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How Deep is Your Knowledge? Consideration to the Breadth and Depth of Knowledge of CAD/CAM in M3-powered Technology CTE Classes

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How Deep is Your Knowledge? Consideration to the Breadth and Depth of Knowledge of CAD/CAM in M3 Powered Technology CTE Classes

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Abstract

The Making as Micro-manufacture (M^3) model describes an approach for authentic learning experiences for production in high-school classrooms. M^3 couples the practice of Making (electronics, use of computer-controlled fabrication machines, and programming) with production engineering processes to produce highly customized, low batch-volume products, such as instructional science kits for elementary school classrooms. Of the skills students learn, Computer-Aided Design/Computer-Aided Manufacturing (CAD-CAM) is a key facet to the use of fabrication tools (e.g., 3D printers or laser cutters) in the M^3 model. One problem, when taken into consideration of an M^3 implementation, is to what ends should CAD-CAM skills be covered in the class. How can students be effectively taught CAD-CAM essentials for practical use in M^3 while still avoiding a deep dive into the minutiae of the software/hardware considerations?

This paper highlights a CAD-CAM sequence taught within an online distanced M^3 powered class. We performed qualitative and quantitative analysis of student's submitted assignments and recorded interactions with online mentors, demonstrating how students develop core CAD-CAM skills and identify key challenges students face in the M^3 structured class. Findings from the study illustrated how students were able to develop core competencies such as in CAD-CAM while characterizing the kinds of mistakes that students make in developing said competencies. We conclude on the illustration of a future iteration of an M^3 curriculum, one where the challenges students typically face in CAD-CAM are purposefully woven into the assignments themselves, serving as a way to provoke awareness and improvement in skill development.

Introduction

'Making through Micro-Manufacturing' (M^3) [1, 2] provides a model of how to couple the flexibility of 'Making' with the concerns of production engineering. Such an approach in production emphasizes customizability and personalization in product design. Because of the interdisciplinary nature of M^3, this production paradigm calls upon a variety of skills across Making (e.g., programming, digital fabrication, basic electronics tool use, and theory) along with production engineering concerns (e.g., volume production and supply lines). Altogether, M^3 illustrates a means for how to design and produce a wide array of products that can reflect the interests of both creators and consumers. Through M^3, creators' production process can go beyond the traditional 'boutique' manufacturing approach (i.e. the production of a singly produced, specific artifact) to the production of many.

M^3 as a production approach has implications for how we might educate students starting from high school for jobs, education, and leadership roles that will likely arise from this paradigm. An approach like this could be applied in a high-school technology career and technology education (CTE) classroom where students engage in these varied subjects. Students in an M^3 based CTE can engage in Making and production concepts in an applied setting, directly applying knowledge in the design, prototyping, and production of end-use products. Where students are lacking knowledge in a certain domain, students can seek solutions through their peers, mentors, or online communities. Such an applied approach of these varied subjects would need a horizontal approach, where the focus isn't necessarily depth in any one subject area (while the student ought to have certain core competencies as to be literate in that subject) but to have a wide knowledge base that is integrative in their interdisciplinary dependencies in-situ.

Computer-Aided Drafting and Computer Aided Machining (CAD-CAM) is one of the myriads of subjects that students are exposed to in M^3 [3, 4]. CAD-CAM is used by practitioners to support the design of original parts (e.g., parts for a multi-segmented lamp with appropriate fits for electronic components), the re-mixing of pre-existing model files found on online repositories (e.g., reshaping the model file for an Arduino case for a robotics project), and specification of machine code for end-product use or prototyping (e.g., printing out the aforementioned lamp geometry with 100% infilling for appropriate strength). The need for students to use CAD-CAM in a multi-disciplinary environment, such as the case of M^3, reflects a wider need for the tool itself to support the design and implementation of products in industry [5, 6]. Owing to the ubiquity that CAD-CAM offers to industry, one should take consideration to its use as an element in engineering pedagogy in relation to ABET Student Outcomes [7]. Criterion 3 of student outcomes is concerned with the issues of how students apply engineering knowledge, identify problems, and communicate with various audiences, a function to which CAD-CAM can serve as a medium for the ideation of design concepts, prototyping for design exploration, and production at various stages to communicate iterative changes across stakeholders. CAD-CAM should also be considered in light of criterion 7, facilities, where not only students learn how to use CAD-CAM as a kind of software for engineering design, but also as a means for production whether it may take place in the prototyping or final production stage, necessitating an understanding of how to operate assorted machines (e.g., 3D printers, CNC machines, laser cutters) for production. Altogether, CAD-CAM is a facet one should take in consideration for the training of K-12 students for either industry or for higher education.

Despite what CAD-CAM can offer for industry, education, and the interplay of the aforementioned in M3, there are certain challenges associated with the tool. First, CAD-CAM is inherently time-consuming to develop skill in its use; oftentimes working mastery of CAD-CAM is needed in the classroom with less than a semester's time [6]. In addition, CADCAM courses often required continual learning over longer periods of time beyond a single course. Second, supplementary materials used by instructors in teaching CAD-CAM is often aligned with the implementation of a specific CAD-CAM system, focusing more on operational knowledge and less on the more generalable content matter for practice (e.g., a typical instructional text would describe the steps in selecting the appropriate user interface options to operate the virtual camera on screen as opposed to providing familiarity with the spatial-visual relationships that are needed to properly orient virtual camera). These noted challenges are present in university-level engineering coursework which is already limited in terms of time constraints.

The M^3 model describes an approach for authentic learning experiences in the classroom. In the context of M^3, there are many other subjects and activities that demand equal attention; with the noted challenges in CAD-CAM education, there is a potential problem for students to successfully understand and wield CAD-CAM as a tool in an M^3 aligned curriculum. We pose the following research question for our work: **How can students be effectively taught CAD-CAM essentials for practical use in M^3 while still avoiding a deep dive into the minutiae of the software/hardware considerations?**

In pursuit of this question, we observed a CAD-CAM sequence taught within an online distanced M^3 powered class. We organized our CAD-CAM sequence in accordance to a scaffolding informed pedagogy [8]. Scaffolding refers to the ways in which instructors can help students to engage in a task that is beyond the student's immediate ability and knowledge [9]. The idea is that the task in question is simplified in such a way that students can take on the task in a way close to the existing abilities of the student while serving as a way for the student to focus on a particular skill at the time of instruction. By taking this approach, student's can develop skill, knowledge, and independence in the topic of focus, enabling the student, when assessed by the instructor, to gradually transition to more advance topics [10, 11]. Scaffolding influenced the design of how we introduced concepts in CAD-CAM to students as we shift focus from different topics through the life of the online CAD-CAM sequence. By emphasizing specific concepts such as CAD-CAM operation and then, after appropriate assessment and remediation, we can then lead students to shift focus on more specific topics of skill such as multi-plane modeling or modeling for real-world use. In this paper, we will highlight how students develop basic competency in CAD-CAM operation as they initially focus in control and transition towards the topic of modeling for real-world use.

Learning Outcomes and Metrics

Below, we describe the expected learning outcomes of students after online, practice-based learning class and our metrics for said outcomes.

Virtual Camera Manipulation

Outcome: Virtual camera manipulation refers to how one can control the existing viewport of a given CAD-CAM system so to closely examine the elements of interest in either 2D or 3D space and perspective. Students will demonstrate competency in using this CAD-CAM control by how the relative proportion of object model relationships. Practically, models will be placed in a manner using the camera where placement is based on an understanding of their relationships across various perspectives as models are aligned to another while avoiding unintended gaps of space between them.

Metric: We will examine if there are instances of floating geometry, this referring to erroneous placement of geometry in 3D space with the student's expectation that they are aligned with other geometry from a given perspective but not accounting for other perspectives that indicate that it is either ahead or to the back of the objects of interest for alignment.

Geometric Modeling

Outcome: Students will produced models using additive and subtractive modeling techniques. These produced models will be created from CAD-CAM system provided geometric primitives and will be made distinct by the demands of visual and functional requirements for modeling.

Metric: We will examine if there are instances where primitives are built up to complex forms using either additive or subtractive techniques. Primitives should be modified for the purpose of supporting the visual and functional requirements of the modeling assignment.

Object Transformations

Outcome: Students will be able to apply three dimensional transformations such as translation, rotation, and scaling to situate geometric primitives in 3D space. This is a critical step in CAD-CAM where objects are produced based on the relative position of geometric primitives with respect to one another.

Metric: We will examine if there are instances where models are transformed across the 3D space to support the visual and functional requirements of the modeling assignments.

We assessed student's gradual performance through the use of two CAD-CAM assignments, one taking place immediately after the focus of the before mentioned outcomes and one assigned later on for the purpose of modeling for real-world use. The assignments will be described in section 4.3. In the sections that follow, we will demonstrate how the CTE classes are taught core CAD/CAM skills and how students and college-aged STEM mentors work together to achieve learning goals.

Background

Defining Making

Making refers to the 'Maker Movement', the burst of personalized and technically adept artifacts produced by hobbyists and professionals. The explosion of artifacts arising from the Maker movement can be attributed to the greater availability of electronic and computer components alongside advancements in access to and use of fabrication technologies (e.g., 3D printers) [12, 13, 14, 15]. The major implications of this movement is the diversity and wide proliferation of technology with a higher level of sophistication and design artifacts that can be produced and consumed by society.

Broadly speaking, the practice of Making refers to the creation of any kind of tangible artifact spanning anything from sketches to manufactured products [16, 17, 18, 19]. What is critical to Making is the context in which these artifacts are made and the community's cultural practice towards technology interest and practice. For the context of our work, we frame Making from an agnostic perspective toward what equipment or facilities are used, instead focusing on the emergent cultural practices that arises from the community it takes place in.

Making has been recognized for its support in the classroom, where students are able to directly apply science concepts directly in projects gaining both lived-experience of science concepts as well as the development of self-efficacy in said concept. One challenge to this benefit is the issue of situating Making in the classroom. Currently, Making is scaffolded in the classroom with kits. Kits such as LittleBits [20], Lego Mindstorms [20] can enable Making experiences in the classroom but because of their design for accessibility, this same design constrains the range of what the kits can do or obfuscates how any STEM concepts may exist outside of the classroom [21].

Defining CADCAM

CAD-CAM involves designing components via the joint use of modeling, prototyping, and the generation of programs to produce solid, physical products [3]. Effective use of CAD-CAM systems depends on the mastery of processes across the various systems [4]. CAD-CAM is a ever-changing field driven by developments across software, hardware, information technology, and core theories on modeling, design, and manufacturing. Because of this fluid, advancing nature, CAD-CAM proves to be challenging to be mastered by practitioners [3].

CAD-CAM skills take place in the actions such as modeling prismatic parts and rotational parts or creating assemblies [6, 4]. Activities include software familiarization (e.g., CAD and CAM programming), hardware familiarization (e.g., CNC machines or 3D printers), and integration of the aforementioned technologies [22]. Core CAD-CAM skills identified by Jerz et al. include 1) "Develop the ability to use computer-aided design (CAD) software and create part models, assemblies, and drawing." 2) "Understand CAD/CAM technologies and ability to create physical parts." 3) "Understanding of engineering graphics principles and how designs are communicated in industry." [6]. In addition, engineering graphics core-competencies include paper and pencil drafting skills (e.g., orthographic views, working drawings, dimension, isometric views), as well as 2-D computer-aided design and 3-D solid modeling skills [6, 5].

Students can best learn CAD-CAM by following a sequence of exercises that emphasize hands-on involvement. In addition, students can benefit by having access to audio-visual demonstrations that best demonstrate best-practices [6]. Djassemi describes an approach to a CAD-CAM course focused on hands-on experience with integrated product design and its situation for manufacturing and rapid prototyping [22].

Methods

Study Context

Through our university's prior relationship with work in the South Texas border communities, we were able to set up a connection with local schools to pursue a collaborative relationship to investigate how the M^3 model can serve to situate Making in the classroom setting, emphasizing a hands-on approach to learning on aspects such as tool-use and production processes.

M^3 in the Classroom

Through the M^3 model, Making is situated in an environment where products are designed with consideration to the expectations and deadlines of its stakeholders. Figure 1 characterizes the framework for our M^3 aligned class. In designing the course, to the production process of the kits, we identified the core skills needed for the students, these being Making (e.g., soldering, wire connections, 3D fabrication) and production engineering (e.g., volume production and supply lines) skills.

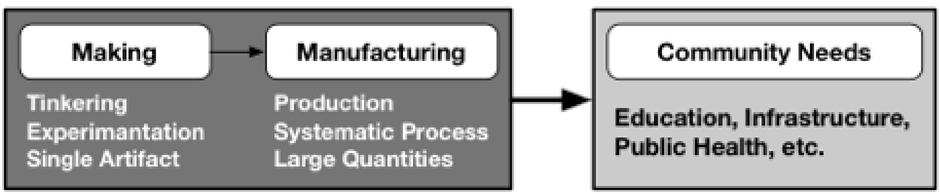

Figure 1: Micro-manufacture model

In the course, we supply students with a fully furnished Makerspace, teaching them the core competencies required to operate the associated tools, skills, and production processes needed to act in an M^3 production pipeline. Class was conducted by an undergraduate or graduate student acting as a mentor to hold class via teleconferencing applications. Initially, the mentor teaches students basic skills related to producing kits considering both concerns for Making and production engineering. After students demonstrate core competencies in practice, we have the students engage in a 6-week production line for producing instructional science kits (Figure 2). Each instructional science kit involves a mix of electronics and 3D printed parts that serve to model science concepts.

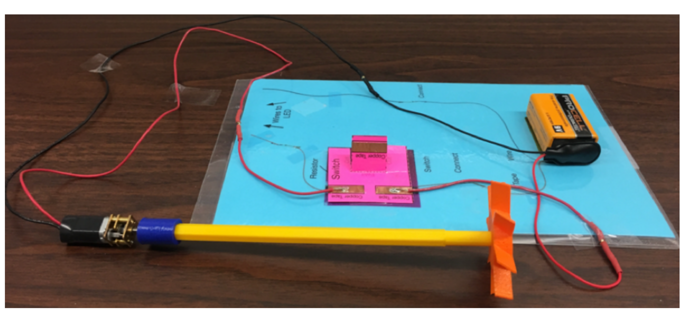

Figure 2: Example instructional science kit produced by high school students.

Initially, students work under a production trial run without the pressures of an exact customer to consider, the purpose of which is to expose the students to what a potential production schedule could look like. Towards the later 6 week periods of the school year, the students are then expected to produce and deploy the instructional science kits in participating local classrooms. The eventual goal of the course is the eventual mastery and semi-autonomy of students to act as a low-volume production shop; figure 3 summarizes how the role that students in the class serve as a Making-production team and their relationship to their client (i.e., elementary school science classrooms) and support (i.e., the University research team and mentors).

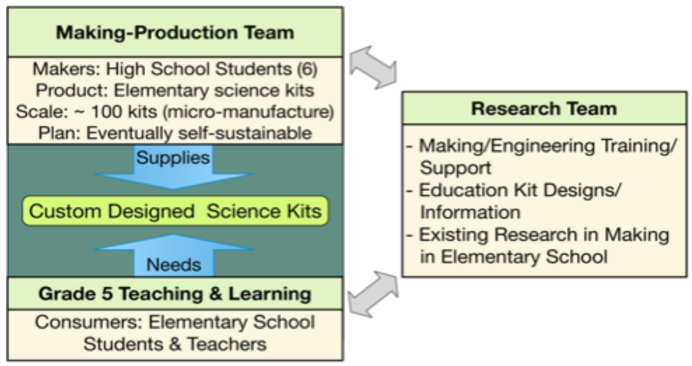

Figure 3: M^3 in the Colonias relationships across highschool students, elementary school teacher, and university support team.

CAD-CAM in the M^3 Class Context

CAD-CAM is one of the essential core skills that are needed by students in our M^3 program to aid in the production of instructional science kits. CAD-CAM skills are utilized to model new parts for use in the kits themselves, to modify existing model files found on online CAD model repositories (e.g., Thingiverse), and finally, CAD-CAM skills are used in interacting with the 3D slicer programs that are used to take 3D files and ultimately fabricate physical 3D objects for practical end-use in the instructional science kits.

During the year 2020, owing to the COVID 19 Pandemic, our present study population was shifted to purely online supported (i.e., asynchronous communication by way of Slack and synchronous communication by Zoom teleconferencing application). Instructors used this current state of events to emphasize content that could be readily engaged with the resources available by students. There was a total of 7 individual class assignments that took place over a period of 1 and half months. Two instructors were assigned to two different groups of high school students to conduct the course.

Orientation to TinkerCAD

Here we will describe one of the areas of CAD-CAM we emphasized core-skills. We examined outcomes through a lens of fabrication to highlight the potential of models for eventual 3D print and end-use. The first-class assignment focused on orienting students to the TinkerCAD web application. Instructors taught students how to use the virtual camera, how to model geometry through the use of existing geometric primitives, and how to perform object transformations (e.g., translation, rotation, and scaling) through the manipulation tool (Figure 4).

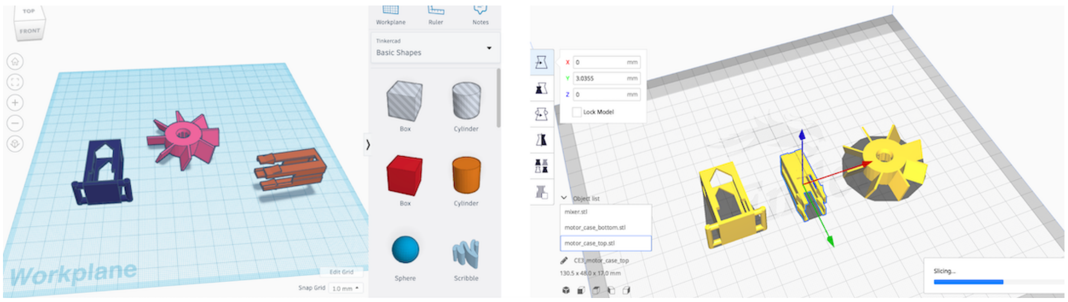

Figure 4: TinkerCAD Web Application. Left image displays 3D models in TinkerCAD. The right image shows the same models placed in the Cura 3D slicer program for 3D print preparation.

Instructors assigned two kinds of course materials using both asynchronous and synchronous methods to support students' learning objectives. Aynchronous materials include instructor assigned tutorials and interactive demos that are available via Autodesk's TinkerCAD web application portal. Synchronous materials include instructor led demonstration of TinkerCAD, using basic examples of use such as pointing out the controls for manipulating the virtual camera, creating geometric primitives, and modifying geometric primitives by way of transformations (e.g., translating a cube along the x-axis) or by modeling (e.g., combining geometric primitives to produce a humanoid shape) (Figure 5).

After students reviewed relevant online videos and followed after the instructors' example, the students were given a modeling assignment. The assignment, creating a house, required students to apply camera controls, transformations, and additive/subtractive modeling techniques to complete the task. Students were expected to create geometry for the external appearance of the house (Figure 8).

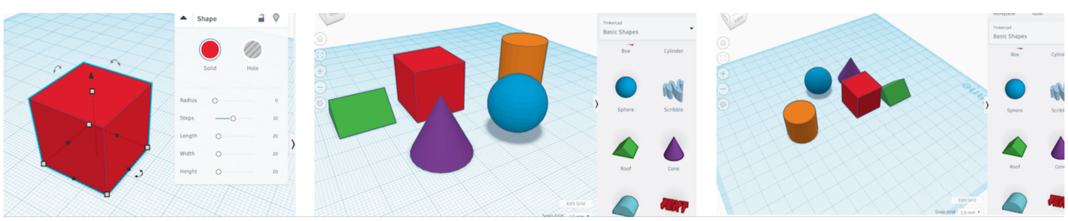

Figure 5: Left image: Rotation, scale, and translation tool used on a cube primitive. Middle Image: A set of geometric primitives available in TinkerCAD. Right Image: User-controlled scene change by virtual camera.

CAD-CAM Assignment for Sequence

We examined two of the students' assignments after they mastered core skills in CAD-CAM in Tinker-CAD.

The first assignment, 'House', we examined how 'Correct Modeling','Correct Camera Use', and'Sufficient Transformation of Primitives' were exhibited by students' submitted assignments.

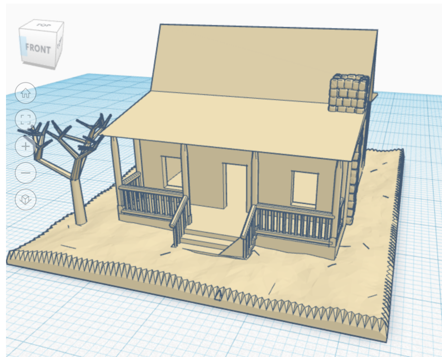

Figure 6: Example of a TinkerCAD created house produced by a student from the CAD-CAM sequence.

The intent of the assignment is for students to use the combined skills noted previously to produce the exterior of a model home using a single-story plan. Students were expected to use their modeling skills to appropriately shape construct the visual appearance of a house to motivate students to model towards sufficient complexity away from supplied geometric primitives.

The second assignment given to students in the CAD-CAM sequence required students to rely upon skills that were assessed in the first assignment in order to create a name plate using the additional tool, the work-plane. The work-plane tool enables the user to situate geometry with respect to any plane that can be identified within the modeling space (Figure 7). For example, to situate a cube exactly on one of the faces of a cylinder, students would select the work-plane tool, drag and drop the work-plane visual on an identified face, the modeling scene's build plane will then be oriented with that face. From there, the student can then place geometry oriented to the face, now recognized by the program as the main orientation of the modeling space.

Through these two assignments, we will demonstrate student's learning outcomes where students first acquire core CAD-CAM skills and then apply said skills in a precise application scenario, as presented by the second assignment.

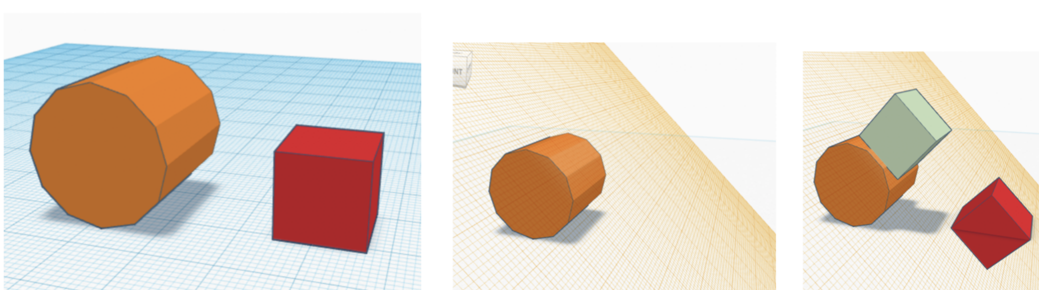

Figure 7: Using TinkerCAD's work-plane tool to situate a cube onto the faces of a cylinder relative to its orientation space.

Results

Our approach to teaching CAD-CAM in the context of M^3 is still in-progress as we continue to investigate approaches of how to situate it within a horizontal learning environment. Here we will describe preliminary data on our curriculum approach specific to CAD-CAM across all 3 classes. We'll describe findings from students' activities in CAD-CAM activities.

In figure 8, we characterize students' performance in the core CAD-CAM skills we taught students. From the "House" assignment, we found that 7 (63.3%) of the students' submitted assignments demonstrated 'Correct Modeling', 8 (72.3%) of the students' assignments demonstrated 'Correct Camera Use' and 'Sufficient Transformation of Primitives' out of the total student assignments submitted (N=11). Of the student's assignments that did not match our metric, deviations from proper use could be attributed to using either additive or subtractive modeling techniques but not in combination with one another, floating model geometry as a result of erroneously placing it without examining the view from other angles, or the house model appears to simple to still recognize the primitives it was based on.

Figure 9 characterizes how students fared in the second assignment, "Name Plate", where students extend their existing CAD-CAM skills to include the work-plane tool. Of the students' admitted assignments (N=10), 5 (50%) of the students' assignments demonstrated correct camera use and 9 (90%) of students' showed correct modeling with the incorporation of the work-plane tool coupled with existing additive and subtractive modeling tools. On camera use, the lowered performance in students' use of the virtual camera can be attributed to how students were still developing an understanding of how to operate the virtual camera where world orientation changes relative to a surface as opposed to the existing orientation by default. The single instance where a student's assignment did not demonstrate correct modeling was where the name plate had the appearance of the intended design, the student's assignment did not create a geometric model from combining primitives but was the result of a primitives transformed (e.g., student moved letter primitive geometry in place on plate geometry) but did not combine them as a single, distinct geometric model. While the issue does not effect the model in terms of visual appearance, the issue could be problematic if the student were to move the nameplate model in thinking it was a single piece but instead would separate the primitives in moving pieces.

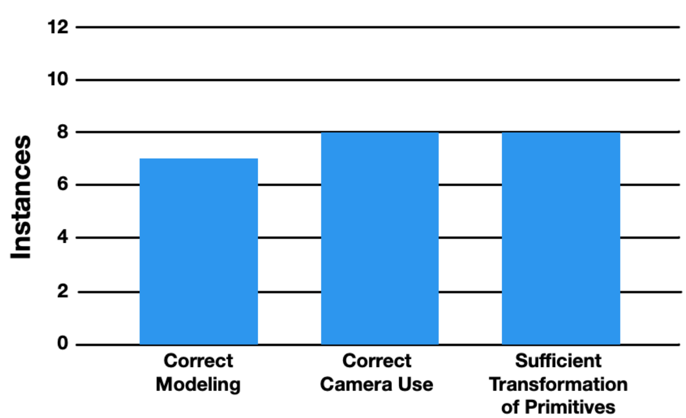

Figure 8: Frequency counts of TinkerCAD design elements by student assignments in Orientation

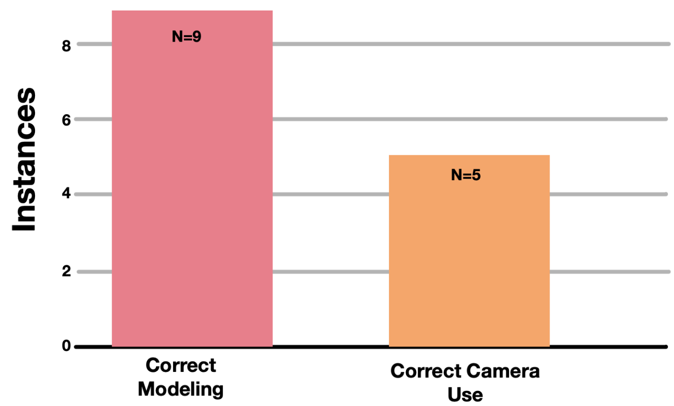

Figure 9: Frequency counts of TinkerCAD design elements in the ”Name Plate” assignment

Discussion

CAD-CAM courses are subject to the challenge instilling key skills in students in a constrained time span, more-so in an M^3 curriculum where there is the added issue of other subjects to expose students and need to engage in hands-on, scenario-driven projects. Here, we will consider approaches on how to pinpoint on key areas students struggle with and how they might be remedied in future iterations of our M^3 curriculum.

To address camera manipulation competency, outside of basic operation, we could design an assignment where students can situate geometry through geometric transformations like translation but asking students to perform the transformation across viewing perspectives and projection types. The purpose of an assignment like this would expose students to the idea of how relative location of geometric objects can vary based upon view point and the need to maintain cohesion across all points in design.

As students build upon their skills in camera manipulation, the next assignment we could give to students could emphasize both additive and subtractive modeling in simple shapes such as letters. In terms of sequence, we could have students engage in additive, subtractive, and combined approaches in isolation from one another. The purpose of the approach would serve to illustrate to students to the potential that the modeling tools and their variations can serve in various modeling scenarios.

Limitations

One challenge we faced was the primarily online experience of the students in the classroom. Owing to the restrictions in class representation, students were unable to physically access the necessary equipment to fabricate the projects they have created during the sequence. As restrictions will be removed in the future, we plan to incorporate regular cycles of fabrication so students can see the end-effect of their designs in CAD-CAM software and understand the implications of the production pipeline concerning computationally fabricated geometry.

Another issue of concern is the lack of an immediate comparison group lacking the treatment described in this paper. As the study progresses in future iterations, we will examine an appropriate analogous class to further validate the approach described here.

Conclusions

M^3 provides a model where the combined skills of Making and production engineering can create a authentic learning experience for students for flexible, low-run volume production. There are a variety of skills and knowledge that students are exposed to in an M^3 informed classroom, CAD-CAM of which is the interest of this work. A challenge in designing such an M^3 class are the demands that comes with functional use of CAD-CAM is the time required to develop competency while there are other subjects students are gaining experience in within the course. Of interest to engineering education, we used a scaffolding methodology where we isolate certain facets of CAD-CAM practice so students can develop skill and later translate that skill to more advance topics, we could potentially address the aforementioned issue in CAD-CAM's inclusion in a M^3 classroom. Our approach can serve as a example of how to pinpoint CAD-CAM topics for emphasis and how to transition from topics of interest in light of limited class time for functional use by students. We were able to demonstrate a sequence in which CAD-CAM was situated within a M^3 powered classroom where students learn a variety of different skills that could be utilized to engage in design and production. In addition, we were able to identify and quantitatively characterize the areas where students' tend to struggle when developing mastery of skill competency in CAD-CAM, pointing to ways we could design assignments to help students hone their skills.

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