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Making STEM real: the design of a making-production model for hands-on STEM learning

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ABSTRACT
In the face of information technology changes, not all students will have access to the means to prepare for this future of work. In addressing this issue, in this study, the authors investigate the impact of a 'Making as Micro-Manufacturing (M^2)' model in motivating STEM-activity participation and developing self-efficacy among high-schoolers hailing from an underserved community. The approach involved integrating practice-based learning and activities into a high-school class curriculum resulting in the production of small-batch volumes of products in real-world settings for everyday use like instructional kits for elementary school learning. Pre- and post-surveys were administered to ascertain the differences in students' Making and engineering self-efficacy tendencies. Our results saw increases in the students' Making and engineering self-efficacy across multiple dimensions and in-situ during a production process. In addition, our results also quantify and characterize that kinds of helping behaviours that occur in the students' own self-organised production team.

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Making; production; manufacturing; STEM identity; self-efficacy

Introduction

With digital information technology becoming ubiquitous, rapid changes have been taking place in the modern workplace. Under such circumstances, there is a pressing need to prepare students for the changes taking place in the workplace while anticipating how this same workplace will transform as advancements in technology will take hold. As technology continues to advance and change how we understand our roles in the workplace and what we can do, students must develop both technology fluency and flexible, self-guided learning schemas (Flinchbaugh, Valenzuela, and Li 2018; Ross, Romich, and Pena 2016). Students can obtain such outcomes through the possession of both STEM knowledge and self-efficacy.

In the face of these apparent changes, one question that comes to mind is the issue of equity, particularly that of rural and minority students, these being underserved communities. Equal opportunity for participation in STEM is not a constant, adversely affecting students hailing from underserved communities, limiting these students' potential to pursue STEM careers. Such a limitation can be attributed to two factors. First, owing to limited opportunities (attributable to dual trends of specialising less in sciences as well as difficulties in underserved communities to attract and retain qualified teachers; Barbour 2007; Barley and Brigham 2008; Simonson et al. 2006) to learn STEM content, they subsequently do not achieve the identity formation and self-efficacy that

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comes with practice and engagement with STEM. Second, owing to established self-confidence in STEM, students from underserved communities could be discouraged from pursuing STEM-related post-secondary education or jobs past high school.

One potential solution to broadening STEM exposure and self-efficacy for students is to consider the benefits of Making in STEM learning. Making is commonly understood as the use of fabrication technologies (i.e. computational fabrication tools like 3D printers producing prototypes for quick design and re-design turnaround times) for the production of personally defined objects (i.e. creating a consumer quality drone through the joint use of 3D fabricated parts and available electronic components). Educators have acknowledged how Making can instil the values of personal production, community, and problem-solving attributes that can be conducive to STEM learning. The rationale for such an interest is in the argument that those who engage in Making could develop a mindset that empowers one to think in an optimistic matter, possess the resilience to persist in the face of challenges, and the means to draw on personal hands-on experience and on others to overcome these challenges (Wyld and Dierking 2015). Such a frame of thinking, termed the 'Maker Mindset', can potentially serve as a vehicle for students to develop deeper mastery of STEM concepts relevant to their daily life and future careers. Owing to the locality of rural communities, Making has the potential to act as a public utility to support creativity, learning, and openness with one another, more so when such a Maker culture is far from a large population centre (Ensign and Leupold 2018).

In recognition of the aforementioned benefits in the classroom, there has been a variety of different Making-inspired interventions to instil active STEM engagement. Examples of such interventions include Lego Mindstorms (Church et al. 2010), LittleBits (Career and Technical Education Texas Essential Knowledge and Skills 2014; Bdeir 2009), and Makey-Makey (Collective and Shaw 2012). However, despite the purpose of these kits, they all share a major limitation in their design enabling transferrable STEM learning. These kits are what can be considered 'sandboxed' in their latent STEM concepts. What we mean by this is while students can engage in STEM concepts in the previously mentioned kits, because of the kits' designed need for accessibility by age and classroom management, the STEM concepts are difficult for students to recognise in real-life scenarios (Jenkins and Bogost 2015).

Our work describes a pedagogical approach that makes the latent concepts of STEM visible to students while still conferring to the Maker Mindset, creating a practice-based learning environment where students develop a breadth of skills in STEM and deepen these same skills through community-centred products. We do this by extending Making beyond the typical boutique manufacturing approach where products are made through artisanship and with limited automation. Instead, we add the attributes of manufacturing and production at the scales of low-volume production, necessitating students to develop deep, self-constructed knowledge and practice. Students can develop such practices because where boutique manufacturing does not require repetition (i.e. products do not require repetition are made manually using limited means of automation; Kera 2012) in the inclusion of manufacturing attributes, students can become aware of issues such as scaling and repetition, modular design, flexible processes, and resource management. We describe this approach as 'Making through Micro-Manufacturing' (M^2). M^2 combines the practices of Making with the concerns of manufacturing and production engineering, scaled at the tens of hundreds, rather than the larger scale normally assumed in large-scale mass manufacturing paradigms. Through this approach, students can achieve STEM learning outcomes and self-concept development. In pursuit of this interest, our paper poses the following research objective:

We seek to create a Making-based classroom curriculum such that students can develop a Maker Mindset such that the STEM learning benefits can be conferred.

In addressing our research objective, we will pose the following research questions:

Research Questions	Contribution to Research Objective:	Metric of Effectiveness:
RQ I: Are there significant differences in students' Making skills attainment after year 1 of the M^2 based program?	By examining the changes in students' self-assessment in Making across year 1 (training period), we can determine if students have experienced changes in their self-concept on these subjects.	Examine students' yearly pre and post assessments of their Making self-efficacy, using an adaption of 'Sources of Self-Efficacy Scale' (Schlegel et al. 2013).
RQ II: How did students transfer their Making practices M^2 production after year?	By examining the inflection point represented by the transition from classroom-developed knowledge in M2 practices to the application of these same practices in real-world, time-pressured scenarios, we can characterise how students respond to the pressure and how their self-assessment improves through experience in real-world scenarios.	Examine students' weekly Making and Engineering self-efficacy to account for how self-concept changes as students transition from instructor-driven course delivery to student driven by problem-based learning and time pressure for product.
RQ III: How is the Maker mindset represented through problem solving across members of the M2 classroom?	In the Maker mindset, individuals possess the means to either solve problems faced in the form of one's own accrued knowledge or seeking help towards more knowledge others. As the M2 classroom develops established practices by the end of year 2, we can demonstrate how the Maker mindset can manifest, characterising the behaviours of students.	Examine students' daily practices in class and characterise different types of practices that are initiated by students.

Our paper will answer these research questions by examining a Making classroom informed by the M^2 production model (Mitchell et al. 2017; Okundaye et al. 2018a, 2018b). We will design the Making classroom where the application of Making and production skills are situated in time-pressured, real-world scenarios for manufacturing and production with client concerns. We assess outcomes in students' professions through the products of their managed course projects tests, surveys, and interviews. This paper is structured as follows. First, we will present background work detailing Making, the M^2 model, and our pedagogy that informs and guides our work. Next, we will detail our curriculum and classroom implementation over our 2-year longitudinal study. Then, we will analyse our results, focusing on the impacts of this project on students' STEM learning and self-efficacy.

Relevant background on techniques and strategic frameworks

In this section, we will proceed as follows. First, in the subsection, 'Techniques Utilized in "Making through Micro-Manufacturing" (M^2)', we will describe Making and its benefits to STEM learning, while noting the existing weaknesses in prior Making interventions from literature. We will next cover the M^2 production model, highlighting it as a means to 'ground' Making in the classroom. In the next subsection, 'Strategic Frameworks for Situating M^2 as a STEM Learning Model', we will discuss the theories of 'Communities of Practice' and 'Zone of Proximal Development', highlighting their utility in flexible learning scenarios. Finally, we will detail our collective theoretical model that brings together the approach discussed here and how it informs our curriculum design.

Consideration to self-concept and self-efficacy for STEM learning outcomes

Identity development has an important role in how individuals, specifically students, develop capability and identification with a specific subject. Self-identification refers to how one understands themselves in a specific role or performance domain, representing a part of one's own self-concept (Osborne and Jones 2011). Building on self-identification, self-concept is the entirety of one's understanding of the self, arising from the various activities that make up one's daily life (Bong and Skaalvik 2003). Self-concept is malleable subject to change as one engages with their lived-in experiences of the environment (e.g. outcome interactions with peers or materials; Bong and Clark 1999). An individual can experience self-concept cognitively (i.e. the awareness and understanding one has for their traits and abilities) and affectively (i.e. one's own sense of self-worth subject to approval or disapproval at any given time; Bong and Clark 1999; Covington 1984; Pajares and Valiante 1999). Self-efficacy is a sub-component of self-concept that is concerned with how individuals cognitively assess their own capability to perform a given action, or as defined by Bandura, 'the conviction that one can successfully execute the behavior required to produce the outcomes' (Bong and Clark 1999; Pajares and Valiante 1999; Bandura, Freeman, and Lightsey 1999).

Consideration to self-concept and self-efficacy has relevance in how the Maker Mindset can be conferred to students in STEM, specifically how students appraise their own skills and see themselves involved in STEM. For example, control theory points to how one's self-concept can serve as a guiding force to drive motivation and decision-making specific to a domain (Carver and Scheier 1982). Through the lens of control theory, in the context of high-school students' pursuit of STEM, can factor into decisions towards such as what they believe themselves capable of doing and whether or not it is feasible, based on self-concept, to pursue an education and career in STEM (Erikson 2007; Schlegel et al. 2013; Wurf and Markus 1991).

Techniques utilised in 'Making through Micro-Manufacturing' (M^2)

Making generally refers to activities taken on by individuals that focus on the creation of self-designed artefacts utilising fabrication tools that enable their customisation for their own personal end-use. Making is often understood to involve the joint use of fabrication technologies such as 3D printers to create structures that hold together electronic components and computing hardware to create interactive, personally defined objects (i.e. creating an interactive LED umbrella through a 3D printed case holding an Arduino with 3D printed LED connectors attached to the umbrella). The rise of the 'Maker Movement' can be attributed to the joint availability of programming libraries, digital fabrication equipment, and electronic components to support the depth and sophistication of Making projects we know today (Baudisch and Mueller 2017; L. 2009).

Outside of the general description of Making, there are several definitions, each providing a different lens of analysis to uncover the practices of Making. Martin (2015) defined Making as a class of activities centred on the practices of designing, building, modifying, and repurposing materials for a novel or utilitarian end-use. Sheridan et al. (2014) viewed Making as creative activities based on the convergence of art, science, and engineering, where individuals use digital and analog technologies to explore ideas, learn technical skills, and create new products. Similarly, Kuznetsov and Paulos (2010) interpreted Making as part of 'Do-It-Yourself' (DIY) practices which primarily focuses on creating or modifying objects through one's skills and acquired knowledge. The above-mentioned definitions serve to describe how Making has been understood and discussed within the contemporary literature. For the purposes of this work, we will define Making through the combination of these varied definitions, where collectively, Making is the self-motivated construction of personally defined artefacts via the joint use of skills in the following technologies: (1) basic electronics, (2) computer-controlled fabrication equipment (i.e. 3D printers), and (3) programming libraries. Making focuses on the relationship between the Maker, materials, and the process by which the materials are transformed into personally defined artefacts for use. Knowing how to actively transform materials through processes for Making and understanding how to weave around problems within the process is what it means to possess a 'Maker Mindset' (The Maker Effect Foundation 2015). Researchers have recognised how such a mindset, and by extension, the practice of Making, can serve as a vehicle to create compelling and deep learning experiences in STEM, as well as the development of self-efficacy in STEM (Blikstein 2013).

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With the confluence of Making and STEM learning, there have been efforts to support Making in the classroom, such as via implementation kits like LittleBits, Lego MindStorms, etc. (Bdeir 2009; Klassner and Anderson 2003). The kits enable the students to grasp STEM content in ways that are amenable to classroom management and age appropriateness. A limitation to these kits is that they can be thought of as existing within a 'sandbox' as aforementioned. While students are able to engage STEM concepts in the space of the kit, it is difficult for students to translate their knowledge outside of a kit, akin to how sand outside of a sandbox serves little function outside of its space (Jenkins and Bogost 2015). However, if students cannot recognise these same concepts outside of the kit, STEM learning stops short in the context of the classroom. For example, when representing electronics concepts as modular electrical blocks, as is the case in 'littleBits', this representation may not serve to translate to encountered concepts with actual, discrete electronic components and their relationship with one another.

Owing to the issues inherent in existing Making kits as covered previously, we are motivated to find a means of embedding Making in the classroom, all the while maintaining the transferability of STEM knowledge and skill outside of its context. One such approach was found in employing the 'Making through Micro-Manufacturing' (M^2) model, a production model that couples the practices of Making with the concerns of real-world production (Okundaye et al. 2018b). Making, as situated in M^2, is extended as follows. Making in M^2 evolves beyond the production of singular artefacts towards the production of multiples at scale, meaning that artefacts are produced with a focus on reproducibility for low to mid-volume production; this takes into consideration how an artefact can be made at scale and what production techniques and materials would be amenable to this. Artefacts created through this production approach have the flexibility of design and customisation made possible by Making-conducive resources alongside production and manufacturing techniques to produce artefacts efficiently at scale.

M2 differs from the traditional classroom kit approach, where there is an emphasis on constructivist learning on the part of the student through practice-based scenarios that necessitate students to understand the tools and theory of Making to complete an objective, this being production at scale. Employing the M^2 model in the classroom confers the following benefits for students' STEM learning and self-concept development. First, because students are directly involved in the production of artefacts, students have agency in their creation and design, resulting in end-products that are personally, culturally, and socially relevant to students. Second, when the artefacts of production are employed for real-world end-use, it can unveil to students the inherent value of production processes in society and its impact on day-to-day life. Finally, the M^2 approach to classroom production creates scenarios where students are engaged in direct applications of STEM knowledge outside of the classroom for long-term (weeks or months) production timescales, creating a deeper understanding of STEM concepts.

Strategic frameworks for situating M^2 as a STEM learning model

The M^2 model implemented in this project is based upon three major theoretical frameworks that correlate interrelationships among mentors and peers within the classroom.

Practice-based learning (PrBL) refers to an educational approach where individuals are placed in *messy scenarios* where individuals consider what they know and don't know, and create self-generated solutions to address gaps in knowledge for an individual's own end goal (Savery and Duffy 1995; Shaffner 2003). PrBL's utility in a M2-based classroom comes from the application of industrial production concerns and its interplay with dynamic forces outside of students' control (e.g. deadlines, customer feedback, and public relations). The M^2 model proposes that students in the classroom could achieve desired STEM learning outcomes by employing practice-based learning.

Communities of practice (*CoP*) explain how communities establish and distribute knowledge of a given practice. CoP is based on two components: *Joint Enterprise* (e.g. the end goal of the practice) and *Shared Repertoire* (e.g. the shared resources of the group) (Wenger 1998). The community in question is focused more on the practice and social capital of the group and less on the end product. Practically, CoP focuses on uncovering the actions that individuals use in the support of a practice or narratives related to practice (Dubé, Bourhis, and Jacob 2005; Lesser and Prusak 2013). CoPs can illustrate how knowledge is propagated among peers and how mutual trust is established in the support and flow of knowledge. In an M^2 classroom, establishing a CoP enables an implicit design that leverages how a joint enterprise and shared repertoire can create a classroom culture developed from the ground by students and how practices are influenced by such a culture. CoP in M2 centres on PrBL, where students work together to learn subjects that solve problems as necessitated by the production scenario.

Social development theory

The last guiding theoretical framework is Vygotsky's (1978) social development theory on the zone of proximal development (ZPD). ZPD examines how learning flows from a more knowledgeable other (MKO) (i.e. teachers or more experienced students) to a novice (i.e. less experienced students) (Daniels et al. 2007; Vygotsky 1978, 1980). Through the MKO, students are guided and assisted in understanding concepts and techniques that otherwise would be difficult for them alone to catch (Ardichvili, Page, and Wentling 2003). ZPD, for our purposes, can illustrate how students can be given a path towards learning specific skills and knowledge in an M^2 classroom through the careful interactions between the MKO (e.g. either a student with more experience in M^2-related content or by the instructor) and the naive student. In MKO to naïve student interaction, there is due consideration to what the student can do by themselves and lack the ability to do at the moment. The MKO can modify learning activities that are attainable by the students' present skills and, in time, through the gradual layering of challenging topics, the student can expand their effective ZPD for a given subject.

Illustration of the theoretical model

Figure 1 provides a model illustrating the relationships across the theoretical frameworks covered previously. M^2 builds on the Making concept (creation of personalised, tangible artefacts using tools) whereby it introduces the concerns of manufacturing and production engineering to enable individuals to engage in a form of small to mid-volume production, marrying the personalisation of design with the technical knowledge of mass production. Because of the M^2 utility for mass production at a smaller scale, this allows for its placement within a classroom setting, allowing students to observe various practical facets of production starting from design, prototyping, quality control, and finally, end-products.

Owing to the intertwined nature of M^2 in the classroom, the cooperation of teachers and students is necessary for successful production outcomes. For this, a community of practice is needed to develop a shared culture united towards a common end goal and a means by which knowledge flows across all participants. Such knowledge would typically arise from an MKO, which can be a teacher who guides students through issues inherent to M^2 (whether it be of Making or production concerns). In our model, we posit that students can become an MKO themselves as students develop a key interest in a specific area of M^2 and guide other new students in a similar classroom production environment. In the next section, we will detail the implementation and results of the model.

Class intervention

The basis for this work originated as an Early-Concept Grant for Exploratory Research (EAGER) from the National Science Foundation (NSF), spanning two academic years, which focused on how an M^2-based high-school curriculum could be designed for self-sustainable production with consideration to a low-resource and underserved rural setting.

In this section, we will first describe the overall curriculum design and then describe our study assessment methods, detailing how we quantified and qualified students' learning and experiential

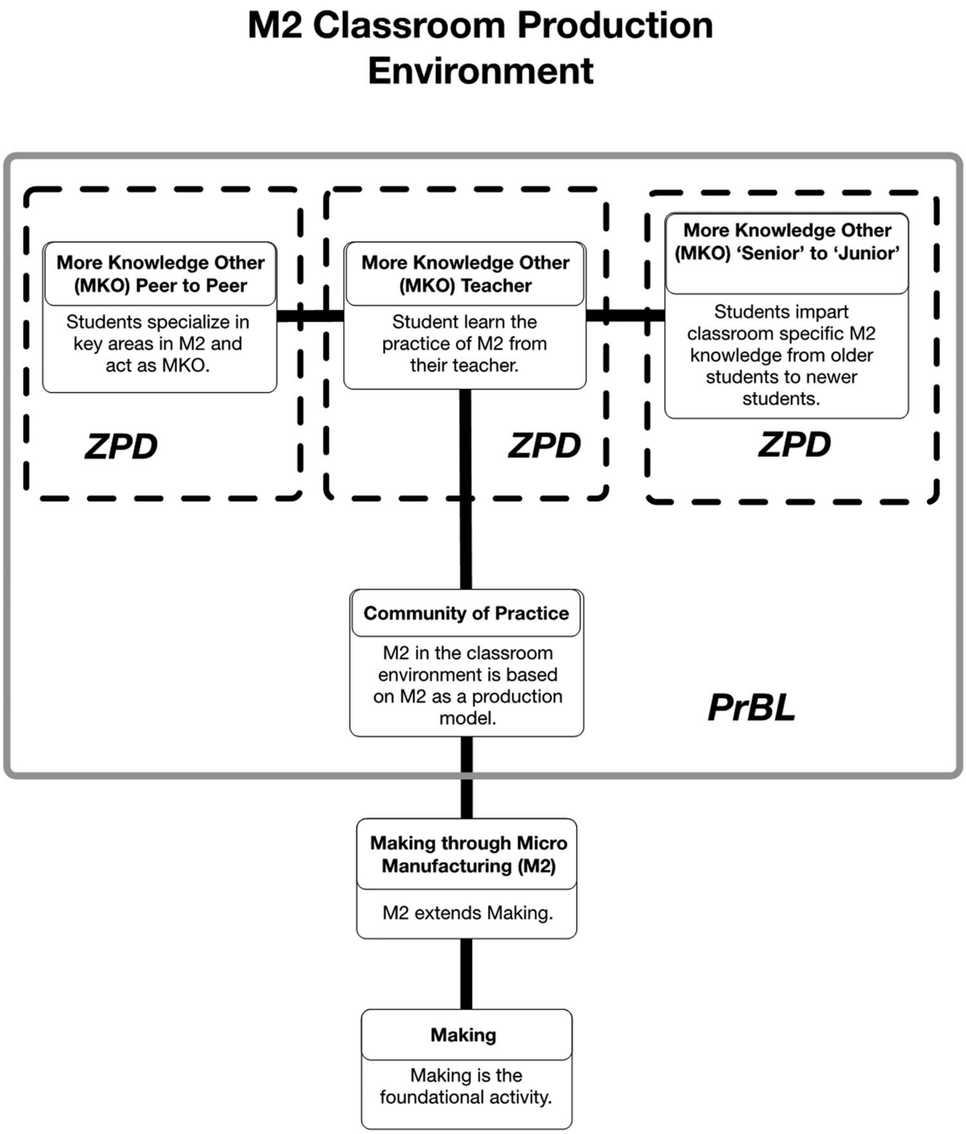


Figure 1. M2 classroom production environment.

outcomes in the course. Finally, we will describe how we situated our study in the context of the Colonias, under-resourced, primarily Latino communities located on the rural Texas-Mexico border.

Curriculum design

Building on the combined theoretical framework from our chapter, 'Relevant Background on Techniques and Strategic Frameworks', we developed a curriculum aligned to facilitate the M^2 model. The curriculum has two major components separated across the two high-school class years. We used year 1 to guide students to develop familiarity with Making techniques and use year 2 to situate these skills in the context of low-volume production operations.

For the first class year, our curriculum focused on students' development of foundational Making skills such as basic soldering, wire connections, design and 3D printing, circuits, and fabrication (Figure 2).

Technical Skills Outcomes	*Instructional Strategies and Assessment*
Making skills (with a focus on micro-manufacturing)	
Additive Manufacturing	Use basic shop/power tools and 3D printers to fabricate conceptual designs created using CAD tools.
Electronic prototyping	Use Arduino (an open-source platform) to create interactive electronic objects (e.g., create an array of LED situated on 3D printed connectors working together to present animated designs), as well as use relays and transistors in circuits to perform simple logic, using bread boards.
Basic electronics and circuits knowledge	Use electronics knowledge by applying Ohm's law to create electrical circuit designs appropriate for a given purpose all the while sourcing appropriate parts for intended design.
Basic LED, rotational & vibrating motor knowledge	Acquire and use knowledge of individual electronics components for production of interactive components for the instructional science kits.
Electronic Fabrication	Soldering (wires, copper tape, components, pins), crimping, and heat shrink.
Model and Prototype Building	Build a model with existing resources for a design and feasibility check. Once actual production material is received, build a production prototype.
Chart Preparation	Laminating, creating table charts that the elementary students can understand concepts represented by produced instructional science kits.

Figure 2. Year 1 curriculum content outline.

Year 2 of the curriculum shifts the focus of Making skills toward production management concerns (e.g. bulk production, supply chains, and inventory management) (see Figure 3). The intent behind this approach is to follow through the production aspects of the M^2 model, creating the conditions for a scenario where students can translate their conceptual knowledge of production through their established Maker skills in students' efforts to build objects for everyday use by the community. For year 2, the students produced, instructional science kits (Figure 4), Making-based assemblies designed to engage elementary school students in specific science concepts, incorporating a mix of 3D fabricated parts, basic electronic components, and computer-controlled elements.

Study situated in the Colonias community

We situated our study in an under-served, economically distressed Latino community located at the southern tip of the Texas-Mexico border. This particular community, commonly referred to as a Colonias, is an unincorporated low-income area that typically lacks basic infrastructure services like potable water, paved roads, and waste management. The specific Colonias community of interest had a consolidated school district, providing educational services (K-12) within the adjacent area. Our decision to situate the study in this community was based on our interest in studying an exemplar for under-served economically distressed communities, thereby lacking the opportunities to attract and maintain quality STEM educators. While communities like the Colonias are disadvantaged in their means to join broad participation in STEM, these communities support one another deeply, owing to the close-knit nature of the small size locale (e.g. many of the students' parents are employees of the consolidated school district, serving as teachers and administrators). For the Colonias community, this close-knit nature manifests as active interest and engagement in students' school activities.

During the duration of the study, the Colonias community was well aware of the high-school students' efforts in this project as seen in the student-produced kits for elementary school classroom (Figure 4). Such close-knit relationships within the Colonias community represented an opportunity to examine how the M2 production can be used not only as a vehicle for STEM education, but also as a means of community engagement. As a result, for the students who participated in our class study, the community exposure of their participation represented a sense of 'prestige' for the involved students.

Technical Skills Outcomes	Instructional Strategies and Assessment
Industrial engineering skills (with a focus on operations management and production planning)	
JIT Workplace Organization	Clean and organize workplace on the first day of every module
Engineering and Continuous Improvement	Design a kit with material available in-lab or locally and brainstorm other locally-available material that can be used as replacement
Purchasing	Develop a purchase order assessing existing inventory, anticipated production, safety stock and scrap/rework estimates
Project Management	Develop a process flow diagram, estimate time for each task and create a production cycle Gantt chart. Identify bottleneck resources and critical path.
Production Planning	Assess strengths and weaknesses of team members, account for skills and availability, develop production schedule and sequence
Total Quality Management	Perform a quality check on kits for design and form. Also, ensure the kits are safe to be handled by the elementary school students before and during usage.
Demand Management	Interact with the elementary school students and their teacher to see how they are using
Career development skills (with a focus on self-development and behavioral competencies for college and career success)	
Communication skills	Deliver an oral presentation to school and local community leaders by the end of each module. The project manager communicates roles and responsibilities to other team members and holds team members accountable.
Interpersonal skills	Complete a Plus/Delta feedback survey each day to reflect about what you did good that day and what and how it can be done better in the future
Dependability, punctuality, initiative	Show up on time, submit daily report, weekly report by a deadline (8pm), and complete deliverables by the fifth week for each module. The External Relations Manager (ERM) manages internal and external communications and expectations regarding deliverables, updates, etc. The Production Manager (PM) manages production plan, timeline, and monitors task status to meet deadlines.
Ability to write workplace documents	The Sourcing Manager (SM) tracks supply inventory & daily usage, submits purchase order to Texas A&M University. The Administrator (Admin) drafts agenda for daily workshop activities, and takes detailed meeting notes.
Self-development skills and interpersonal skills	The Project Manager (PM) calls the team for daily huddle to provide updates from previous day, highlight accomplishments from previous day, and remind the team of the plan for the current day.

Figure 3. Year 2 curriculum content outline.

To kick off this effort, an open call was placed in the Colonias' high school to recruit sophomore and junior students for the first semester of year 1 with the support of the school administration. The schoolteachers helped to circulate the application forms among students. Sophomore and junior

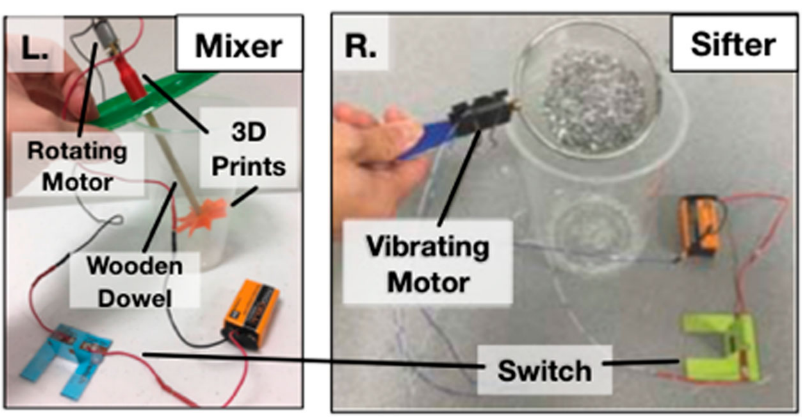


Figure 4. Example instructional science kit, 'Mixer and Sifter kit for "Mixtures and Solutions" curriculum segment'.

students were targeted because this project lasted two years and participants needed to have at least two years left in their schoolwork. A total of 13 applications were initially received. Ten-minute teleconference interviews were conducted asking students to reflect on their academic interests and career goals. In the interest of obtaining a diverse participant pool, we considered gender balance, participant interests, backgrounds, and career goals for the university research team to select the students for the inaugural class – altogether, six students (three males and three females) were selected to participate in this project.

Developing the Colonias class implementation

Year 1 served the purpose of preparing students on how to engage in real-world Making and production scenarios for the upcoming 'customer' needs and constraints in year 2. This involved the university research team teaching students the exact skills and techniques required in digital fabrication, basic electronics, and basic programming. During year 1, we excluded the conditions required by the customer (e.g. a 5th-grade science teacher and students) and constraints (e.g. the kits must be manufactured and fulfilled within a given 6-week timeline). With input and guidance from our partnered school district, a high-school class was created to house our class curriculum.

In developing the class, it was necessary to provide the resources to establish a Makerspace with the Colonias' high school. Two members of the university project team surveyed the existing infrastructure in the Colonias high school to assess available classroom and the equipment needed to establish a Making/Production workspace (Makerspace). Consequently, the following were provided for the workspace: soldering irons, hand tools (e.g. wire cutters, screw kits, and crimps), a variety of instrumentation supplies (e.g. resistors, LEDs, copper tape, wires, and Arduinos), fabrication tools (e.g. mid-sized 3D printer and lamination machine), and a large size television screen for teleconferencing. For data collection, we provided video and audio recording equipment in the form of portable audio recorders, small-scale HD action cameras, and a wide field-of-view web camera. Student desks were placed in front of the large screen TV monitor in a manner facilitating the project team members (from the university) could instruct them online, view their work, and interact with them. A snapshot of the classroom setup is presented in (Figure 5).

Class delivery for years 1 and 2

During year 1, the class was conducted via teleconferencing, led by either an undergraduate or a graduate student from the research team at a large research university in Texas, USA. The instructor would introduce a major technical topic, explain its theory/application, and finally, its relevance to Making. During class, the instructor would demonstrate any procedures involved and students would follow. During these times, the students were able to observe the instructor and request help or feedback for class activities.

Year 2 took on a similar approach to year 1 on the part of teleconference-based daily class representation. However, for year 2, the instructor took on more of a mentor role, whereby the class was charged with the responsibility of producing and deploying six instructional science kits for use in a local 5th-grade science classroom. During year 2, six students were assigned formalised roles for producing six kits and deploying them as per schedule. For each science kit deliverable, members of the MPT took on roles such as the Project Manager, Production Manager, Continuous Improvement Specialist, and others (Okundaye et al. 2018b) and rotated through these roles to follow a six-week production/deployment schedule as per the elementary school class schedule requirements. The MPT members also supported the elementary school teachers in their classrooms in using the instructional kits, and subsequently collected real-time feedback on the usability of the instructional kits.

Our interaction with the classroom follows an action-oriented approach, having sensitivity to the experience of the students and school while following through the structure we had in mind for the research.

Figure 5. High school students in the Maker space (Okundaye et al. 2020).

Data collection

In the interest in examining students' self-efficacy and Maker mindset development, we used two forms of quantitative assessment. Self-efficacy for Making was assessed through the adapted constructs of Usher and Pajares' Sources of Self-Efficacy Scale (Usher and Pajares 2009). The scale consists of four dimensions: mastery experience, vicarious experience, social persuasions, and physiological state (Figure 6). This included inquiries such as: 'I do well on even the most difficult things to make', 'I imagine myself working through challenging things successfully', 'I have been praised for my ability in making things', and 'Making things takes all of my energy', etc. Students were asked to rate how they agreed with each statement on a scale from 1 (definitely false) to 6 (definitely true). We asked students to complete this assessment at the start of the school year and the end of the school year as well.

As aforementioned, our self-efficacy scale was adapted from Pajares' Sources of Self-Efficacy Scale (Usher and Pajares 2009). Five subject matter expert raters evaluated whether items assess defined content. Results showed that this scale had a high level of content validity. We also tested the convergent validity and reliability of the measures. For both pre- and post-tests, the composite reliability and Cronbach's α coefficient for each dimension were from 0.75 to 0.96. The values of whole self-efficacy pre-and post-tests are 0.91 and 0.96. All reliability values exceed cut-off scores and fall within the ranges from acceptable to excellent. Both factor loadings and average variance extracted (AVE) of four dimensions all exceed 0.5, indicating that convergent validities for four dimensions were established.

To obtain regular feedback, we also had students complete a weekly survey that assessed their Making and Engineering skills, based on the questions seen in Figure 7. We asked students to complete the weekly survey starting from the (students developing foundational skills) to the end of year 2 (students implementing and deploying science kits in local elementary schools).

To gain granularity of students' in-situ activities, we recorded daily class interactions through video and audio capture. Specifically, we examined students' behaviours and interactions during the production cycles, especially the student interactions in year 2, where students were charged

Dimension	Definition
Mastery Experience	*"Students complete an academic task, they interpret and evaluate the results obtained, and judgments of competence are created or revised according to those interpretations."*
Vicarious Experience	*"Students build their efficacy beliefs through the vicarious experience of observing others. Students can gauge their capabilities in relation to the performance of others. Students compare themselves to particular individuals such as classmates, peers, and adults as they make judgments about their own academic capabilities."*
Social Persuasion	*"Encouragement from parents, teachers, and peers whom students trust can boost students' confidence in their academic capabilities. Supportive messages can serve to bolster a student's effort and self-confidence, particularly when accompanied by conditions and instruction that help bring about success."*
Physiological State	*"… self-efficacy beliefs are informed by emotional and physiological states such as anxiety, stress, fatigue, and mood. Students learn to interpret their physiological arousal as an indicator of personal competence by evaluating their own performances under differing conditions."*

Figure 6. Four dimensions of sources of self-efficacy.

with the responsibility of producing and deploying the instructional science kits. In year 2, after the six-kit deployments were successfully completed, we conducted interviews with the students to capture the benefits they gained from the study in the form of a 30-question survey that was conducted in a semi-structured fashion to probe the usefulness of the study, Maker mindset, and career goals. Altogether, we used both quantitative and qualitative data sources in order to triangulate the students' overall Making and production experience in the M^2-based classroom.

Qualitative data analysis

Data collected (including conversations, online chat, interviews, questionnaires, and videos) for qualitative analysis was engaged via the use of narrative inquiry. In narrative inquiry, there is an intent to understand the lived experience of participants through collaborations across researchers and participants, over time, in a set place or various places (Strauss and Corbin 1990). Through such an approach, understanding can be achieved, enabling the researcher to understand where participants are coming from and ascertain participants' possible futures. Qualitative data analysis was conducted on the recorded audio-video data alongside notes. Qualitative coding was performed using 'MaxQDA' (Kuckartz and Rädiker 2019), a qualitative data analysis software. In terms of specific coding procedures, we used the grounded theory approach as employed by Charmaz and Strauss (Charmaz and Belgrave 2012). During the first phase of coding, *open coding,* a label is applied to a specific phrase or discussion, representing an idea of interest without any interpretation beyond what is clearly stated within the utterance; for example, participant P1 expressed their interest in

Making Self-Efficacy	Engineering Self-Efficacy
I am good at buildings or making things.	*I feel am very good at engineering.*
How much do you think you can make it?	*Being good at engineering is an important part of who I am.*
I can do things on my own.	

Figure 7. Making and engineering self-efficacy weekly survey items.

the Making class was how new the concepts seemed, so the assigned code is 'P1 – Prior Interest in Program is Novelty'. In the next phase of coding, 'focused coding', generated codes from the open code phase are organised into related categories; for example, codes, 'P1 – Prior Interest in Program is Novelty' and 'P1 – Prior Interest in Program is Learning' can be organised into the category, 'Reasons for Students joining Making Class'. Finally, thematically related categories are further grouped together during the 'axial coding' phase; for example, the axial code 'Students' Interest in Making class' is built from the categories, 'Reasons for Students joining Making Class', 'Elements of program students are interested in', *and* 'Things students would like to make'. The coding procedure was conducted by a team of five coders. After completion of open coding by each coder, the primary coder reviewed the codes generated. The inter-rater agreement was at 80%. The Codebook is provided in the Appendix.

Results

RQ1: Are there significant differences in students' making skills attainment after year 1 of the M^2 based program?

A total of 12 questionnaires were collected for both pre and post-tests for self-efficacy dimensions and changes ($N = 6$ for pre-test and $N = 6$ for post-test). All items in the scale were averaged to produce a summary score for each student. The score illustrates the extent to which students agree or disagree with a specific facet of the experience of Making which includes 'Mastery Experience' (ME), 'Vicarious Experience from Adults' (VA), 'Vicarious Experience from Peers' (VP), Vicarious Experience from Self (VS), Social Persuasions (SP), and Physiological State (PS). We compared the students' pre and post-study scores for all facets and their aggregate for overall Making experience by averaging the pre and post-scores respectively. Given that only six students participated in the class, statistical power was low and therefore inferential statistical tests were not used. Students' averaged scores for 'sources of self-efficacy in Making' saw increases across most of the individual facets with the exception of *physiological state,* where it saw a decrease in the post-test scores (Figure 8).

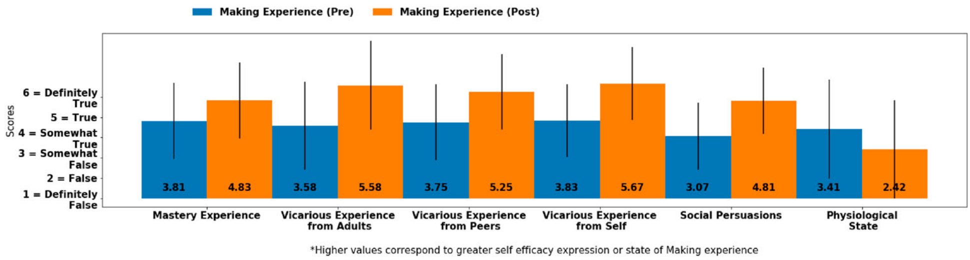
Student's overall Making experience, averaged across the dimensions of Making, rose from the pre-test score ($M = 3.58$, $SD = 1.75$) of 'somewhat true' to post-test score ($M = 4.76$, $SD = 0.73$) where students reported that it is 'somewhat true' or 'true' that they had efficacy in their ability to engage in Making (Figure 9).

What we can attribute to change in students' mastery experience self-assessments is the applied scenario which students used their developed Making skills. Unlike a traditional classroom where students can learn the aforementioned skills, the students had multiple opportunities to use these skills more than once in the PrBL setting, across a variety of different use contexts for the different kits they made during mock production. Through these different use scenarios, students are able, through repetition and error, to recognise how their skills can vary in different scenarios and adjust them accordingly.

RQ2: How did students transfer their making practices M^2 production after year 1?

Figure 10 show the average scores of the students' Making and Engineering self-efficacy surveys across the 6-week period of the first Making and production pipeline during year 2. What is worth mentioning is that this particular production pipeline had the expectation of following a given schedule for eventual in-classroom deployment for an elementary science class.

Making self-efficacy remains relatively flat with a slow increase with average scores at a moderately high level. However, when comparing the results of the first time and last time, the average score increased from 3.89 to 4.33. Time 4 witnessed a drop attributable to the need to make the parts for the instructional science kit with the added time pressure for completion before deployment, on time 5.



	Mastery Experience		Vicarious Experience from Adults		Vicarious Experience from Peers		Vicarious Experience from Self		Social Persuasions		Physiological State	
	Pre-Test	Post-Test	Pre-Test	Post-Test	Pre-Test	Post-Test	Pre-Test	Post-Test	Pre-Test	Post-Test	Pre-Test	Post-Test
M	3.81	4.83	3.58	5.58	3.75	5.25	3.83	5.67	3.07	4.81	3.41	2.42
SD	1.87	0.51	2.18	0.6	1.86	0.69	1.79	0.55	1.65	1.27	2.43	2.03

Figure 8. The change of making self-efficacy dimensions.

The average scores for engineering self-efficacy showed more fluctuation with time 2 representing the lowest point of self-reporting. However, the trend line climbed upward indicating an increase of students' engineering self-efficacy. Weekly engineering self-efficacy saw a similar decrease at time 4 and a subsequent increase at time 5 as was seen for Making self-efficacy. What could be attributable to this characterisation is the shift in experience from preparing the instructional science kits in the mock-production cycle to producing for real-world expectations. As students experience the pressure that comes with the expectation to deliver, students find that they are not as fully prepared as they thought they were. However, the students did recover as they completed and deployed the instructional science kits, even improving their initial self-efficacy overall.

RQ3: How is the maker mindset represented through problem solving across members of the M2 classroom?

Social interaction and helping behaviours increased

Based on data collected towards the end of year 2, we examined a class sequence when new students were introduced to the class with the prior students returning from the prior class year. Here, we examined instances that demonstrated CoP-associated behaviour.

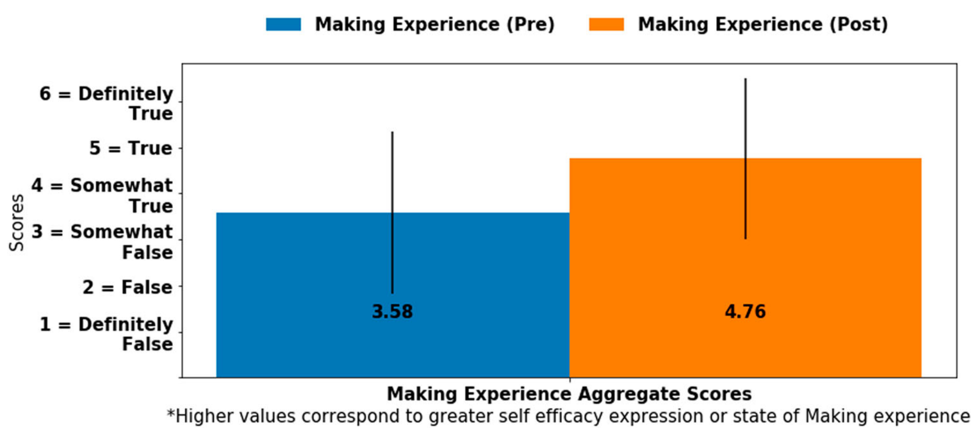


Figure 9. Overall making sources of self-efficacy score.

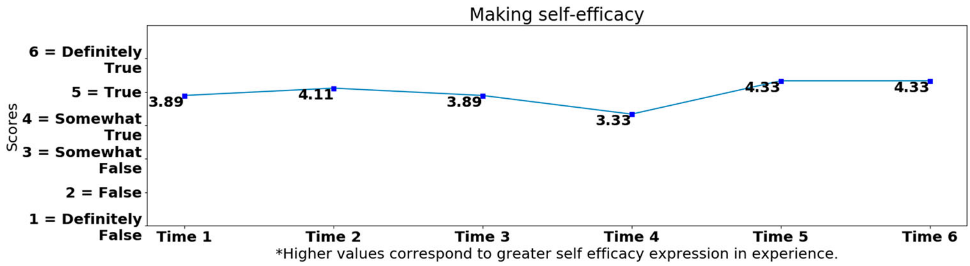


Figure 10. Making self-efficacy across six times in year 2.

We identified the vectors of help distribution across 'New Student' and 'Senior' students, as well as teachers and distant online mentors. Our ranking of the frequency of help given across members is as follows where senior students engaged in the most helping instances, then teachers, new students, and finally, the research team (Figure 11). From the perspective of who received the most frequent help, the 'New Students' were the most, followed by senior students, teachers, and finally the research team (Figure 12).

Personal impacts experienced by students

In this section, we will describe two case studies that depict the personal impacts that were experienced by high-school students. Here, we will describe two of our students' experiences as an exemplar. The names of the students have been anonymised. In the following subsections, we will describe each students' reflections on their growth throughout the 2 years of the Makers program.

'Mario': Responsible agent in production team. Prior to entering the Maker Production class, Mario (pseudo name) had experience in Making related tasks such as disassembling and reassembling phones when a repair was needed. Because of his prior experience with electronics, Mario was comfortable with taking on the role of project manager for the first production unit of year 2. Mario was by nature, a reserved, quiet, and introverted student. However, Mario tended to be more vocal when issues of technical knowledge or technology use arose, as evidenced by him solving technology-related issues in class and aiding other students as well.

During weeks 1 and 2 of the first semester of year 2, Mario was appointed the role of team leader. During this time, Mario was expected to enact this role by keeping other students (i.e. team members) accountable for their roles and ensure that productivity was constant, and if not, find

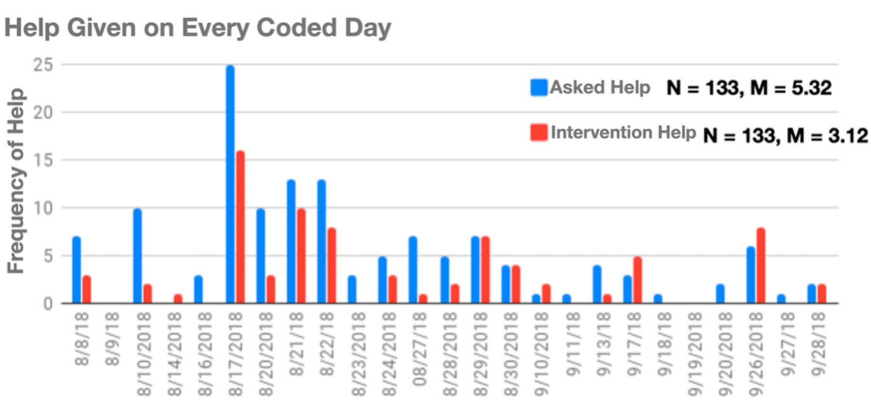


Figure 11. Engineering self-efficacy across six times in year 2.

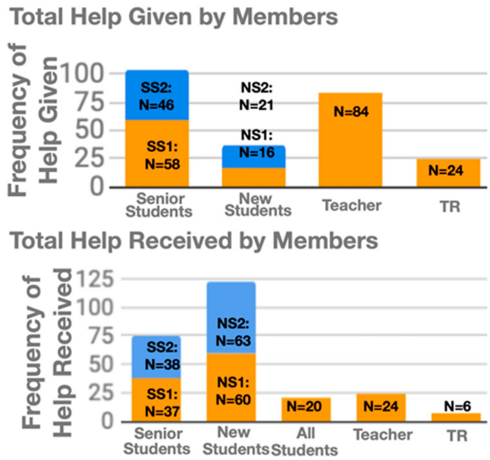


Figure 12. Times of help given and received by project members.

solutions to ensure that production was possible. In addition, Mario, in his leadership role, needed to act as a liaison between his team and the university research team acting as mentors (e.g. *mentor asked the class how the shared online cloud repository was organised, Mario spoke up and led the discussion on the organisation of the repositor*).

Another example, as seen in week 3 where the class was moving towards prototyping the kits, Mario identified an issue in one of the 3D files provided by the mentor team. Mario pointed out to the mentors that the 3D design if printed as specified by the existing '.stl' file in the classroom's 3D printer, would have inappropriate tolerances that would ensure proper use in the instructional science kits, leading to a mechanical failure if deployed as is within the intended elementary school classroom setting. In light of the aforementioned issue, Mario proposed a solution in the form of adding a post-processing step to alleviate the existing issue in the design without the need to waste time and resources to redesign and print new parts. In Mario's solution, he suggested that they take the existing parts that they produced and use a sander to properly fit the parts to achieve their intended tolerance for use in the kits.

In another instance, during week 6 towards the end of the deployment review, Mario was assigned a different role for the next 6-week cycle. While Mario enacted his new role, Mario still demonstrated leadership qualities when he coached other students on the implementation of battery assembly for the kit for that given unit. Mario demonstrated such traits whenever technology implementation was a chief concern when problems arose.

'Lucinda': Leading making and production. Lucinda's (pseudo name) involvement in the Makers' program can be characterised by her gradual development as a leader, this is seen as she became more aware of how activities and interpersonal relationship dynamics figure into the day-to-day proceedings of production in class. During the first production cycle, when Lucinda was gaining familiarity with Making, she began to take on leadership roles. A key instance was seen when she took it upon herself to assign production roles to the other students in the class, despite not assigned the role of project manager. In the 4th and 5th weeks, Lucinda continued to demonstrate leadership skills as she guided other students through a review of the current production unit's lesson plan.

Another instance of Lucinda's leadership was during a class-wide conversation concerning the scheduling of extracurricular class events around production goals. During the teleconference session, an on-site teacher informed mentors that the students would have an upcoming volleyball game. Many students in the class had roles related to the volleyball game such as serving as athletes, cheerleaders, or yearbook club members. While some students offered reasons why they could not take additional time to keep up with production, Lucinda spoke on the behalf of the class. Following Lucinda's initiative, she led the class to consider how they will alter the existing production schedule in the face of the new constraint made apparent to the class.

During the post-mortem review of the kit production and deployment, Lucinda was assigned a role of project manager for the next unit. Building on her developed knowledge from the prior unit, Lucinda was better able to follow up with her knowledge of the organisation with direct action. One such example can be seen when the class was asked for ideas for the upcoming kit unit on 'Forms of Energy'. Here, Lucinda took inspiration from her prior experience in a STEM summer camp, identified an application from the summer camp for implementation, and suggest its value within the current production cycle. Through Lucinda's introduction of the idea, it better served the class as a whole for discussion, serving as an anchoring scenario to guide the students' design of the instructional science kit on forms of energy, encouraging students and students to ask questions to mentors and motivate further research on the topic.

Conclusion

This paper reported the implementation of the M2 mode as a vehicle for STEM learning in an underserved community and population. We observed how the PrBL nature of the class and its resultant CoP arose, leading students to engage in self-constructed scenarios of STEM application in its management and practice. In addition, we witnessed how the students, through the practice-based scenario, were able to engage in the STEM material from mock production to real-world production, illustrating how students' self-concepts in the material can be challenged and subsequently bolstered from real-world engagement.

While we were able to demonstrate how a STEM-based Making and production class can be implemented in rural communities, our work is not without limitations. Owing to the small participant size, we were unable to apply inferential statistical tests, limiting our quantitative analysis to pre and post-survey comparisons. Another issue in the study is the format of class instruction, this being the teleconference-based classes. While we were able to teach students the hands-on activities pertaining to the tools, electronics, and fabrication equipment used in production, there was additional effort needed in communication when issues of hands-on content were concerned.

Future work will address limitations in our study two-fold. First, to validate our intervention, we will seek out comparable underserved communities that share similar economic circumstances as those examined in this paper. Second, we will examine how to overcome this disconnect between distant mentors and students by examining how different technologies such as telepresence robotics can serve as a stronger proxy for distance mentors.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Appendix

Codebook

Role Assignment:

- ■ **Definition**:
  - ● Student's actions and reactions to assigning roles to one another before starting a production.
- ■ **Example**:
  - ● P6 – take communication manager role even P4 wants it first
  - ● P4 – volunteer for communication manager but agree to cooperate
  - ● P1, P3 – persuade P2 take sourcing manager role

○ **Working together**:

- ■ **Definition**:
  - ● Instances where students/instructors work together to accomplish tasks within the class.
- ■ **Example**:
  - ● P4 – follow P5 to check on the 3D printing process
  - ● P2, P4 – focus on trimming and folding paper
  - ● P6 – suggest working together and getting things done

○ Instructor commentary:

- ■ **Definition**:
  - ● Instances where instructor interact with students and responds to the question or provides an answer.
- ■ **Example**:
  - ○ Instructor states that too many students are working on same task
  - ○ Adult questions if students are working

- Answering Questions:
  - **Definition**:
    - Instances of answers provided by instructor regarding students' questions
  - **Example**:
    - Teacher – Kit Clarification
    - Teacher – Process Clarification

- **Focus on task**:
  - **Definition**:
    - Instances of how students maintained attention to tasks during the Maker class and the extent to which attention was maintained.
  - **Focus on task**
    - **Example**:
      - P4 working with 3D printer
      - P6 gets up to help teacher when something goes wrong with Skype
  - **Somewhat-on-focus**:
    - **Example**:
      - P5 Distracts P6, P6 continues working, P5 pays attention again
      - All students except for P5 are conversing while working/more or less on task
      - All students minus P3 work on templates and converse while being on task
  - **Distraction**
    - **Example**:
      - *P4,5,6 distracted by P6's laser while instructor is talking*
      - *P3 – not engaged in task, conversing*

- **Asking questions**:
  - **Definition**:
    - Instances where students ask questions pertaining to the practices in the classroom,
  - **Process Clarification**:
    - **Example**:
      - *P6 asks mentor about project, mentions not wanting to waste*
      - *P1 – ask P5 what he is doing (question efficiency)*
      - *P6 – Question on the deadline*
  - **Asking about concepts**:
    - **Example**:
      - P6 – Asks adult for confirmation, scientific concept, correct

- **Giving answers**:
  - **Definition**:
    - Cases where students respond to questions given by other students/instructors or offer solutions without prompting.
  - **Management**:
    - **Example**:
      - Students managing students for task focus:
        - P6 – suggest working together and getting things done
        - P5 – suggest to keep the deadline and work as a team
        - P4 – suggest to stick to schedule and finish on time
        - P1 answers, P4,6 try to correct her, she hushes them
        - P1 says, 'Guys, we only have one week to finish the project.'
  - **Answering Peer Questions**:
    - **Example**:
      - *P2 – provides P3 information about design*
  - **Announcing Tasks/Instructions:**
    - **Example:**
      - *P1 initiates the group taking pictures of motors for instructor*
      - *P1 says, 'Guys, we only have one week to finish the project.'*
  - **Validating Peers:**
    - **Example:**
      - *P5 looks to P1 for justification to his answers*
      - *P4 – follow P5 to check on the 3D printing process*
  - **Providing Instructions:**
    - **Example:**
      - *P6 states that they found a better way to solder for the project*

- **Students not following instructions:**

- **Definition:**
  - Instances where the students do not follow directions or expectations set out by the instructors of the class.
- **Example:**
  - *P6 – Arrives Late*
  - *P2 – Fake Working*

○ **Student interests:**
- **Definition:**
  - Instances where the student audibly express interest or disinterest to specific aspects of the Making classroom experience.
- **Example:**
  - **Things students would like to Make**
    - **P1: Looked up how to make portable charger**
  - **Elements of program students are interested in**
    - *P4,5,6: Seem frustrated with assignment (can't tell what it is)*
    - *P6 says he hates reports*
    - *Talking about their tasks, problem solving*
  - **Reasons for Joining Making Class**
    - *P1 – Prior Interest in Program is Novelty*
    - *P1 – Prior Interest in Program is Learning*

○ **Affect:**
- **Definition:**
  - Instances where the student audibly expresses affect to some experience within the classroom.
- **Example:**
  - ***Affect towards class presentation:***
    - *P6 – Shy to Present*
    - Students shyly answer when they don't know answer
  - **Affect towards production process:**
    - P5, P4 laugh when hearing things are redesigned – negativeP4, P5, P6 laugh at how long wiring would take, stressed?
    - P1 – upset at P6, happy with P3 (working together)
  - **Affect towards skill assessment:**
    - P6 – over confident, saying 'it's a cake' on wiring