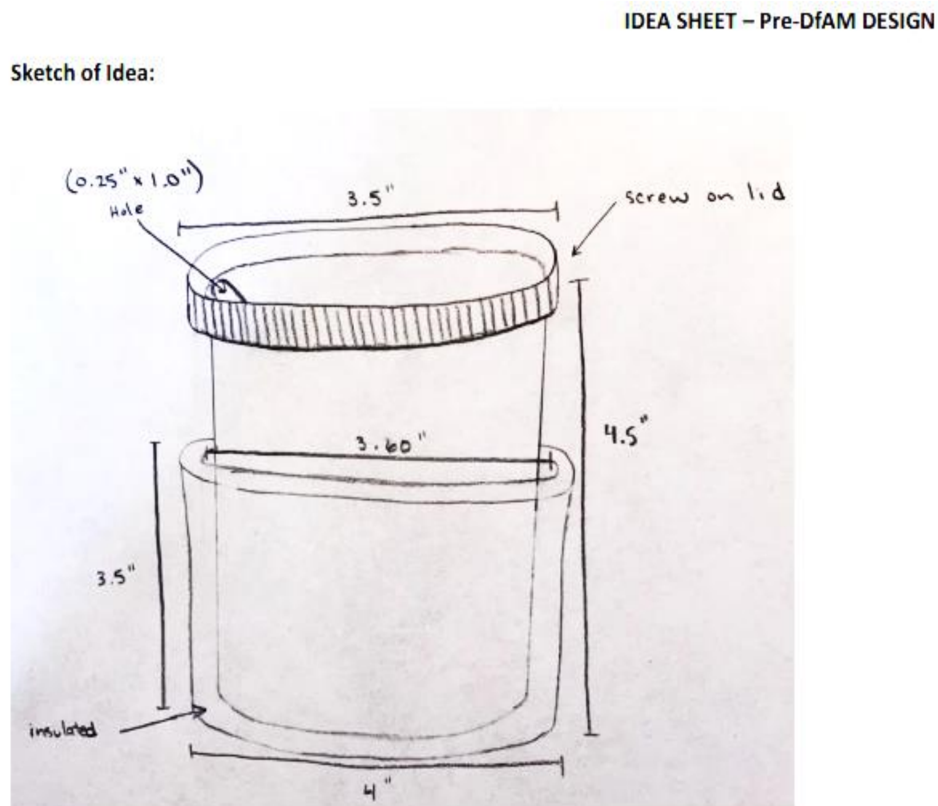


Figure 59. Sample of experimental group participant pre-design outcome.

The design shown in figure 59 was given a pre-intervention score of 64% by evaluator 1 and 58.3% by evaluator 2. The post design shown in Figure 60 was given a post-intervention score of 77.2% by evaluator 1 and a 91.7 % by evaluator 2.

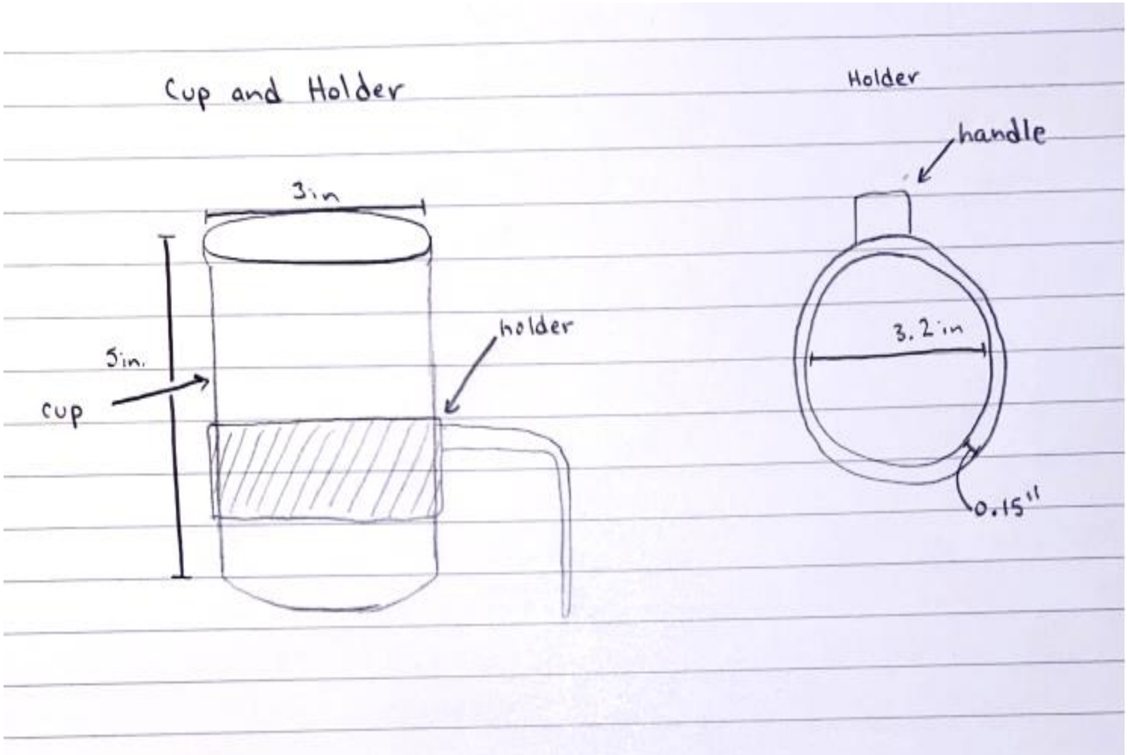


Figure 60. Sample of experimental group participants post-design outcome.

The design shown in figures 59 and 60 show the pre- and post-design outcomes of the same participant. Figure 61 and 62 shows the pre and post intervention designs of another participant's design (sample 2) which was given a 58.3% and 80.6% respectively, from evaluator #1. The pre and post intervention design score was 41% and 71.2% respectively, from evaluator 2.

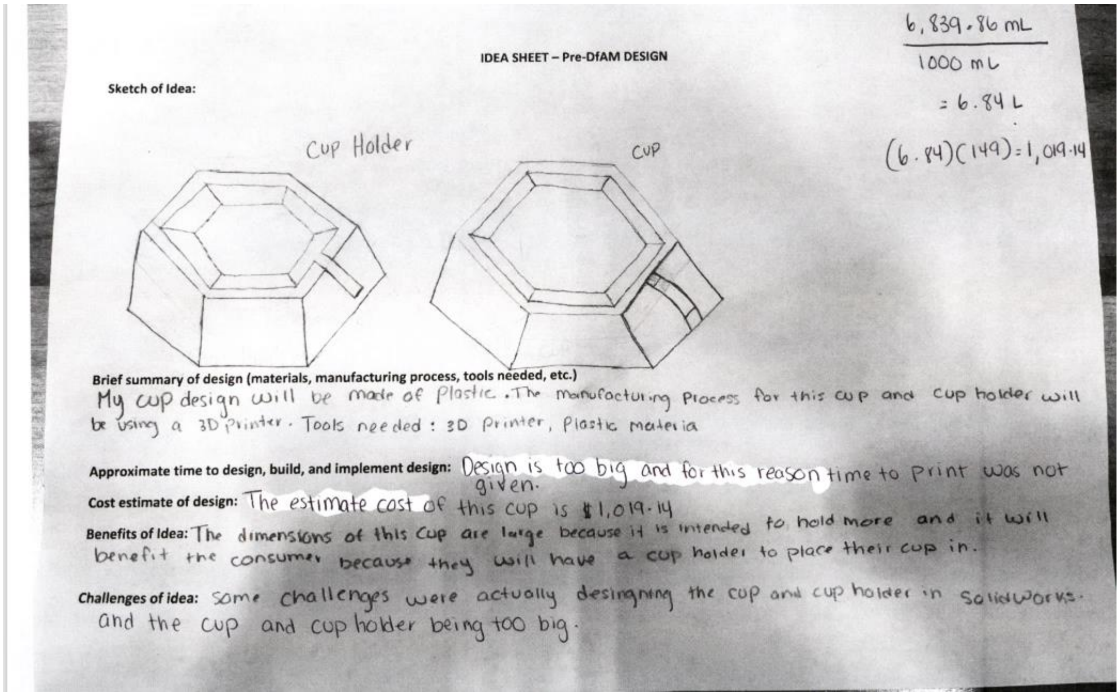


Figure 61. Sample 2 of experimental group participant post-design outcome.

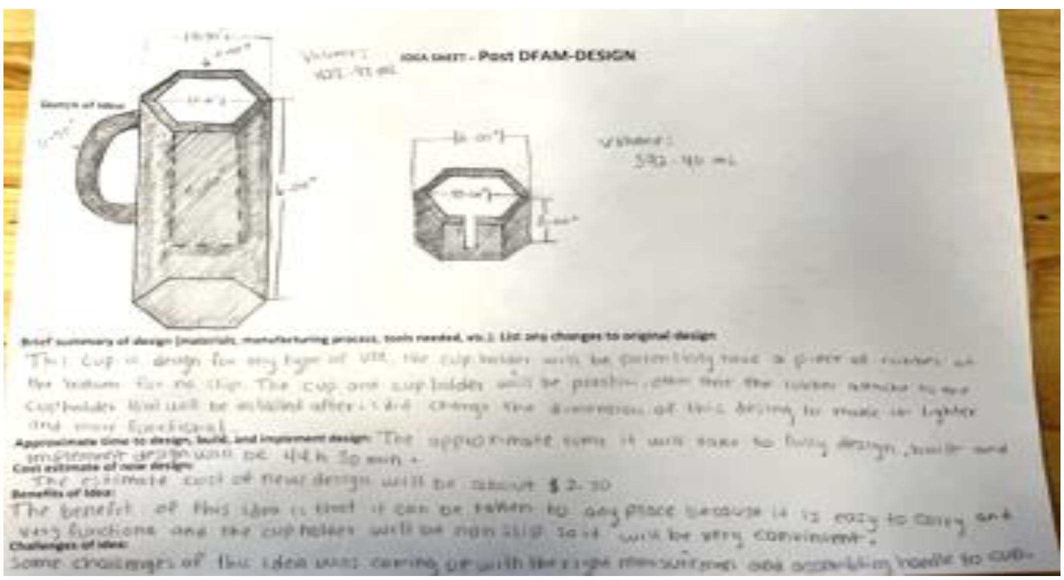


Figure 62. Sample 2 of experimental group participant's post-design outcome.

Figure 61 and 62 shows that the participant from the experimental group considered the cost of the part and re-designed by changing the dimension of the part to use less material which ultimately reduced the total cost of the design.

4.8. Upper-Level Engineering Students AM & CAD Experience on DfAM Outcomes

Research question # 2 sought to investigate the effect of prior AM and CAD experience on pre- and post-tests and design outcomes after DfAM training. I hypothesized that experience in AM, engineering concepts, and CAD will lead to increased scores after DfAM education training.

The following sections describe the data gathered from the experimental and the control groups' pre- and post-tests as well as the pre- and post-design outcomes as it relates to the participant's prior AM and CAD knowledge.

<u>4.8.1. Experimental Group</u>

Figure 63 reveals that the participants that received formal and informal CAD/Solid Modeling training prior to the DfAM workshop showed a higher average AM pre- and post-test score than the participants that had no prior knowledge of CAD/Solid modeling.

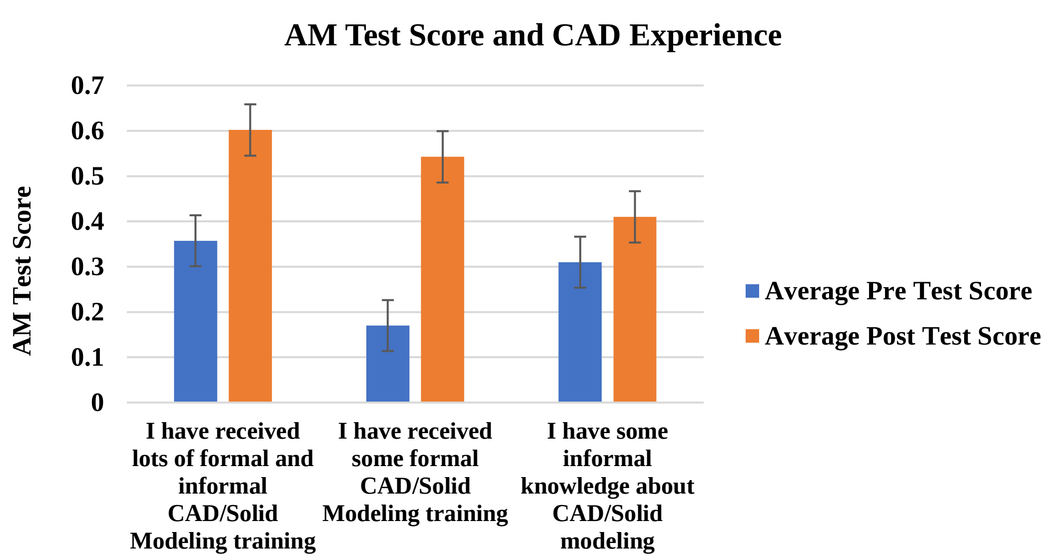


Figure 63. AM pre- and post-test scores and CAD experience.

Participants with a lot of formal CAD training received the highest post-test average of 60% compared to individuals that received some informal CAD training that scored 41% on the post-test. Participants in the group with the most prior knowledge showed a 68 percent change between pre and post-tests while the group with the least formal training showed a 32 percent change in the pre- and post-test scores.

Participants with some informal knowledge about AM showed the highest increase between pre- and post-AM test results. This group had the highest score in the post test. Participants that received a lot of formal and informal AM training showed the least change in pre and post test scores. Participants that had never heard of AM before the training workshop showed a high increase between pre- and post-test scores.

Participants in each category of prior CAD training showed a significant increase in design scores post-intervention. Each group showed similar increases in design score after intervention which is highlighted in Figure 64. Participants that received formal and informal CAD training showed an average pre-design score of 59% +\- 3.9 and a post-design score of 73% +\-4.6. The individuals with some informal CAD training had a slightly lower pre- and post-design scores of 56% and 68%.

Overall, there was an increase in design score after the training workshop which showed the effectiveness of the DfAM training in improving student design outcomes.

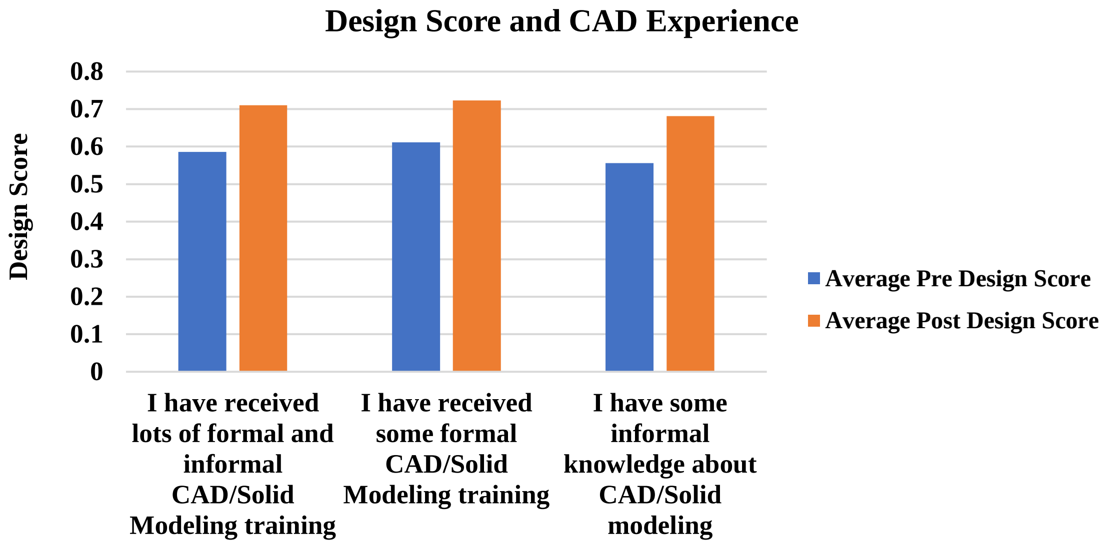


Figure 64. Design scores and CAD experience in upper-level students.

4.8.2. Control Group

24% of the participants in the control group reported no prior knowledge of AM while 76% reported that they have some informal knowledge of AM. There was no significant difference between the test and design scores of the students with prior knowledge and those with some informal knowledge of AM. The students with no prior knowledge averaged 12.6%+/-0.05 on the pre-AM knowledge test and received 14.6% on the post-AM knowledge test (Student's t-test, p=0.42). The group with some informal knowledge in AM received a pre-test average score of 14.2%+/-0.08 and a post-test score of 12.6%+/-0.06 (Student's t-test, p=0.65). The average pre-design score for individuals with no prior experience was 46.8% +/-0.04 compared to a post design score of 48.63 +/-0.08. The individuals with some informal knowledge of AM received an average pre-design score of 48.11%+/-0.05 and an average post-design score of 48.63% +/-0.04.

CAD experience and design and test outcomes were investigated in the control group. There was one participant in the control that had no prior experience with CAD and received an average score of 51.4% for their pre-design score and 54.2% post design. The participant's design scores were similar in all categories of CAD experience. Participants with some formal knowledge of CAD had an average pre and post design scores of 48% +/- 0.04. Participants with many years of formal and informal training in CAD had an average pre-design score of 46.3% +/-0.08 and post design scores of 48.16 % +/- 0.07.

The individuals in the control group that received many years of formal and informal CAD training received an average pre-test score of 20.3% +/-0.07 and an average post-test score of 14.6% +/-0.04. Participants that received some formal prior CAD training scored an average pre-test score of 11.6% +/-0.07 and an average post-test score of 12.9% +/-0.06. The participants in the control group reported a lack of experience with DfAM. 90% of the control group never heard of DfAM prior to participating in the control study.

The results from the comparison of the control and the experimental group's AM and CAD experience on DfAM training outcomes reinforces that DfAM training has a positive effect on design outcomes and AM knowledge. Participants with prior CAD/solid modeling experience showed a higher score in their design outcomes.

The experimental group showed higher pre- and post-test and design scores after DfAM training. The results from the control group showed that CAD experience had no significant impact on design outcomes and AM knowledge after DfAM training. The results from the experimental group showed that participants with formal and informal training in CAD and AM scored higher on the pre- and post-designs than the group of participants that received only informal CAD and AM training prior to the DfAM training workshop.

4.8.3. DfAM Training Outcome and Engineering Major

The planned major of each participant was collected in the pre-survey. Participants in the experimental group included majors such as biomedical (N=1), industrial engineering (N=3), and mechanical engineering (N=7). Figure 65 and 66 shows the planned major and the design and test outcomes pre- and post-DfAM training. Participants with a major in mechanical engineering had the highest average pre- and post-design score of 60%+/-4.8 and 73.3% +\-4.5 respectively. The industrial engineering students scored an average pre-design score of 53.7%+\-3.2 and a post-design score of 71.8%+\-4.2. The biomedical engineering student in the sample who claimed to be an expert in AM, scored 57% on the pre-design task and scored 70.9% on the post-design task. This finding must be investigated further due to the higher number of mechanical engineering students compared to the sample of industrial and biomedical majors of the participants in the study.

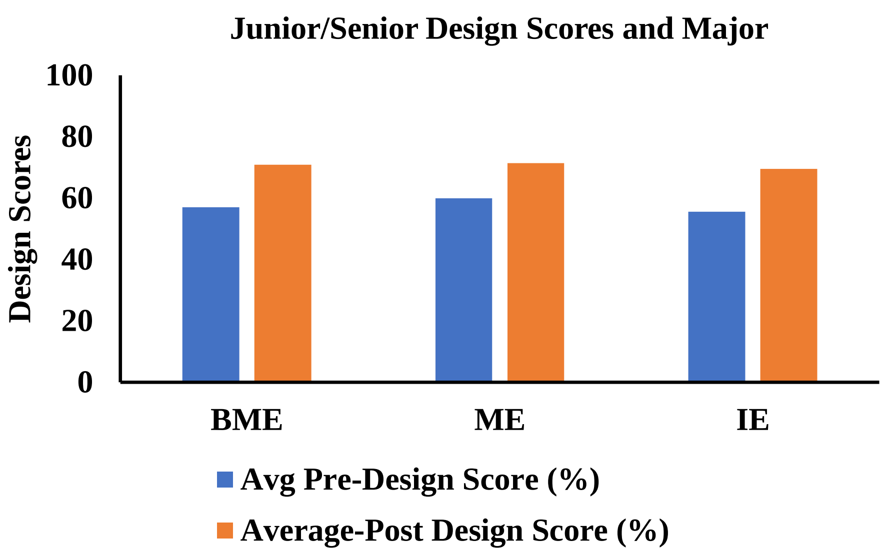


Figure 65. Design scores and major year of study

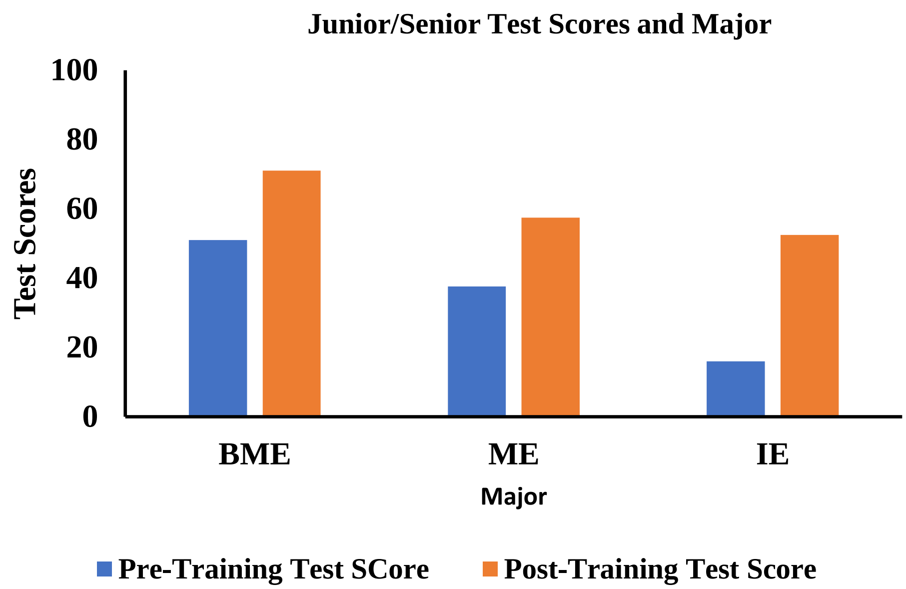


Figure 66. AM test scores and major year of study.

4.9. Engineering experience and DfAM training Outcome

Engineering experience can affect the outcomes after DfAM training. The participants with work experience showed an average pre-design score of 58.38% +/-0.047 and a 71.08%+/-0.053 average post design score. One individual from the experimental group that had no work experience received an average pre-design score of 55.6% and a post-design score average of 71%. There was no significant difference between participants with no work experience versus those that had work experience. The relationship between work experience and design outcome after DfAM training should be explored with a larger sample in future studies.

4.10. Participants' Perceived Usefulness of DfAM Training

The participants' view of the usefulness of the DfAM training workshop was collected during the post-survey. Figure 67 shows that 50% of the participants in the experimental group found the training workshop beneficial while 5% did not find it to be beneficial. 25% of the participants found the DfAM training workshop extremely beneficial.

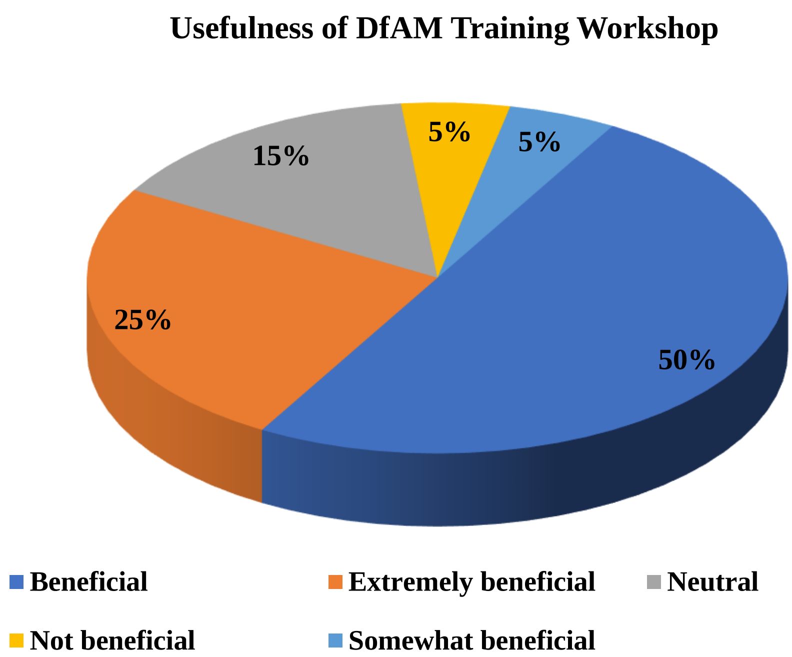


Figure 67. DfAM training workshop usefulness feedback.

Similarly, most of the first-year participants found the DfAM training workshop useful. 63% of first year participants found the DfAM educational intervention beneficial, 12% found it extremely beneficial, 4% found it somewhat beneficial, 18% was neutral while 3% did not find it beneficial.

The DfAM educational intervention along with the assessment tool provided in this work can increase student self-efficacy in both opportunistic and restrictive DfAM. Students can benefit from the workshop as well as the assessment tool to improve designs.

The survey results showed that 21% of first year students in the study had no knowledge of AM or 3D printing. This supports the importance of introducing AM and DfAM concepts early in first year courses to improve student design choices for use in future engineering courses. The results from the study can inform educators' choices in content that must be covered to prepare students with the tools needed to successfully design parts for additive manufacturing.

5. Integrating an instructive DfAM training framework with Technology-roadmapping

This chapter answers the following research question:

Research Question #3: What aspects of DfAM can be emphasized to prepare students for future AM applications? A map of the differences in AM technology process parameters in conjunction with DfAM training can be used to enable designers to manage the available AM technologies that will be encountered in future applications in industry. The available AM technologies' specifications on build orientation, anisotropy, and geometric complexities can be included in DfAM training to equip future designers with the necessary knowledge of the capabilities of each AM process technology.

5.1. Chapter Overview

In recent decades, additive manufacturing (AM) technologies have provided an unprecedented opportunity for designers to overcome the traditional manufacturing limitations and produce complex and novel parts. To harness the many advantages of AM, it is essential for designers to realize the fundamental concepts of design for additive manufacturing (DfAM). In essence, there have been many attempts to provide integrated frameworks for DfAM [59]–[62]. Standardizations and guideline developments are underway to advance opportunistic and restrictive principles of DfAM. There has been a steady increase in the number DfAM publications in the past nine years (with total number of 13,429 and exponential growth rate of 37%) which is an indication of efforts to respond to the DfAM needs. In fact, designers should realize that the design freedom offered by AM comes at a cost of expensive fabrication, unexpected failures, necessary redesign, and inevitable post-processing.

The DfAM objective has been set to efficiently utilize the AM potential and evade the limitations. AM limitations can be classified to design, fabrication process (e.g. machine capacity), limited pool of available materials, and post-processing limitations [63]. It should be emphasized that understanding the fundamentals of DfAM does not eliminate the need for understanding other non-AM manufacturing processes. Moreover, while process simulation for AM technologies is still under development, designers are required to understand the basics of DfAM combined with certain numerical and analytical modeling to produce functional AM components.

When designing for AM, designers should keep in mind the advantages that lead to extensive use of AM in the first place [64]. For instance, lead-time reduction is a potential advantage of AM that part designers might be considering. Other generic and design-related advantages of AM include parts consolidations, optimized geometry, free-form parts, easier design change, reduced tooling, and low-volume manufacturing. Furthermore, traceability and repeatability should be also taken into considerations especially for aerospace parts that need to pass the barrier of certification [65].

There is a strong tendency in academia and professional institutions to expand AM education for young engineers as part of Industry 4.0 framework [3], [10]. Researchers have started working on educational frameworks to produce AM-skilled workforce [53], [66]. In essence, the compound annual growth rate of 21.75% for AM [67] signifies that academic efforts in developing AM educational frameworks is a promising investment. Nevertheless, there has been little research on DfAM training. Effective education and training models as well as research on assessing the model's effectiveness are needed for DfAM.

There are still a number of important questions regarding DfAM training that have been not addressed in the literature. For instance, what aspects of DfAM can be further emphasized to prepare students for future AM applications; or to what extent we need to discuss various AM Technologies. Moreover, since it might be very time-consuming to go over all AM technologies, is there any method to narrow down the technology training in DfAM. It should be also emphasized that new AM technologies are coming to the market which makes the design trade space even more complicated.

Building upon the experiences gained in the previous study [66], this study introduces a novel DfAM approach by integrating the methods and tools of technology roadmapping (TRM). This study presents the idea that TRM is able to provide a better and bigger picture of available AM technologies during DfAM training. In practice, designers need to be aware of what each specific technology can do for them after obtaining knowledge on DfAM basics. In other words, an effective DfAM training should integrate a set of fundamental design knowledge with practical knowledge regarding various AM technologies. In this study, it is assumed that the designers have already answered the suitability question and it is confirmed that AM can add value to design and production process. In engineering education, a particular attention is given to functional part design with an objective to achieve functional and cost-effective engineering parts. Therefore, the focus in our DfAM training is on functional features. However, non-functional features may be added to connect certain features, enhance weak spots, and help for higher printability. The remainder of this chapter is organized as follows. Section 2, provides an overview of DfAM. Section 3 introduces TRM and focuses on TRM tools that could be applied in DfAM training. Section 4 presents the framework.

5.2. General DfAM Guidelines

In order to develop a DfAM framework, it is reasonable to start with the basics of design for manufacturing (DFM) and adapt them for DfAM. Traditionally, DFM guides designers to minimize manufacturing difficulties and costs [64]. Furthermore, certain studies focused on manufacturability analysis in AM [68], [69] which is beyond the scope of this research. In classical DFM, designers usually start by process and material selection followed by manufacturability evaluation which consists of the three steps of verification, quantification, and optimization [63]. Following the DfAM literature, it seems intuitive for DfAM practitioners to start with manufacturability evaluation followed by process selection which normally initiates via material selection. The process and resource selection may continue by considering build orientation, design complexity, support for over-hang features, easiness for support removal, assembly constraints, sharp contact tip avoidance, anisotropic properties, etc.[70]–[73]. There are certain considerations related to the fabrication technology including build volume (i.e. part size), build rates, feature resolution, feedstock, economics, etc. The need for multi-alloy parts will narrow down the selection into certain technologies. To this end, understating various AM technologies is an essential part of DfAM.

5.2.1. DfAM Technologies

The technologies to be discussed in DfAM can be classified into design-related technologies, fabrication technologies, and post-fabrication (i.e. post-processing technologies). Despite all the new developments in recent years, current computer-aided design (CAD) systems have certain shortcomings with respect to DfAM [74]. There is a tendency to improve CAD systems capabilities to design novel and more complex shapes, and to include the material and properties representations [74]. For instance, designing lattice structures similar to what exists natural and biological systems are in demand. Advances in CAD systems will enable designers to straightforwardly model and fabricate macro and micro-scale lattice or cellular structures. Lattice structures have found applications in medical, aeronautical, and automobile industries to reduce part weight and increase energy absorption in designs. Lattice structure designs can be distinguished by their unit cell types [75]. An important aspect of these unit cells is the overhang angle which will be discussed further in section 5.4. In addition, lattice structures made with different AM technologies will be different in accuracy, relative density, and energy absorption.

It is also important to mention two design technologies which were empowered by AM; (i) topology optimization (TO), and (ii) generative design (GD). The former aims mainly to perform shape optimization within a predefined boundary condition under certain loads and constraints. GD refers to set of design space exploration methods enabling designer to consider numerous possible designs within CAD environment [76].

It should be emphasized that based on specific design reequipments DfAM can be further directed to definite goals such as design for high-volume production, design for highly-customized parts, design for minimal cost, design for minimal post-processing time, design for a specific AM process, design for minimal material utilization, design for improved functionality, design for hybrid AM, design for product lifecycle, and so on. Therefore, several design tools might be needed to achieve design objectives.

The main objective of DfAM is reducing manufacturing costs and achieving the desired quality. The literature suggests that a large portion of the total AM cost (sometimes up to 70%) could be related to post-processing operations [77]. For metal components, post-processing is a necessity to achieve the desired metallurgical characteristics and quality conformance. Post-processing in AM can be divided into six categories, each category with particular set of available technologies:

- Machining
- Finishing (surface finishing, coating, polishing, cleaning)

- Joining (welding & brazing)
- Removing (build plate, support, power)
- Heat treatment
- Inspection

In essence, the ultimate objective in post-processing is to satisfy design requirements. For instance, part shrinkage and distortion may happen in certain AM process. In addition, the surface texture is dependent on AM fabrication process and certain parameters such as deposition rates. Although such issues should be resolved throughout post-processing, designers need to properly plan these adjustments in the design process. In practice, post-processing deals with changes in geometry, physical dimensions, and metallurgical properties. For this, designers should normally consider excess materials or design features to facilitate the post-processing process. It is important to emphasize that design, fabrication, and post-fabrication process affect the final part performance.

5.2.2. Redesign for AM

Designers have many reasons to redesign existing products. The reasons for redesign can be divided into market drivers and requirements, performance, and cost reasons [78]. The trend for redesign in AM was dominated by performance reasons. In particular, redesigning has shifted to designing more complex parts by adding internal and external features. Heat exchangers are good example of successful redesigns via AM [72] [79]. In addition, part consolidation may justify the need for redesigning several interacting components [65]. Part consolidation may save production time and reduce component by eliminating mating surfaces and assembly requirements. The consolidation may offer advantages with respect to reduced tooling, lower weight, reduced labor cost, and easier or faster certification process. For more information on redesigns, readers are referred to [72].

5.3. Technology Roadmapping (TRM)

Technology roadmapping (TRM) evaluates the current state of available technologies and provides a pathway to achieve and/or apply technologies for future research and developments. In other words, TRM is a time-based strategic planning tool used to apply emerging technologies in order to gain competitive advantages and respond to varying demands and market shifts. Good examples of such emerging technologies include artificial intelligence and internet of things which are being utilized by a growing number of industries to increase their market share and business performance. It implies that TRM should be able to systematically identify emerging technologies and markets, consider organizational objectives, and provide technology alternatives for current and future investments [80].

Phaal et al. [81] introduced various types of graphical TRMs which present the necessary information in concise format and should be followed by an appropriate documentation. The authors in [81] emphasized the fact that TRM is a learning experience itself. The recent book on TRM by Prof. de Weck [82] is certainly the most comprehensive reference in this matter. The author presented his advanced technology roadmap architecture (ATRA) in four steps. The first step, titled "where are we today", is simply the assessment of current technologies and can be integrated to training programs. The next two steps in ATRA are about to evaluate and specify where a company could go or should go. These TRM steps are also significant and applicable at the design stage.

5.3.1. TRM vs. Process Selection

The current trend in DfAM literature is to provide guidance or frameworks for process selection [77]. However, it should be noted that applying TRM would be more practical than a rudimentary process selection. In essence, TRM instructs the designers to be aware of the long-term strategic goals. Moreover, a routine process selection may work for many applications, but for particular applications, such as aerospace components, more assessments should be done to justify the use of a specific technology. Here, we review the process selection in AM and highlight the relevant challenges.

The process selection for metal AM is normally initiated by evaluating technical advantages and constraints offered by each fabrication technology. Designers should realize that AM is not constraint-free, and depends on technologies, the constraints could be drastically different. The evaluating factors can be classified to design features, metallurgical, and cost-value considerations [77]. There are many factors (i.e. criteria) mentioned in the published literature[77] to be considered in the process selection. These factors include, but not limited to, material selection, single or multi-alloy builds, overall size, part complexity, resolution of internal features, build rates. In the process selection, which can be an iterative and tedious process, the designer is expected to holistically considers the above-mentioned factors. It should be remembered that these selection factors are normally integrated and interwoven. For example, if a process is merely chosen because of the suitable build volume, other design requirement such as resolution or performance might be at risk.

It should be also emphasized that dealing with process selection is different in DfAM training. Particularly for engineering students, we do not want to limit the idea generation stage by discussing process limitations. However, professional engineers are expected to face numerous genuine constraints. The goal in the proposed instructional framework is to initiate with design freedom along with understanding significant aspects of AM design process. For this, TRM tools can be very helpful. In this section, three TRM tools are introduced and relevant examples – with educational purpose - are presented.

5.3.2. Figures of merit (FOM)

Designers normally focus on different goals during the design process. Figures of merit (FOM) is a tool (and an essential step in TRM) that help designers to choose the technology they need to use in present day and probably in the future. Generally speaking, FOM is a helpful tool to apprehend technological progress over time [83]. FOM is typically a good indication of performance or specific aspect of a system or technology. The goal of using FOM is not only to show the progress, but to make some aspects of technologies explicit and revel the theoretical limits. Thus, for DfAM training, one important question is what FOMs can be used. It is evident that we need to find valuable and instructive FOMs to be used in DfAM. This FOMs can be dynamic or updated over time as technologies or various features of technologies evolve over time. In essence, DfAM training needs more helpful FOMS which include but not limited to technology progression rate, productivity, efficiency, sustainability, and lifecycle properties. For instance, the mean time to introduce new materials in metal AM is an indication of an important capability of AM technologies. The general type of FOM can be further expanded to performance specific FOMs such as applied energy vs microstructure characteristics or capital efficiency of adding a layer.

To provide examples of FOMs, we consider the metal AM technologies. Table 17 provides the classification of available metal AM technologies along with their energy sources and type of feed stock. Just understanding the significant impacts of energy sources and feed stocks on quality of additively manufactured metal parts would be a thoughtful step toward a better process selection. For instance, Table 19 shows three energy sources in different color that do not reach sintering or melting temperatures during fabrication. Table 19 also shows the technology readiness levels (TRL) for the metal AM technologies [77]. All the metal AM technologies are available through AM service providers. Early industry adoption, comprehensive material characterizations, standard development, traceability, technological breakthrough, and many more impactful factors are contributing to the level of TRL.

Table 19. Classification of metal AM technologies

Metal AM Technology	Energy Source	Feedstock	TRL
Powder Bed Fusion	Laser	Powder	9
	Electron beam	Powder	7
Directed Energy Deposition	Laser	Powder	6
	Electric Arc	Wire	6
	Laser	Wire	6
	Electron beam	Wire	5
Solid-State Ultrasonic	Ultrasonic	Foil	9
Friction Stir Deposition	Friction	Bar stock	3
Cold Spray	Particle acceleration	Powder	6
Sheet Lamination	Laser	Foil	3

Currently, there are around 50 different metal alloys available to be used in metal AM technologies [65]. These alloys include some popular and well-known high temperature aerospace alloys. Table 20 presents available alloys in metal AM for each technology. Presenting these two tables, i.e. FOMs, would help the trainees realize that powder bed fusion (PBF) technology which applies powder feed stock and laser as the heat source has the highest TRL and highest available alloys. The other technology with good potentials would be the directed energy depositions (DED) with a reasonable TRL, good pool of available alloys, and the possibility of using wires for higher build rates. It is important to note that the average build rate of wire in DED technology is six times greater than powder build rate. Moreover, the build rate of Laser DED with powder is almost 7 times greater that Laser PBF.

Table 20. Available alloys in metal AM technologies

Metal AM Technology	Nickel-based	Iron-based	Copper-based	Aluminum-based	Titanium-based
Laser-PBF	13	13	6	10	3
Electron beam-PBF	7	4	1	2	3
Laser-DED (powder)	12	12	5	8	3
Electric Arc-DED	7	12	0	8	2
Laser-DED (wire)	5	8	1	1	3
Electron beam-DED	3	5	1	4	2
Solid-State Ultrasonic	4	5	2	7	2
Friction Stir Deposition	4	7	2	7	3
Cold Spray	8	5	6	8	3

Figure 68 shows another important aspect of TRM which requires understanding the development trend and major milestones for each technology over time. It can be observed from such FOMs, that after almost two decades of research and development, PBF technology reached the required TRL to be used in medical devises and jewelries. In addition, the broad applications of PBF in aerospace industry was not possible without development of globally recognized standards.

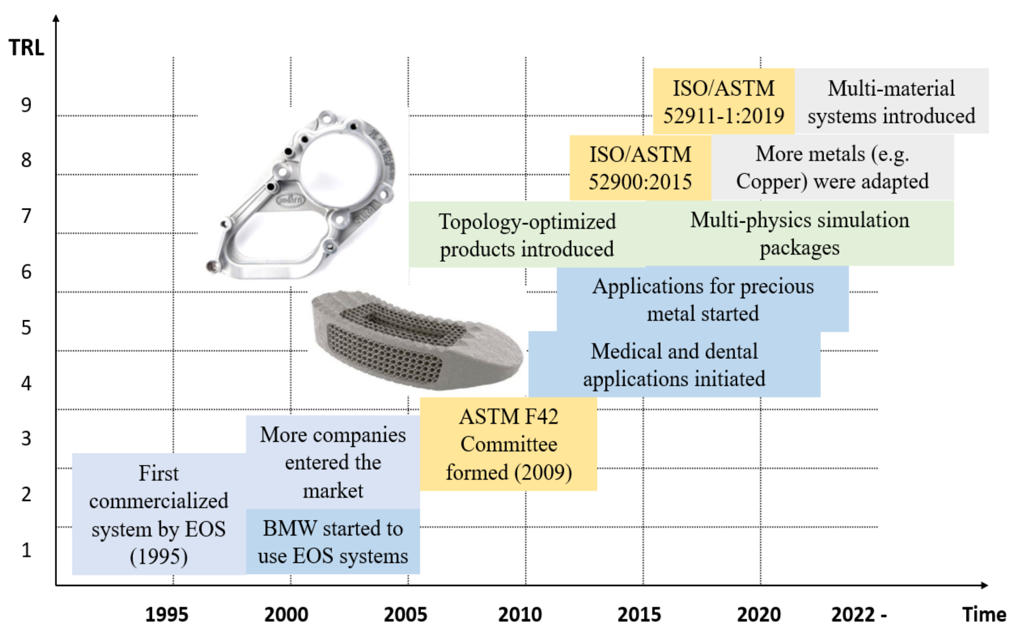


Figure 68. Development trend over time for PBF technology

There are currently four ISO/ASTM standards and two NASA standards specifically developed for PBF technology. It should be emphasized again that the figures presented in this study are for educational purposes. The figures and their relevant data are inspired by the published literature. Obviously, such data is approximated and subject to change.

5.3.3. Object-Process Methodology (OPM)

OPM is a standardized conceptual representation tool with an ability to describe complex system architectures in a single integrated model [83], [84][85]. As the name implies, OPM divides the system elements into objects and processes connected through different types of structural or procedural links.

Processes in OPM affect the objects in various ways. Principally, objects are generated, altered, or consumed by processes. OPM has been applied for TRM to represent roadmap scope and demonstrate the main objects[83], [85].

In this section, an example of using OPM to display various metal AM technologies is presented (Figure 69 and 70). This diagram was made for educational purposes using OPCAT software package. It should be noted that OPM consists of graphical (diagrams) and textual system representation. The textual model is the linguistic equivalent of the graphical model and is known as object-process language (OPL). The OPL related to this example is presented in Appendix G.

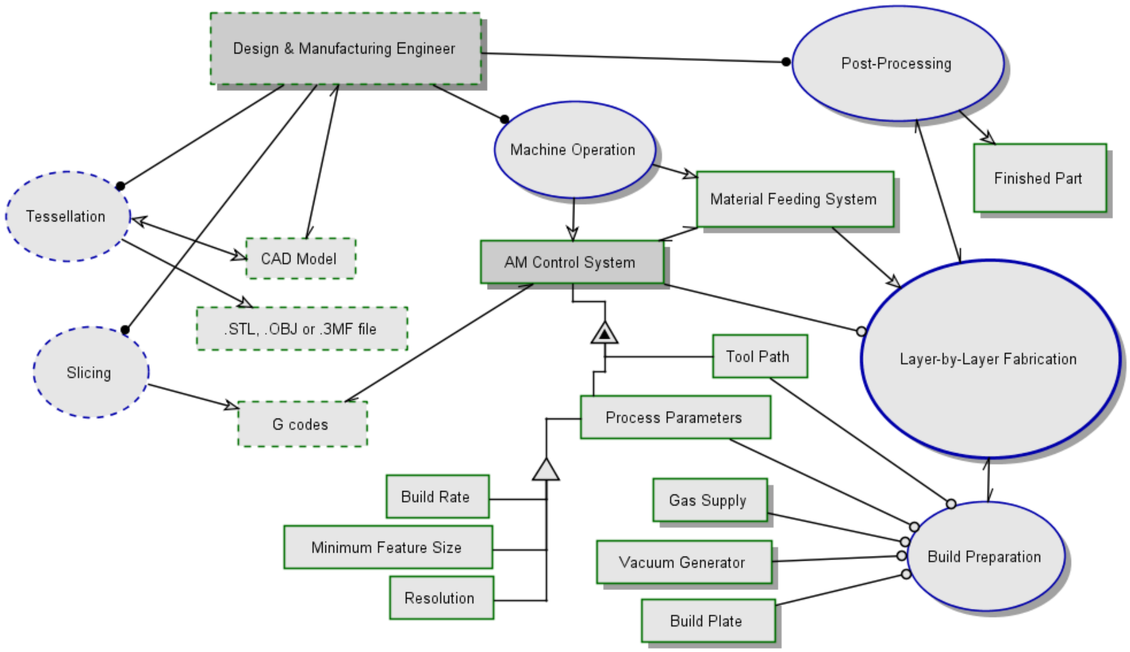


Figure 69. OPM diagram for metal AM technology

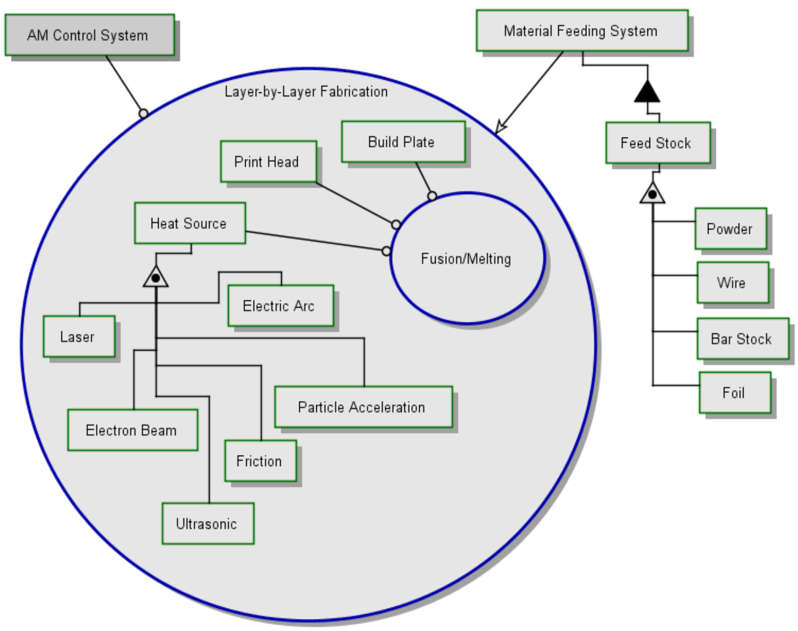


Figure 70. Sub-diagram for layer-by-layer fabrication (please see Figure 58)

5.3.4. Dependency Structure Matrix

Dependency Structure Matrix (DSM), also known as design structure matrix, is a powerful tool to represent and analyze complex systems [86]. A DSM shows bilateral relationships or connection between N system elements through an N-Squared matrix. There are various types of DSM with broad applications across multiple industries for product design, system architecture, and project management [87]. DSM is recommended in early stage of TRM to identify interdependencies among the roadmaps [83]. In this study, a new type of DSM which is known as multidomain matrix (MDM) was developed. In principle, MDM highlights inter- and intra-domain relationships. An example of the MDM used for manifold microchannel heat exchangers. is shown in Figure 71. In this MDM, the objective is to identify the intra-domain relationship between geometric features, process parameters, and certain post-processing activities. For instance, through this MDM, one can observe a significant effect of all the process parameters (Columns F-I) on minimum wall thickness. Obviously, this is due to the fact that many thin walls used in those heat exchangers.

DF1 - Horizontal Hole	Geometric features	A	A					X	X			X		X		
DF2 - Vertical Hole		B		B				X			X					
DF3 - Max. Overhang Angle		C			C			X	X							
DF4 - Bridging Dist.		D				D		X	X				X			
DF5 - Min. Wall Thickness		E					E	X	X	X	X				X	X
PP1 - Layer Thickness	Process Para.	F	X	X	X	X	X	F						X		X
PP2 - Laser Power		G	X		X	X	X		G					X	X	X
PP2 - Scanning Speed		H					X			H				X		
PP3 - Hatching Dist.		I		X			X				I			X		
PoPr1 - Powder removal	Post-Processing	J	X									J				
PoPr2 - Support removal		K				X							K			
PoPr3 - Surface Finish		L	X					X	X	X	X			L		
PoPr4 - Machining		M					X		X						M	
PoPr5 - Heat Treat.		N					X	X	X							N

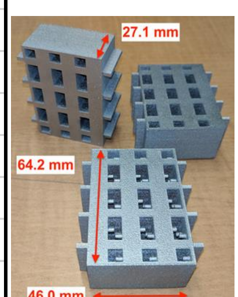


Figure 71. Dependency structure matrix for heat exchangers produced by Laser-PBF.

5.4. DfAM Instructive Framework

The DfAM training framework for integrating DfAM and TRM is presented in Figure 72. This framework is based on observations in previous research [66] which involved 178 first-year engineering students. In this instructional framework, DfAM training starts with a pre-design task that requires students to generate their own designs. At this stage, certain fundamental requirements will be discussed. Next, the DfAM training will be initiated by using several TRM tools to educate students about the available AM technologies and possible future advancements.

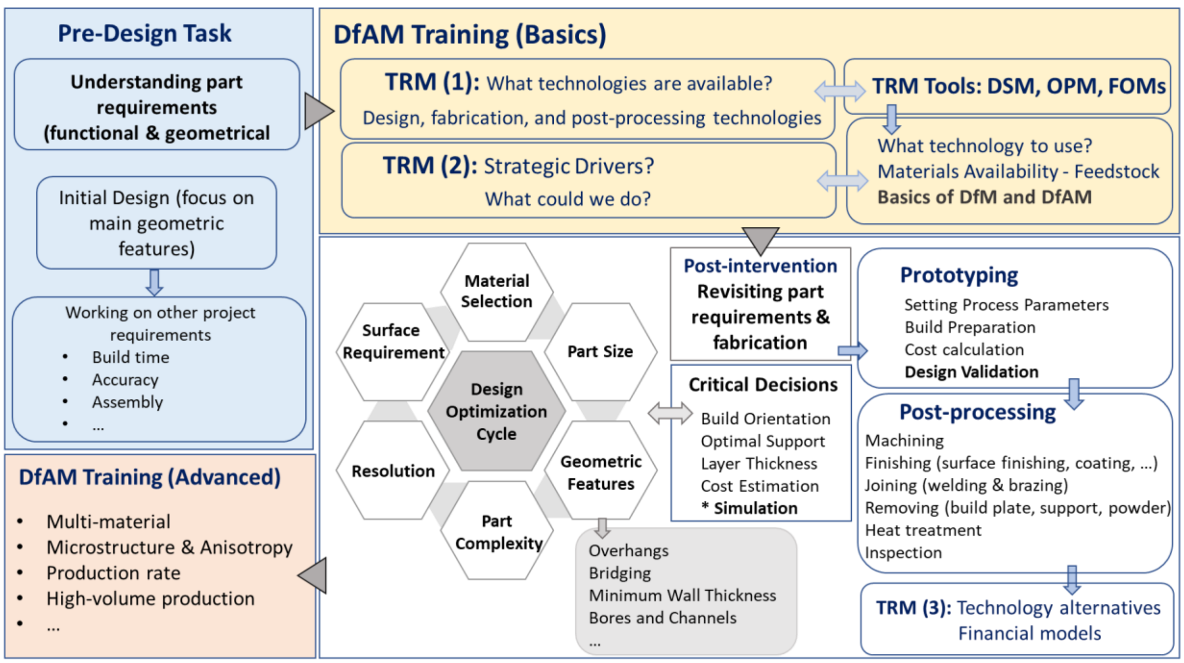


Figure 72. The proposed framework for integrating DfAM and TRM.

This training should be concluded with possible roadmaps for students to follow. This roadmap should clearly answer the questions about what could be done in terms of fabrication and post-processing. In essence, to be able to prototype their design, it is required to focus more on the technologies available at hand. However, the discussion should be further extended to "what should be done" in order to prepare the students for future AM designs and applications. The basic training and prototyping may be continued by an advanced training module. The topics to be included in the advanced AM training include multi-alloy AM, microstructure evaluation, and high-volume AM production. Certain AM technologies allow using multiple alloys in a form of powder or wire during a build operation. It is also possible to apply various alloys in a secondary operation.

The trainees will be particularly instructed about certain critical decisions in the fabrication process which has great impact on properties and performance. Determining a proper build orientation is as an example of critical decisions which needs further elaboration. A proper build orientation ensures the balance between build time, fabrication cost, and quality. To properly handle the critical decisions, a trainee should consider an iterative design optimization process. The process normally starts with material selection and proceed into part size and design features considerations. The build orientation decision determines the build volume required as well as geometrical features such as overhangs and horizontal holes. While one important design objective can be set as minimizing support structures, other possible objectives such as minimizing anisotropy in certain direction or minimal build area might be also considered. It is important to remember that build orientation and material composition significantly influences a part's mechanical properties [73][88]. For example, in material extrusion AM, one should expect lower mechanical strength when material is layered in a direction perpendicular to loading direction.

In fact, build orientation could be a very good exercise for students to fully understand the interwoven relationship between design and fabrication. One task of students in this exercise is developing a comparison list of process parameters. To this end, there are different methods to determine the build orientation. In effect, simulation tools could be very helpful at this stage.

Shape and geometric features need to be carefully considered in the design optimization process. Some of these features were used in the presented DSM in section 5.3.4. Obviously, the allowable values for such features vary depending on AM technology utilized. Moreover, these key geometric features might serve as design constraints for a fast and successful AM build process. The key features include:

- The ratio of vertical feature to horizontal feature size known as aspect ratio;
- Maximum horizontal distance to be printed without support; i.e. maximum bridging distance
- Maximum overhang angle which can be printed with no support. The angle is measured with respect to the build plate. The allowable overhang angle depends on process parameters and the applied material. For example, the nominal overhang angle for material extrusion and Vat Polymerization (i.e. SLA) in 45°. Obviously, overhang features that exceed the maximum angle threshold need support structure, and therefore, pros-processing which include careful support removal and surface finishing.
- Minimum wall thickness that does not need any support
- Minimum and maximum sizes of cylindrical holes.

To clarify the importance of the above-mentioned key features, it would be beneficial to conduct experiments and prototyping. Here, we provide an example of an experiment conducted for understating the effect of part orientation on vertical and horizontal holes. The students will 3D print a set of holes similar to the part shown in Figure 73. Two AM technologies were used; (i) vat polymerization using Form 3, and (ii) material extrusion using Prusa 3.

The experiment can be repeated by changing the length (to explore warping in material extrusion) and parts' thickness (i.e. hole depth) to explore cylindricity. Table 21 summarizes the experiments results. After printing, the hole dimeters were measured. The absolute error with respect to the actual hole diameters were calculated. The lowest MAPE can be obtained when the vat polymerization process is used in conjunction with a part that is oriented flat on the build plate with no support material added. The highest MAPE was found for parts manufactured via material extrusion in the flat orientation.

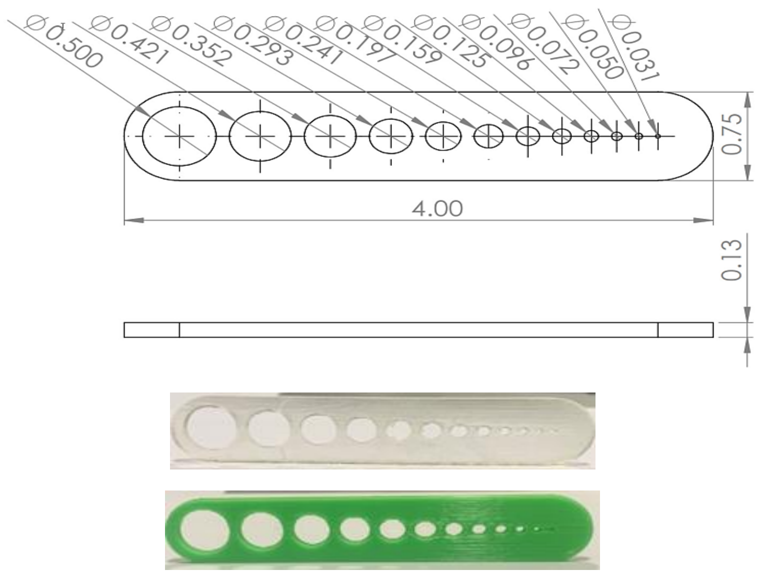


Figure 73. Hole printing test part and the test parts printed in a horizontal orientation via vat polymerization and material extrusion (green part)

Table 21. Mean absolute percentage error (MAPE) for various orientation in vat polymerization and material extrusion prints

AM Technology	SLA	ME	SLA	ME	SLA
Build Type	Flat on Bed	Flat on Bed	Standing	Standing	45 degree
Horizontal Orientation	3.55%	21.12%	7.87%	12.27%	5.37%

The novel DfAM training framework that was developed and described in the previous section can be used to prepare engineering undergraduate students for future challenges in the manufacturing industry. This training can be implemented in the engineering curriculum as a thread. AM technologies should be introduced in the first year while more advanced topics should be covered in the junior and senior year of study.

5.5. DfAM Training Framework in the Engineering Curriculum

The novel DfAM training framework that was developed and described in the previous section can be used to prepare engineering undergraduate students for future challenges in the manufacturing industry. This training can be implemented in the engineering curriculum as a thread. AM technologies should be introduced in the first year while more advanced topics should be covered in the junior and senior year of study.

A description of the necessary topics to be covered during each year of study in undergraduate engineering programs are detailed below.

First Year: These topics must be covered during introductory engineering classes during the first year of study.

1. Introduction to AM.
    a. Introduction to DfAM
        i. Restrictive DfAM concepts:
            1. R1: Using support structures for overhanging sections of a part
            2. R5: Accomodating for minimum and maximum features size permitted in a process.
        ii. Opoortunistic DfAM concepts:
            1. O4: Embedding components such as circuits in parts
2. Introduction of the seven categories of AM.

a. Focus on the available AM technology

    i. Limitations and capabilities in process parameters.

Sophmore Year: These topics should be covered during lab sessions as well as introductory courses offered to sophmore level students. Students should be given hands on experience with the available AM technologies.

3. TRM 1: DfAM discussion must continue with a deeper dive into the capabilities of each AM technologies. Discussion of design, fabrication, and post-processing technologies demonstrated with TRM tools, DSM, OPM, and FOMs. FOMs must show available feedstock materials available for printing and the TRL development of each process over time.
4. Restrictive DfAM Concepts:
    a. R2: Designing parts to prevent them from warping and losing shape.
    b. R3: Designing parts that have different material properties (i.e. strength) in different directions.
    c. R4: Obtaining the desired surface quality
5. Hole test experiement to see the effects of build orientation on horizontal hole dimensions. Compare processes and calculate a mean absolute percent error (MAPE).

Junior Year: These topics should be covered during lab sessions and in classess that discuss manufacturing processes during the junior year of study. The learning focus should be in the TRM 2 stage of the DfAM training framework where students are able to fully utilize the available AM technology in the institution.

6. Opportunistic DfAM Concepts:
    a. O2: Combining multiple parts into a single product or assembly.

b. O4: Embedding components such as circuits in parts

7. Restrictive DfAM concepts:

    a. R3: Designing parts that have different material properties (i.e. strength) in different directions.

8. Introduction to post processing techniques

    a. Machining, finishing, joining, removing, heat treatment, and inspection.

9. Design validation and cost calculation during the processing stage.

Senior Year: These topics should be covered during senior lab sessions, advanced classess that and senior design during the senior year of study. The learning focus should be in TRM 3 where students are exposed to all the AM technologies so that cost comparisons can be made based on process parameters, geometric features (overhangs, bridging, mimimum wall thickness, bores, and channels) and post processing techniques.

10. Opportunistic DfAM Concepts:

    a. O1: Making products that can be customized for different users.

    b. O4: Embedding components such as circuits in parts

    c. O5: Designing products that use multiple materials in a single part or component.

11. Restrictive DfAM Concepts:

    a. R5: Accomodating for minimum and maximum features size permitted in a process.

12. Iterative critical decision making and the design optimization cycle

    a. Optimal support on geometric features, surface requirements

    b. Cost estimation and material selection, part size, and geometric features.

13. Advanced DfAM training in the following areas:

a. Multi-material, microstructure and anisotropy, production rate, high-volume production.

DfAM training should be implemented into the engineering curriculum as a thread that focuses on definite goals such as design for high-volume production, design for highly-customized parts, design for minimal cost, design for minimal post-processing time, design for a specific AM process, design for minimal material utilization, design for improved functionality, design for hybrid AM, design for product lifecycle. Integrating technology roadmapping and DfAM aims to help the designers to perform technology identification and selection more efficiently. Successful implementation of the DfAM training framework will prepare engineering students for future challenges in the manufacturing industry.

6. Conclusion and Future Work

6.1. Summary of findings

A DfAM training framework was developed to train undergraduate engineering students in AM and DfAM as well as increase student DfAM self-efficacy. The preliminary phase of the investigation focused on the use of an assessment framework in conjunction with a DfAM intervention workshop to train first year engineering students on AM processes and DfAM considerations to improve designs. Further experiments were later performed that included the training of upper-level engineering students in a manufacturing processes class. The design outcomes of the DfAM educational intervention training workshop in conjunction with the assessment decision making tool were collected and analyzed. Results showed that student's DfAM self-efficacy, AM and DfAM knowledge, and design outcomes improved after DfAM training. Participant's designs showed an increase in the use of DfAM considerations after DfAM training.

The results from the junior-level class were compared to the results shown in the preliminary study. Students in the junior year had the highest percent change in DfAM SE for obtaining the desired surface quality. The students in the junior year also showed the lowest change in the opportunistic DfAM concept categories. Table 22 demonstrates that the participants in the junior year of study showed a higher percent change in DfAM SE in the restrictive and opportunistic DfAM concept areas compared to the students in the first year of study. The higher percent change in DfAM SE seen in the junior group is due to the higher amount of time that was spent during DfAM training on both opportunistic and restrictive DfAM concepts. The individuals from the junior year of study also were able to have hands on training with the available 3D printers. External funding from the government entities can alleviate the lack of available AM technologies available for student use.

Table 22. Comparison of first year students and junior students DfAM SE changes

DfAM Self Efficacy Concepts	First Year DfAM SE % Change	Junior DfAM SE % Change
Making products that can be customized for each different user (O1)	45%	70%
Combining multiple parts into a single product or assembly (O2)	44%	40%
Designing parts with complex shapes and geometries (O3)	33%	44%
Embedding components such as circuits in parts (O4)	41%	83%
Designing products that use multiple materials in a single part or component (O5)	29%	56%
Using support structures for overhanging sections of a part (R1)	36%	58%
Designing parts to prevent them from warping and losing shape (R2)	34%	75%
Designing parts that have different material properties (i.e. strength) in different directions (R3)	36%	75%
Achieving the desired surface quality (R4)	35%	85%
Accommodating for min and max feature size permitted in a process (R5)	41%	80%

The training resulted in a positive influence on participants' integration of opportunistic and restrictive DfAM in their designs. The assessment rubric encouraged participants to incorporate DfAM principles in their designs after the training workshop. Participants' DfAM self-efficacy increased among males and females after DfAM training. Prior CAD and AM experience shows a positive impact on DfAM training outcomes and AM knowledge tests.

The results of the research advised the development of a process map that must be followed by instructors to effectively train students in DfAM. The framework includes the timing, goals, activities, 3D printed products, and the use of the assessment tool to assess design outcomes. The framework also includes an AM and DfAM knowledge test that will enable educators to assess the knowledge gained after training. Educators can use the training framework to equip students with

DfAM knowledge for future use in engineering classes and design roles in the workforce. This research contributes to the field of design for additive manufacturing (DfAM) integration in education curriculum and improves student self-efficacy in DfAM. This ultimately will address the lack of qualified workforce that are prepared to take on design roles in industry.

The lectures given during the training workshop thoroughly covered an introduction of AM processes as well as restrictive and opportunistic DfAM concepts over a one-week period. Lectures in AM and DfAM were offered over the course of one week in three fifty-minute class sessions as opposed to one day, one-hour sessions used in other DfAM training research. Topics covered during the introduction included demonstrations and discussions on the differences between subtractive and additive manufacturing, the seven categories of AM processes, an overview of AM processes, modern uses of AM, and the benefits of AM. Two AM processes, material extrusion and vat polymerization, were emphasized in the study.

Restrictive and opportunistic DfAM concepts were detailed during the lectures. Restrictive DfAM concepts that were covered include the following: 1) build time, 2) minimum feature size, 3) support material use, 4) self-supporting angles, 5) bridging limits, 6) material anisotropy, 7) surface finish and 8) warping. Opportunistic DfAM concepts that were covered include 1) geometric complexity, 2) mass customization, 3) printed assemblies & part consolidation, 4) multi-material structures and 5) functional component embedding. Students were required to incorporate and address restrictive and opportunistic DfAM concepts in their final designs.

Student designs were then collected and assessed pre and post training workshop using the assessment tool described in Appendix A. The same post intervention AM and DfAM test was administered to investigate changes in AM and DfAM knowledge post workshop. The students completed the post-intervention survey at the end of the intervention workshop which can be found in Appendix E. A large amount of student data was collected and analyzed pre and post intervention to draw conclusions on the effect of the DfAM intervention on design outcomes and DfAM self-efficacy.

The results show that DfAM training is effective in increasing DfAM self-efficacy in first year and upper-level undergraduate engineering students. Student designs scores increased significantly after the DfAM training that was offered. DfAM training improved design outcomes in all participants regardless of year of study. Overall, all the students in the study reported low DfAM SE in embedding components such as circuits in parts. This must be addressed in the engineering curriculum to improve student DfAM SE in this area. It was observed in the study that the students' restrictive DfAM SE was lower than their opportunistic DfAM SE which shows that the students are somewhat aware of the capabilities provided by AM technologies but are not capable or aware of the restrictions that are associated with AM technologies.

It was observed in this study that DfAM training can be drastically improved if integrated by TRM. Integrating TRM with DfAM would provide answers to what and when a technology is needed beside offering justifications about why such technology is needed. The training for DfAM based on TRM would be more beneficial in preparing the future workforce. The entire TRM process consists of many steps such as identification, selection, acquisition or development of technologies. It is obvious that integrating TRM and DfAM aims to help the designers to perform the technology identification and selection more efficiently. The optimal manufacturing path can be determined by realizing the optimal technology path for the entire AM process lifecycle. In order to see a successful implementation, DfAM should be considered as a multidisciplinary task. TRM can help in this respect and reveal all the requirements and constraints. For instance, one of the important constraints is the supply chain for a specific material or feedstock.

Based on experience in my work with first year and upper-level students, a novel DfAM framework was developed by integrating the methods and tools of TRM.

6.2. Future Work

Future work must offer the DfAM training in a project-based approach to offer participants a variety of learning opportunities. The categories of project goals that should be addressed in the DfAM intervention workshop in the future are hands on skills, design and creativity, content learning, communication skills, and teaming and collaboration. An example DfAM project that can be used in an engineering class can require students to create a 3D model of a machine assembly element and apply DfAM considerations to the final design. The designed parts would then be assessed using the following categories from the assessment rubric shown in Appendix A: part complexity, assembly complexity, number of separate parts, functionality, thin/smallest feature size, smallest tolerance, unsupported features, support material, largest build plate. Students must then be required to create multiple iterations of functional 3D printed parts created in SolidWorks. Each DfAM concept must be emphasized while making improvements to the parts designed. The DfAM education training must be offered over a longer period to increase the time spent on each DfAM consideration and to allow participants to demonstrate mastery in each area of DfAM consideration.

Academic institutions should investigate and initiate offering DfAM training as a thread over the 4 years of the undergraduate curriculum. Design tasks can be tailored to the year of study and build from year to year. This will ensure that sufficient time is spent on exposing students to the available AM processes as well as the DfAM considerations in detail. Student access to AM processes during training can provide students with the necessary hands-on experiences. Institutions must facilitate the increase in availability of 3D printers for all engineering students. It is beneficial to incorporate a worksheet during the DfAM training that focuses on each category of the DfAM consideration and guides students through the process of incorporating a particular consideration in the design. For example, the steps of ‘smallest tolerance’ can be detailed with 3D images to give a reminder that the walls of the part must be more than 1/8” thick. The DfAM training can be mapped to a graphic user interface where each of the considerations are emphasized.

Future development of the training workshop should use the restrictive and opportunistic categories as learning goals as well as assessment targets. This will allow an objective assessment of the restrictive and opportunistic DfAM considerations. Educational tasks that address students’ areas of concern in DfAM self-efficacy must be developed on an ongoing basis using the DfAM self-efficacy tool described in the research study. Each restrictive (R1-R5) and opportunistic (O1-O5) category that is described on the self-efficacy scale can be used as a learning objective when planning lessons and activities in DfAM. DfAM training can improve participants’ incorporation of 1) part complexity, 2) assembly complexity, 3) number of separate parts, 4) unsupported features, 5) largest build plate contact, 5) functionality, 6) smallest tolerance, 7) support material removal, and 8) thin/smallest feature size.

Future iterations of this research should include a brainstorming session to allow students to include meaningful design ideas while making connections. Students need to make connections to learn and produce new ideas. The Pre and Post DfAM Design Idea Sheet, shown in Appendix B, should require participants to provide more detail on the design that is sketched. The drawing should include multiple dimensioned views and include an engineering drawing with top, side, and front views. This allows for more ease in using the objective assessment rubric created in this research. Biomimicry can also be included in design ideas. Students can make insightful connections that add value while meeting the design requirements. The relationship between DfAM training outcomes and participants' field of interest should be investigated in the future.

In addition, future work must include the development of a DfAM conceptual framework that connects learning goals to instructional activities. Future work must investigate the change in DfAM self-efficacy among a more diverse group of participants that can capture how race and gender affect student outcomes in educational settings where DfAM is incorporated. Future work must also include a variety of hands-on workshops for the design challenges pre and post DfAM intervention workshop that can reach all groups of learners. The lectures offered must be longer and thoroughly cover restrictive and opportunistic DfAM concepts over a longer period.

Additionally, future research must investigate how industry needs are addressed by the DfAM training framework presented in this research study. An investigation of how current DfAM training methods or tools address industry needs, and related activities is beneficial to future research on DfAM. Future work must include surveys, interviews, and case studies which will greatly enrich the DfAM training framework presented in this research study. The investigation of the effectiveness of DfAM training workshops must be continued in industry settings. This can be initiated by forming partnerships with engineering companies to continue to prepare current and future designers for design roles in companies that utilize AM processes.

In order to see a successful implementation, DfAM should be considered as a multidisciplinary task. TRM can help in this respect and reveal all the requirements and constraints. For instance, one of the important constraints is the supply chain for a specific material or feedstock.

Although expert knowledge will be an integral part of TRM, future practices should profoundly benefit from more data analytics for improved real-time decision making. In other words, data-led TRM for additively manufactured products is critical to deliver the strategic initiatives. Furthermore, it is important to note that TRM is a vital tool to project future uncertainties. A data-led TRM would consolidate this uncertainty evaluations [89]. In this way, suitable data visualization techniques will be very beneficial. Moreover, the new wave of digitalization, known as Industry 4.0, advocates entirely digital enterprise [90], which in fact, affects the TRM planning and preparation. Even the I4.0 transformation is a TRM process itself. In conclusion, the futuristic changes in manufacturing engineering signifies the need for integrating TRM into certain engineering education themes such as DfAM.

6.3. Limitations

A limitation of the current research is the availability of only two of the AM processes, vat polymerization and material extrusion processes during the training of participants. Future iterations of the study must incorporate other AM processes. Another limitation of the study is the use of a guest lecturer to offer the training during undergraduate class periods. This may have lowered student motivation to apply DfAM methods in the created designs. The short, allotted time for the intervention workshops was also limited in the preliminary study. Another limitation of the study is that the results are skewed towards White or Caucasian male participants. The motivation of the research was to enable educators to incorporate DfAM education in engineering curriculum. This will increase the number of students that are prepared to take on design roles in the workforce and will address the need for AM skilled designers in the work force. One weakness of the research is the lack of access to a more diverse group of participants. Future work must investigate the change in DfAM self-efficacy among a more diverse group of participants that can capture how race and gender affect student outcomes in educational settings where DfAM is incorporated. There is a need for instructors to incorporate a variety of design activities in the engineering curriculum as well as extracurricular settings so that a diverse group of students can gain confidence in DfAM concepts. Educational facilities must pursue initiatives that allow underrepresented groups to make gains in DfAM self-efficacy which may improve diversity in educational institutes and industries. Future research can further explore gender differences in DfAM self-efficacy using a sample that includes a higher number of participants that are females.

A training program that promotes the use of additive manufacturing in higher education design courses was developed along with an objective assessment tool. Instructor use of the training framework will effectively train students in AM and DfAM in a variety of engineering classes. Future work must also include a variety of hands-on workshops for the design challenges pre and post DfAM intervention workshop that can reach all groups of learners. The results of this research will contribute to the field of DfAM integration in engineering education curriculum and will improve student self-efficacy in DfAM and improve student's capability to incorporate DfAM considerations in designs which will prepare them for future design roles in multiple industries.

The motivation of the research was to enable educators to incorporate DfAM education in engineering curriculum. This will increase the number of students that are prepared to take on design roles in the workforce and will address the need for AM skilled designers in the work force. A limitation of the study is that the results are skewed towards White or Caucasian male participants. There is a need for instructors to incorporate a variety of design activities in the engineering curriculum as well as extracurricular settings so that a diverse group of students can gain confidence in DfAM concepts. Educational facilities must pursue initiatives that allow underrepresented groups to make gains in DfAM self-efficacy which may improve diversity in educational institutes and industries. Future research must further explore gender differences in DfAM self-efficacy using a sample that includes a higher number of participants that are females.

Additionally, future work should investigate the connection between student's engineering motivation and career pathway motivation on the DfAM training outcomes. A training program that promotes the use of additive manufacturing in higher education design courses was developed along with an objective assessment tool. Results showed that there was an increase in the utilization of DfAM in design concepts. The work will contribute to the field of DfAM integration in engineering education curriculum and will improve student self-efficacy in DfAM.

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Appendix A: Assessment Rubric

Design for Additive Manufacturing (DfAM) Rubric   **Total Score:________________**

Metric	4	3	2	1	0	Score
Part Complexity	Complex curves that cannot be machined. There are interior features or surface curves that are too complex to be machined.	The part curvature is complex (splines or arcs) for a machining operation such as a mill or lathe	The part can be made in a mill or lathe, but only after repositioning it on the clamp at least once	The part is mostly 2D and can be made in a mill or lather without repositioning it in the clamp	The part is the same shape as common stock materials (square, cylinder) or is completely 2D	
Assembly Complexity	Assembly has unidirectional joints with locking features	Contains joints (slider that allows for linear motion along a single axis) with locking features. Includes a screw pair.	Contains 1 joint(slider that allows for linear motion along a single axis)	Contains joints with no locking features	not present	
Number of separate parts	Part is made as one structure and meets desired function	Part is made as 2 structures and meets the desired function	Part is made as 3 structures and meets the desired function	Part is made of 4 or more structures and meets desired function	n/a	
Functionality	Mating surfaces move and experience moderate forces or are expected to last 10-100 cycles.	Mating surfaces move minimally, experience low forces, or are intended to endure 2-10 cycles	Mating surfaces move minimally and experience low forces and cannot endure any cylces	Surfaces are all non-functional or experience no cylces	Mating surfaces are bearing surfaces or are expected to endure 1000+ cycles. Mating surfaces significantly move, experiencing large forces or must endure 100-1000 cycles	
Thin/Smallest Feature size	Walls are more than 1/8" (3mm) thick	All walls are between 1/16" (1.5mm) and 1/8" (3mm) thick	Some walls are between 1/16" (1.5mm) and 1/8" (3mm) thick	Some walls are less than 1/16" (1.5mm) thick	All walls are less than 1/16" (1.5mm) thick	
Smallest Tolerance	Holes and length tolerances are considered or are not important	All hole or length tolerances are adjusted for shrinkage or fit	Some hole or length tolerances are adjusted for shrinkage or fit	Some intended assemblies do not fit.	Hole or length dimensions are nominal/minimal. Parts do not fit the intended diameter. Parts with overlaps do not connect	
Unsupported Features	Part is oriented so there are no overhanging features	Overhanging features have a mimmum of 45 degrees of support	Overhanging features have a sloped support	There are short, unsupported features	There are long, unsupported features	
Support material removal	No support material needed. There are no internal cavities, channels, or holes	Easily asscessible support material. Material can be easily removed from internal cavities, channels, or holes	Internal cavities, channels, or holes do not have openings for removing materials. Hard to remove.	There are small gaps that will require support structures	The part is smaller than or is the same size as the required support structure	
Largest build plate contact	The part has 1 small or no flat surfaces or forms that need to be exact	The part has 2 small or 2 flat surfaces or forms that need to be exact	The part has 1 medium sized, flat surfaces, or forms that should be close to exact	The part has more than 1 medium sized, flat surfaces, or forms that should be close to exact	The part has large flat surfaces or has a form that is important to be exact	

Appendix B: Pre and Post DfAM Design Idea Sheet

Last 2 characters of Mother's name (e.g., Amy would be MY) ________
Last 2 Last two characters of last name (Murray would be AY) ________
Last two characters of birth city? (e.g., Boston would be ON) _________
Birth Month (January would be 01) _________

IDEA SHEET – Pre-DfAM DESIGN

Sketch of Idea:

Brief summary of design (materials, manufacturing process, tools needed, etc.)

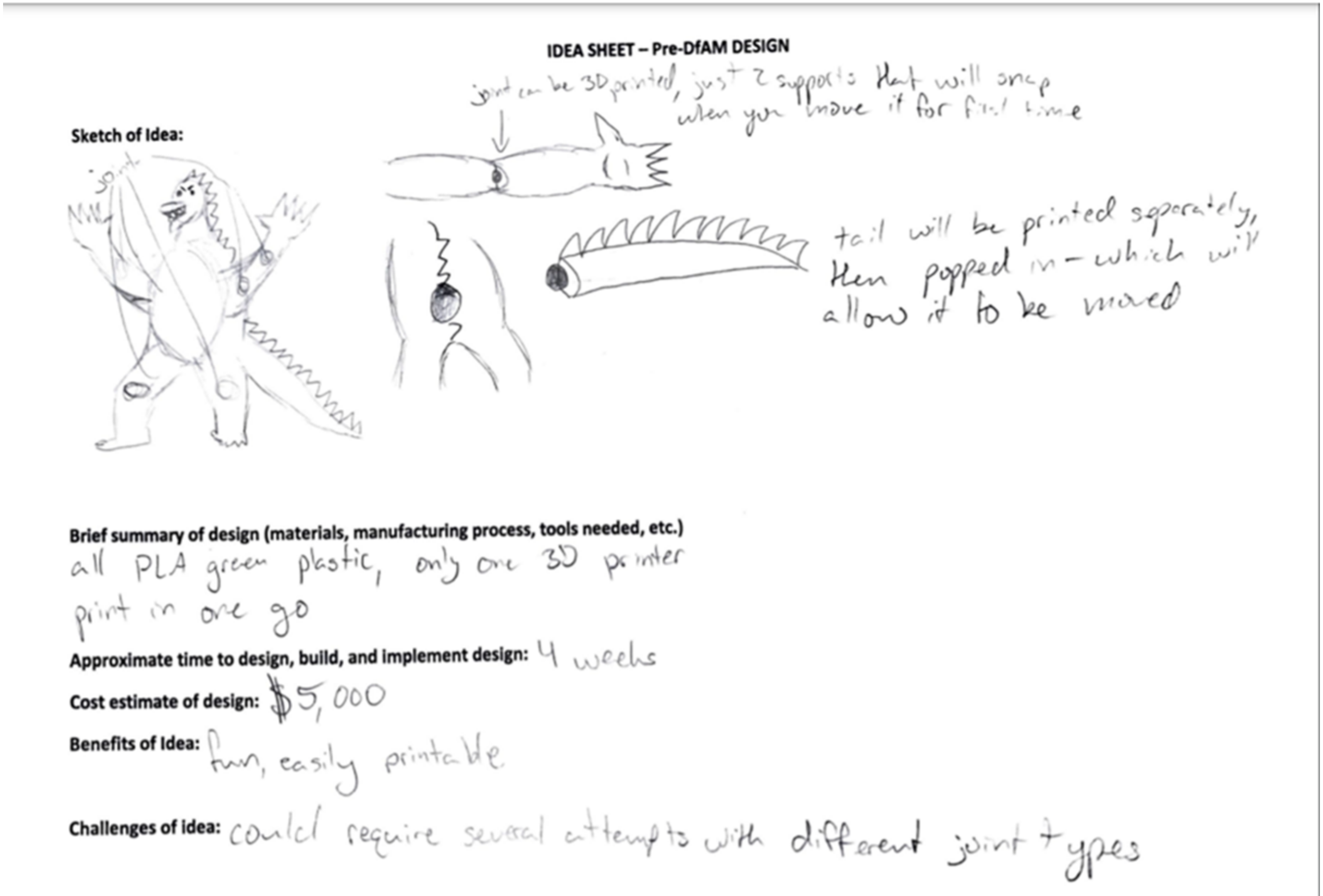
Approximate time to design, build, and implement design:

Cost estimate of design:

Benefits of Idea:

Challenges of idea:

Appendix C: Additional student work pre and post DfAM intervention



IDEA SHEET – Pre-DfAM DESIGN

Sketch of Idea:

joint

joint can be 3D printed, just 2 supports that will snap when you move it for first time

tail will be printed separately, then popped in – which will allow it to be moved

Brief summary of design (materials, manufacturing process, tools needed, etc.) all PLA green plastic, only one 3D printer print in one go

Approximate time to design, build, and implement design: 4 weeks

Cost estimate of design: $5,000

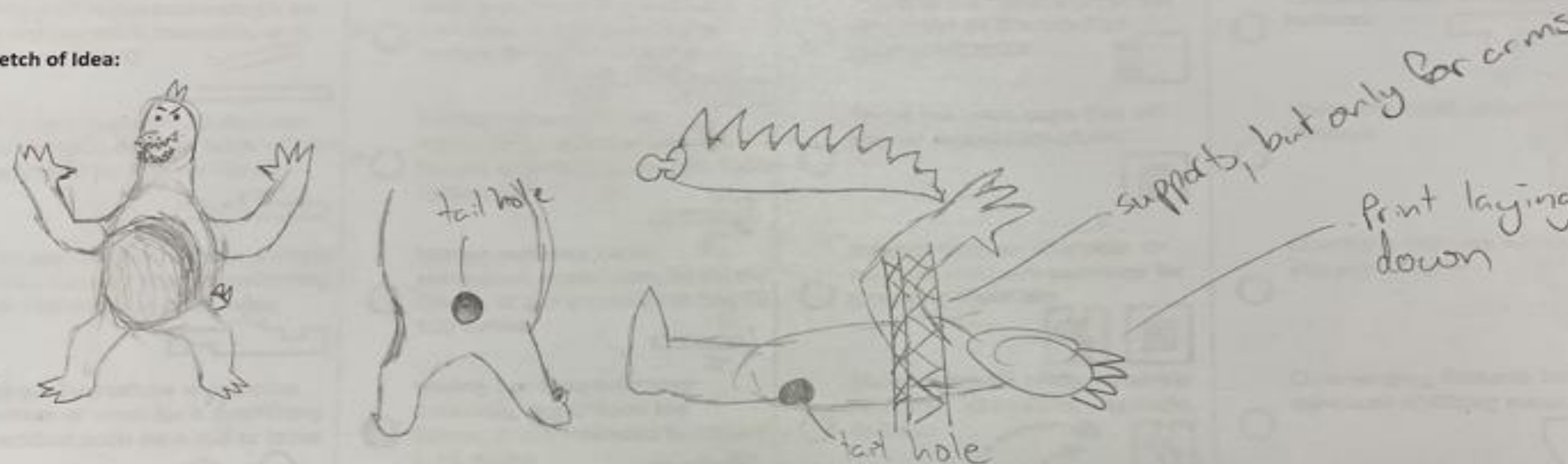
Benefits of Idea: fun, easily printable.

Challenges of idea: could require several attempts with different joint types

Last 2 characters of Mother's name (e.g., Amy would be MY) ME
Last 2 Last two characters of last name (Murray would be AY) RT
Last two characters of birth city? (e.g., Boston would be ON) LE
Birth Month (January would be 01) 11

IDEA SHEET – **Post DFAM-DESIGN**

Sketch of Idea:



Brief summary of design (materials, manufacturing process, tools needed, etc.). List any changes to original design

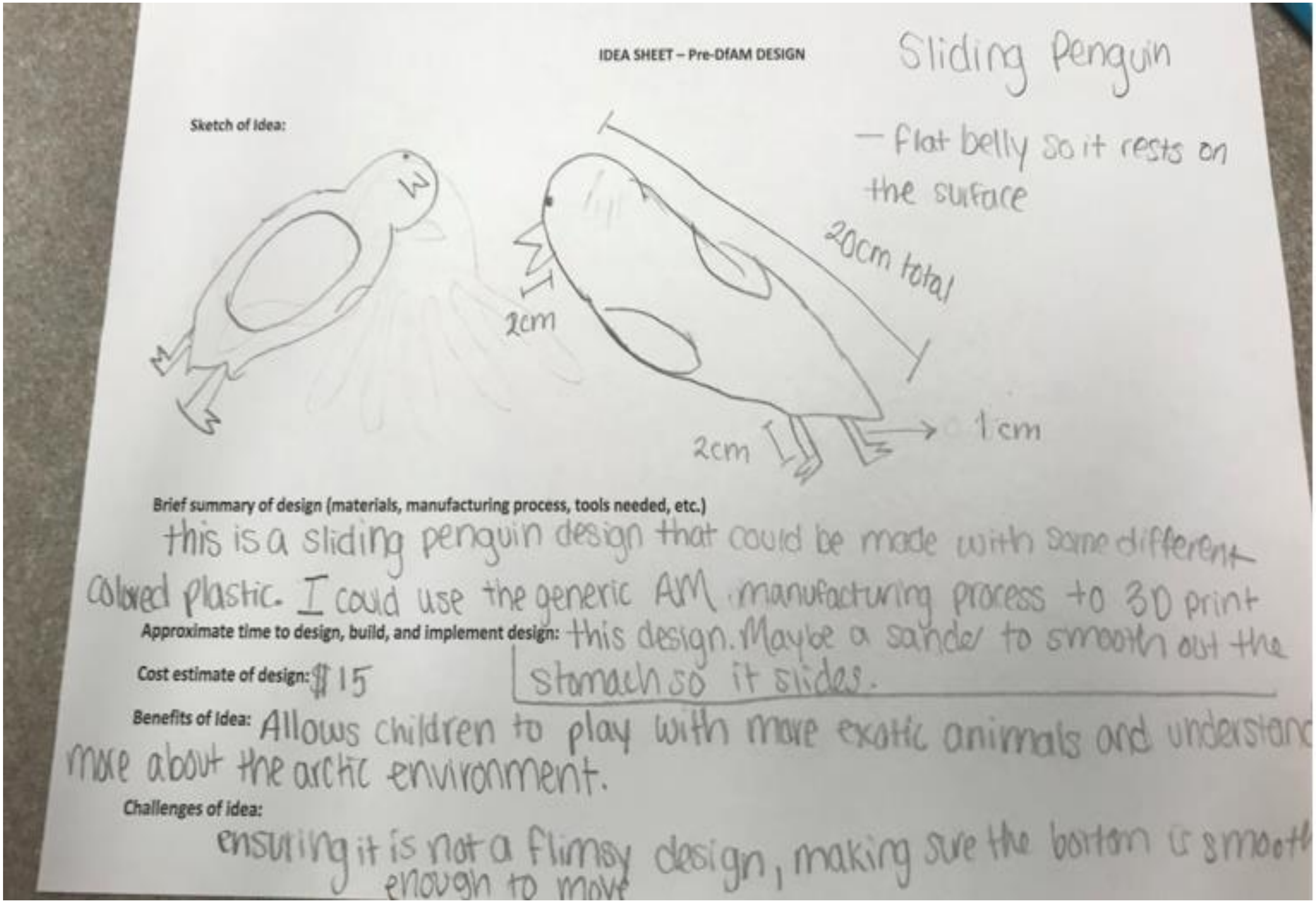
Changes - no internal supports to be broken, only tail will move
print on back of dinosaur to minimize supports
spikes on tail and head only for better contact w/ print bed

Approximate time to design, build, and implement design: 3 weeks

Cost estimate of new design: $5,000

Benefits of Idea:
easier to print than old design

Challenges of idea:
potential overhangs are still many



IDEA SHEET – Pre-DfAM DESIGN

Sliding Penguin

Sketch of Idea:

- flat belly so it rests on the surface

20cm total

2cm

2cm

1cm

Brief summary of design (materials, manufacturing process, tools needed, etc.)

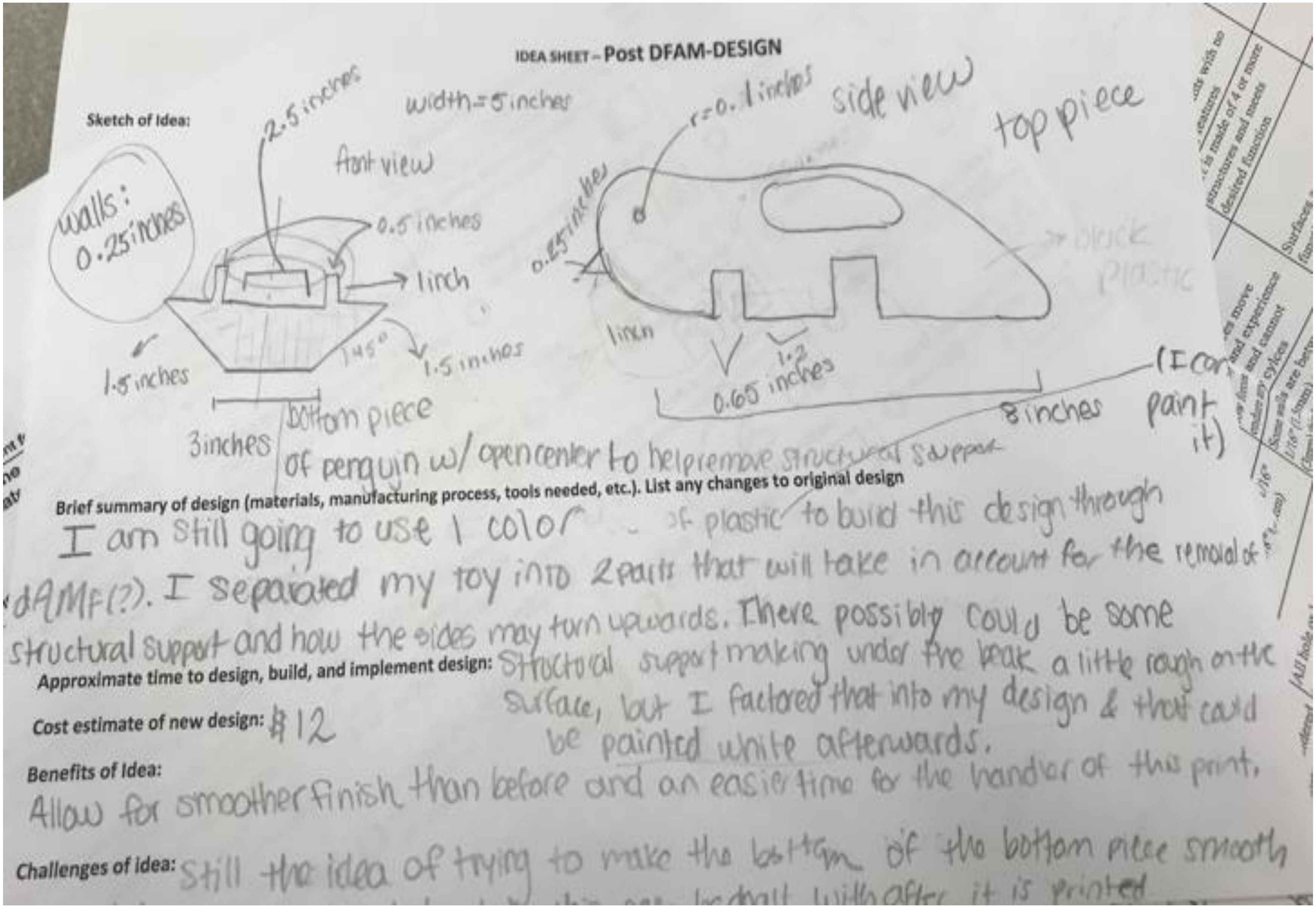
this is a sliding penguin design that could be made with some different colored plastic. I could use the generic AM manufacturing process to 3D print this design. Maybe a sander to smooth out the stomach so it slides.

Approximate time to design, build, and implement design:

Cost estimate of design: $15

Benefits of Idea: Allows children to play with more exotic animals and understand more about the arctic environment.

Challenges of idea: ensuring it is not a flimsy design, making sure the bottom is smooth enough to move



IDEA SHEET – Post DFAM-DESIGN

Sketch of Idea:

Brief summary of design (materials, manufacturing process, tools needed, etc.). List any changes to original design

I am still going to use 1 color of plastic to build this design through dAMF(?). I separated my toy into 2 parts that will take in account for the removal of structural support and how the sides may turn upwards. There possibly could be some

Approximate time to design, build, and implement design: Structural support making under the beak a little rough on the surface, but I factored that into my design & that could be painted white afterwards.

Cost estimate of new design: $12

Benefits of Idea:

Allow for smoother finish than before and an easier time for the handler of the print.

Challenges of Idea: Still the idea of trying to make the bottom of the bottom piece smooth ... with after it is printed

Appendix D: Pre-Intervention Survey

* Required

1. **Last two characters** of Mother's first name? (e.g., Amy would be MY) *

2. **Last two characters** of last name (Murray would be AY)? *

3. **Last 2 characters** of birth city? (e.g., Boston would be ON) *

4. Birth Month (January would be 01) *

5. How would you describe your gender? *

- ◯ Male (including transgender men)
- ◯ Female (including transgender women)
- ◯ Prefer not to say
- ◯ Prefer to self describe as ______ (non-binary, gender-fluid, agender, please specify)
- ◯ Other

6. Which race/ethnicity best describes you? (Select all that apply) *

- ◯ White or Caucasian
- ◯ Black or African American
- ◯ Hispanic
- ◯ Asian or Asian American
- ◯ American Indian or Alaska Native
- ◯ Native Hawaiian or other Pacific Islander
- ◯ Prefer not to say
- ◯ Other (please specify)
- ◯ Other

7. Planned major *

- ◯ Mechanical Engineering (ME)
- ◯ Biomedical Engineering (BME)
- ◯ Industrial Engineering (IE)
- ◯ Electrical and Computer Engineering (ECE)
- ◯ Civil & Environmental Engineering (CEE)
- ◯ Undecided

8. Year *

- ◯ First Year
- ◯ Sophomore
- ◯ Junior
- ◯ Senior

9. Do you have any work experience? (This can include any type of volunteer work) *

- ◯ Yes (if yes, specify below)
- ◯ No
- ◯ Other

10. What engineering careers are you most interested for a future career choice? *

	Extremely Interested	Interested	Neutral	Somewhat Interested	Not Interested
I don't know yet	◯	◯	◯	◯	◯
Process Engineer	◯	◯	◯	◯	◯
Quality Engineer	◯	◯	◯	◯	◯
Project Manager	◯	◯	◯	◯	◯
Global engineering	◯	◯	◯	◯	◯
Mechanical Engineer	◯	◯	◯	◯	◯
Biomedical Engineer	◯	◯	◯	◯	◯
Production Engineer	◯	◯	◯	◯	◯
Entrepreneur	◯	◯	◯	◯	◯
Product Designer	◯	◯	◯	◯	◯
Construction Engineer	◯	◯	◯	◯	◯
Aerospace Engineer	◯	◯	◯	◯	◯
Automotive Engineer	◯	◯	◯	◯	◯
Structural Engineer	◯	◯	◯	◯	◯
Patent Lawyer	◯	◯	◯	◯	◯
Management Consultant	◯	◯	◯	◯	◯
Civil Engineer	◯	◯	◯	◯	◯
Manufacturin g Engineer	◯	◯	◯	◯	◯

11. Are there any other careers that you are interested that was not listed in the question above? *

- ☐ No
- ☐ Yes (please specify below)
- ☐ Other

20. If you have previous experience with design for additive manufacturing (DfAM), please briefly describe what kind and the length (Semester long design course)

21. Please rate your awareness on the following Design for Additive Manufacturing (DfAM) techniques *

	Never heard about it	Have heard about it but not comfortable explaining it	Could explain it but not comfortable applying it	Could apply it but not comfortable regularly integrating it with my design process	Could regularly integrate it in my design process
Making products that can be customized for each different user	○	○	○	○	○
combining multiple parts into a single product	○	○	○	○	○
Designing parts with complex shapes and geometries	○	○	○	○	○
embedded components such as circuits in parts	○	○	○	○	○
Designing products that use multiple materials in a single part or component	○	○	○	○	○
Using support structures for overhang sections of a part	○	○	○	○	○
Designing parts to prevent then from warping and losing shape	○	○	○	○	○
Designing parts that have different material properties (e.g. strength) in different directions	○	○	○	○	○
Accommodating desired surface roughness in the parts	○	○	○	○	○
Allowing for minimum and maximum feature size allowed by a process	○	○	○	○	○

22. Please rate your awareness on the following Additive Manufacturing (AM) processes *

	Never heard about it	Have heard about it but not comfortable explaining it	Could explain it but not comfortable applying it	Could apply it but not comfortable regularly integrating it with my design process	Could regularly integrate it in my design process
binder jetting	◯	◯	◯	◯	◯
directed energy deposition	◯	◯	◯	◯	◯
material extrusion	◯	◯	◯	◯	◯
powder bed fusion	◯	◯	◯	◯	◯
sheet lamination	◯	◯	◯	◯	◯
Wire Arc Addiditve Manufacturing	◯	◯	◯	◯	◯
Vat Photopolymerisation	◯	◯	◯	◯	◯
Sterolithography (SL)	◯	◯	◯	◯	◯
Selective laser sintering (SLS)	◯	◯	◯	◯	◯

23. Please check the response below that relates to your experience with Computer Aided Design (CAD)/Solid Modeling *

◯ I have never heard about CAD/Solid modeling before this

◯ I have some informal knowledge about CAD/Solid modeling

◯ I have received some formal CAD/Solid Modeling training

◯ I have received lots of formal and informal CAD/Solid Modeling training

◯ I am an expert in CAD/Solid Modeling

24. If you have previous experience with a CAD/Solid modeling software, please briefly describe what kind and length (semester long course)

25. How many years CAD experience do you have? *

26. How valuable are the following in engineering curriculum: *

	Extremely valuable	Valuable	Neutral	Somewhat Valuable	Not Valuable
Integration of additive manufacturing	◯	◯	◯	◯	◯
Design planning	◯	◯	◯	◯	◯
Industry preparation	◯	◯	◯	◯	◯
training workshops	◯	◯	◯	◯	◯

27. How beneficial is additive manufacturing knowledge to prepare for industry? *

- ◯ Extremely beneficial
- ◯ Beneficial
- ◯ Neutral
- ◯ Somewhat beneficial
- ◯ Not beneficial

28. Please answer the following with respect to your academic activities *

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
I am good at coming up with new ideas	◯	◯	◯	◯	◯
I have alot of good ideas	◯	◯	◯	◯	◯
I have a good imagination	◯	◯	◯	◯	◯

Appendix E: Pre-& Post-test for AM and DfAM Knowledge

Additive Manufacturing (AM) and Design for Additive Manufacturing (DfAM) Pre-Test

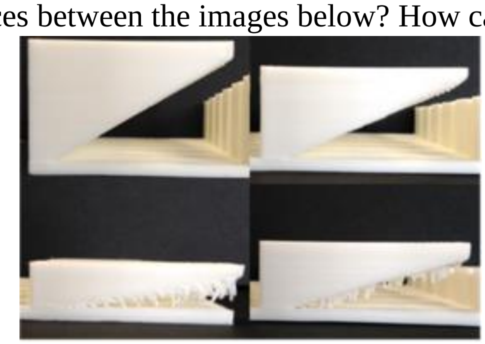
Last 2 characters of Mother's name (e.g., Amy would be MY) ________
Last 2 Last two characters of last name (Murray would be AY) ________
Last two characters of birth city? (e.g., Boston would be ON) _________
Birth Month (January would be 01) _________

1. What is additive manufacturing (AM)? Do you know the 7 categories of AM? If so, list what you know.

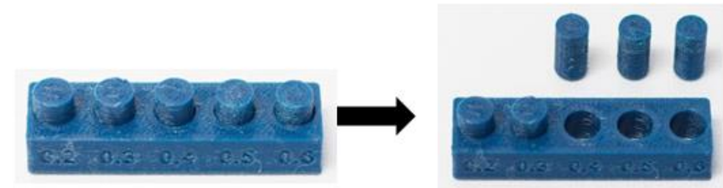
2. What are the limitations of AM? What are the possibilities of AM?

3. The part below was made on an extrusion printer. What phenomenon is shown in the image below? How can this be prevented?

4. What are the differences between the images below? How can this be avoided?



5. What restrictive design concept is being addressed in the image below? Why is this important?

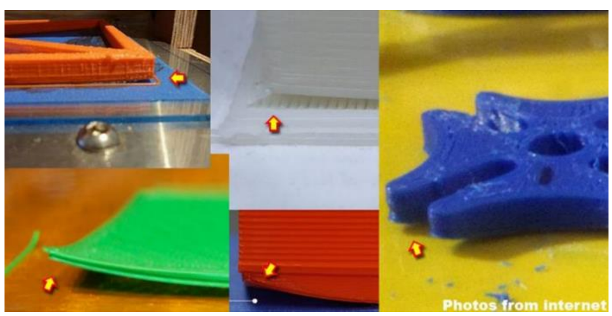


6. How can material costs be reduced? What design methods can reduce weight?

7. How can post-processing costs be reduced when designing a part that will be additively manufactured?

8. What affects a 3D printed parts' surface finish? How can stair-stepping be reduced?

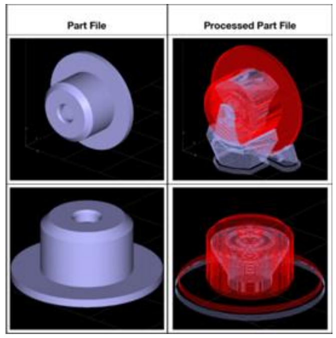
9. What is demonstrated in the picture below? How can this be prevented?



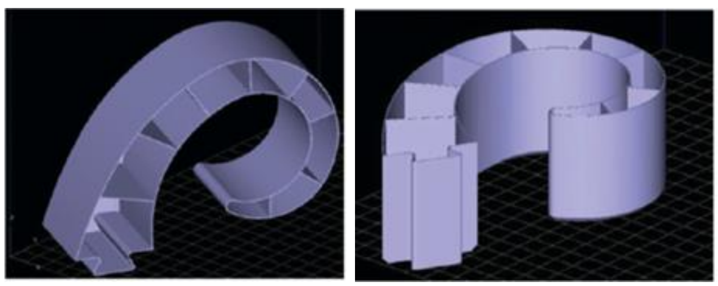
10. How can build time be reduced? Which direction (x,y,z) are material extrusion printers the slowest?

11. What are the benefits of creating parts with multiple materials?

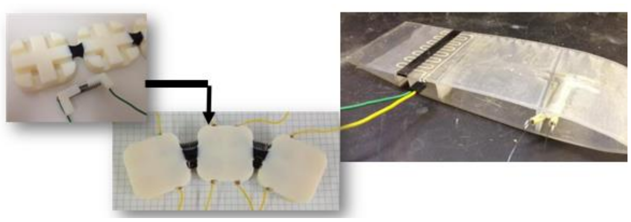
12. Which part will take longer to print? (the top or bottom 3D part?)



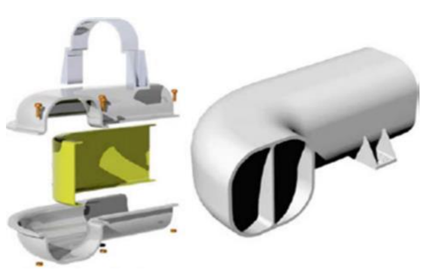
13. Which part below will result in a better surface finish after being printed on a material extrusion printer? Circle the part. Why?



14. What opportunistic DfAM concept is highlighted below? Describe what you see.



15. What opportunistic design concept is highlighted below in the images? What is the benefit?



Appendix F: Sample of student work that compares AM processes

Manufacturing Processes – ME 322

Name (CODE): 1SA2AS05

Additive Manufacturing Lab

**What AM process does the Form 3 printer use?

Vat Polymerization

Your designs will be assessed using the following categories: Time to implement, cost, and quality.

Fill in the table below to compare your first and second designs. Open Preform software and complete the chart.

	Pre - Design	**Post -Design**
AM Process:	Vat Polymerization	Vat Polymerization
Material used:	Resin	Resin
Note orientation:	Out Side of built Plate	Not at an angle
Need for support material:	No	NO
Layer thickness/height:	0.025 mm	0.100 mm
Layer Amount	3037	1371
Time to print:	Not given	24h 30 min
Estimated amount of material to be used (Volume in ml)	6,839.86 mL	428.97 mL
Approximate cost: (Cartridge of Clear Resin $149 per Liter	$1,019.14	$63.92

Draw conclusions about the printability, cost, time to implement, and quality of your designs. You will be comparing the designs for production.

The Printability of my Post-Design was not possible because it was not at an angle, but if angle the cup will be printable. The cost of this cup is very high at $63.92 and it will take 24h 30 min to Print which is also a very long time.

Appendix G: Object Process Language Example

```
Design & Manufacturing Engineer is environmental and physical.
Design & Manufacturing Engineer handles Slicing, Post-Processing,
Tessellation, and Machine Operation.
CAD Model is environmental.
CAD Model and Design & Manufacturing Engineer are equivalent.
AM Control System is physical.
AM Control System exhibits Process Parameters and Tool Path.
AM Control System and G codes are equivalent.
.STL, .OBJ or .3MF file is environmental.
G codes is environmental.
Gas Supply is physical.
Vacuum Generator is physical.
Build Plate is physical.
Material Feeding System is physical.
Material Feeding System and AM Control System are equivalent.
Finished Part is physical.
Build Rate is a Process Parameters.
Resolution is a Process Parameters.
Minimum Feature Size is a Process Parameters.
Layer-by-Layer Fabrication is physical.
Layer-by-Layer Fabrication and Build Preparation equivalent.
Layer-by-Layer Fabrication requires AM Control System.
Layer-by-Layer Fabrication consumes Material Feeding System.
Build Preparation is physical.
Build Preparation requires Vacuum Generator, Gas Supply, Tool Path, Build
Plate, and Process Parameters.
Machine Operation is physical.
Machine Operation yields Material Feeding System and AM Control System.
Tessellation is environmental.
Tessellation affects CAD Model.
Tessellation yields .STL, .OBJ or .3MF file.
Slicing is environmental.
Slicing yields G codes.
Post-Processing is physical.
Post-Processing and Layer-by-Layer Fabrication equivalent.
Post-Processing yields Finished Part.

AM Control System is physical.
Material Feeding System is physical.
Material Feeding System consists of Feed Stock.
            Feed Stock is physical.
Powder is physical.
Powder is instance of a Feed Stock.
Wire is physical.
Wire is instance of a Feed Stock.
Foil is physical.
Foil is instance of a Feed Stock.
Bar Stock is physical.
Bar Stock is instance of a Feed Stock.
Layer-by-Layer Fabrication is physical.
Layer-by-Layer Fabrication exhibits Print Head, Laser, Electron Beam,
Ultrasonic, Friction, Particle Acceleration, Electric Arc, Heat Source, and
Build Plate.
```

Layer-by-Layer Fabrication consists of Fusion/Melting.
Layer-by-Layer Fabrication requires AM Control System.
Layer-by-Layer Fabrication consumes Material Feeding System.
Layer-by-Layer Fabrication zooms into Fusion/Melting, as well as Build Plate, Heat Source, Electric Arc, Particle Acceleration, Friction, Ultrasonic, Electron Beam, Laser, and Print Head.

Build Plate is physical.
Electric Arc is physical.
Electric Arc is instance of a Heat Source.
Particle Acceleration is physical.
Particle Acceleration is instance of a Heat Source.
Friction is physical.
Friction is instance of a Heat Source.
Ultrasonic is instance of a Heat Source.
Electron Beam is instance of a Heat Source.
Laser is physical.
Laser is instance of a Heat Source.
Print Head is physical.
Fusion/Melting is physical.
Fusion/Melting requires Heat Source, Print Head, and Build Plate.