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‘All Together Now’ - Integrating Horizontal Skills in CareerTechnical Education Classes with Making and Micro-manufacturing

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‘All Together Now’ - Integrating Horizontal Skills in Career Technical Education Classes with Making and Micromanufacturing

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Abstract

In the face of ever-growing advancements in information and manufacturing technology, the future of work will demand cross-disciplinary skills. In such a future, individuals will need to continually acquire a breadth of skills and knowledge that goes beyond any one discipline. At present, our education system follows a siloed model whereby students develop expertise within a given discipline but lack the contextual knowledge needed to integrate skills across different disciplines. In preparing students for the future of work, it is thus necessary that our pedagogical model provides opportunities for students to engage in and develop breadth or horizontal learning.

‘Making through Micro-Manufacturing’ (M3) is a production paradigm that couples the concerns of Making with production engineering, achieving the low-volume production (hence the term ‘micro’) of personalized artifacts. M3 can serve as a driver for STEM learning through it’s framework for supporting horizontal learning experiences for students. In this NSF Innovative Technology Experiences for Students and Teachers (ITEST) funded work, we report on a class within a career and technology education (CTE) sequence that uses M3 as a structure to effectively engage high-school students with a low-volume production scenario focusing on a end-consumer product (instructional science kits for local elementary schools). The class charges a M3 student group with the manufacturing of instructional science kits for elementary schools, which integrates basic electronics and digital fabrication to produce the kits at scale. Through the class, we seek to understand how students develop personally-defined depth and breadth of skills across the Making and production aligned disciplines that form the foundation of the students’ practices in the CTE class.

Introduction

The modern global economy can be characterized by how traditional manufacturing and production work is outsourced to low-cost, off-shore labor and automation options. Such shift in manufacturing can be attributed to the changes under *"Industry 4.0"*[1,2]. While such a change is a boon in terms of cost-savings for firms, the end-effect for industrialized societies is the displacement of labor. However, because the traditional manufacturing and production work has moved from the west[3,4], this had created a gap and potential opportunity for a different kind of manufacturing, one characterized by the mass-production of customized goods, empowering small-scale producers to actively participate in the global product and supply chain[5]. The strength of such small-scale production combines flexibility, competency, and innovation, supporting the production of goods not possible at the economies of scale of long-chain mass manufacturing. Such a small-scale production team would be characterized by their broad expertise of skills that are utilized in production, instead of specialization in any one particular set, as favored by large-scale production enterprises. While such a possibility is on our horizon, however, we are not preparing our future workforce for this kind of envisioned work[6]. Currently, our education and career system is optimized for specialization. Let's consider the design of *Career and Technology Education* (CTE) classes. School districts design CTE classes to prepare students for existing work, reflecting the present need and interests for siloed workplaces. CTE's are typically organized in terms of predefined career pathway clusters (e.g., Manufacturing, Information Technology, Arts, A/V Technology). In each pathway, students get the skills that have been identified within that given pathway and are taught the specific set of ways those skills are integrated with one another through hands-on classroom scenarios along with on-site training. While there are obvious benefits in training students in the aforementioned model, we should augment existing CTE programs such that it emphasizes contextual, horizontal integration of skills needed for small-scale, diverse production. In such an approach, students are able to learn in a way where each piece of more knowledge added is integrated into the whole. An added benefit is how relevant the content is made when in real-world applications and how it influences students' own identity in that work.

To address how we may understand how to prepare students for the future of work, we need to take two factors into consideration. The first, is how students participate in formal concepts in classrooms. Students develop familiarity and competency within a given subject and are then placed in sandbox situations, akin to an apprenticeship, where students integrate their subjects' identified skills within a specific scenario. Such an approach would not work for the future of work, where practices are less established and are generative in nature, rising owing to the unique circumstances of a given production scenario. Second, owing to the siloed nature of subjects in schools, there is little crossover between subjects. While students can develop depth of expertise within particular subjects, students are not as well versed in how to integrate various levels of expertise one possesses or across multiple team members, such as in scenarios where future, flexible production systems require.

In this paper, we seek to understand how to design a horizontally integrated CTE learning curriculum so to create generative scenarios where students can apply a broad array of skills for flexible, small-scale production environments. Our curriculum examines how students are given various projects to complete, based on the mix of Making aligned concepts (i.e., basic electronics, digital fabrication tools, and programming) and manufacturing/production concepts (i.e., manufacturing systems, productions schedules, and production management); all this based upon the M3 production model[7,8,9]. To support the design of such a curriculum, we will follow a de-scaffolding approach[10], whereby students are given various projects to complete, initially supported by the research team through prepared materials (based on the aforementioned concepts) and offer direct support during projects; this support characterized as a kind of scaffolding for students to participate in the projects. As students progress through the projects, specific concepts are taken out of focus in place of another, with the expectation that the student assumes responsibility of applying knowledge in the next project. By the end of the class year, students should be able to complete projects autonomously. Through this approach, an but intentional de-scaffolding approach will aid students to shift to take on more responsibility of learning from the teacher to the student[11,10,12].

In our work, we will describe how a specific class sequence approaches horizontal based learning in production scenarios, comparing between two groups. The groups, *Scaffolded* (a class that is given full support in terms of materials and direct intervention by the instructor) and *Descaffolded* (a class that is gradually given less support and expected to take on more responsibility in subsequent classes) are our two groups of observation in these class studies. We pose the following research questions:

RQ1: Are there any differences in students' self-efficacy in horizontal learning based production scenarios between *Descaffolded* and *Scaffolded* class groups?

RQ2: How does *Descaffolded* and *Scaffolded* class groups in how they self-generate solutions in horizontal learning based production scenarios?

Relevant Background

Theory of Expansive Learning

We based our pedagogical approach on the theory of expansive learning[13]. Expansive learning is a theory of organizational learning, proposed by Ëngestrom and derived from Vygotsky's activity theory, that points to how conventional expertise arises from the "development of established competencies within a particular domain" (i.e., vertical expertise). Ëngestrom argues how, in contrast, horizontal expertise arises from the *"capacity to move between activity contexts and to engage in the exchange and mixing of domain-specific expertise"*[14]. In this understanding, expansive learning points to how multiple activity systems are co-developed through a shared object, such as one produced as part of a network or a multi-activity collaboration. Expansive learning has been further developed as a theory to understand employee learning, but has since been applied in educational contexts. For example, Tsui and Law[15] describe a partnership between the University of Hong Kong and partnered secondary schools for teacher education[16]. The partnership developed as a inter-institutional, collaborative project that resulted in a elementary school program where students learn rice planting in a farm, guided by university students. From the project, it was found that benefits conferred included outcomes beyond "formal qualifications, but may include self-assurance, increased capability, improved attainment, greater ability to exercise control over their situations and the development of new attitudes toward learning/working"[17,18].

Identity Formation and Self-Efficacy

In the interest of implementing a learning experience based in horizontal expertise development, it is important to consider the role of identity development. Self-identification, the extent to which one defines themselves to a role or performance domain, forms part of one's self-concept[19]. Self-concept, in its totality, arises from the myriad of ways an individual relates to their activities they have encountered in daily life[20]. *Control Theory*, explains how that a person's self-concept functions as a organization force, driving and guiding processes in self-regulation (e.g., setting motivations or decision making)[21]. People use their self-concept to determine what they are capable of doing, influencing decisions such as field of study, future careers; such decisions having implications for how an individual considers their future "possible selves"[22,23,24]. In conferring the benefits of horizontal STEM learning in students, it is necessary that students are placed in scenarios where they can interact with the active integration of various skills towards generative solutions; through this active integration, students develop experience and in time, confidence that they can work across fields and come up with solutions for whatever possible challenges they may face.

Making and STEM Education

The wider availability of essential electronic components, software libraries, hardware frameworks, and digital fabrication technologies has resulted in the proliferation of unique, personally-defined interactive artifacts[25,26,27,28]. Products of Making can range from sketches to fully manufactured objects[29,30,31,32]. Because of the technical developments, a subculture has arose that is commonly referred to as the *'Maker Movement'*. In *Maker* culture, individuals seek to produce personal and technically sophisticated projects, regardless of whether they may be a hobbyist or a professional, united only in the interest of Maker associated technologies and their democratization of their use.

A major implication of the Maker movement is two-fold. First, through the set of widely available tools and resources (both technical and knowledge-wise), there is the potential for the diversity and wide proliferation of technology that can be consumed,produced, and modified by society, easily speeding up the chain of technical innovation. Effectively, Making is the emergent practices of a community's interest towards technology and its practice of production.

Second, Making has implications for how we teach STEM concepts to students in K-12 education. Making, in attribution to its close interaction with materials and use of technologies, provide learning experiences where students can engage and apply science concepts firsthand in ways that are not as immediately understood within a traditional lecture-based classroom. In addition, active engagement with STEM concepts through Making can aid in the development of students' own self-efficacy with STEM aligned concepts. While there has been recognition of these conferred benefits of Making towards STEM for K-12 education, supportive frameworks such as LittleBits[33], Lego Mindstorms[34] make it difficult for students to extend their knowledge outside of the immediate context of the kits themselves, this attributable to the kits design for accessibility, obscuring inherent STEM concepts[34].

'Making through Micro-Manufacturing' (M3) for Horizontal Learning

'Making through Micro-Manufacturing' (M3) is a production model that provides a framework of how the flexibility of customization that comes with Making can be married with the concerns of production engineering[7,8,35,36]. For this work, we use M3 as a framework to unify the various works we have covered earlier to explain our pedagogical model for our present study. Expansive learning theory explains how horizontal expertise arises from the active combination of various vertically developed expertise in the endeavor of a inter-disciplinary project; for the context of M3, we see such a horizontal integration within the sub categories of Making (i.e., elemental electronics, computational fabrication tools, and programming languages are used to create interactive artifacts) as well as in production engineering (i.e, manufacturing techniques, logistics, and production considerations) and one step further, the interplay of both subcategories (e.g., using Making skills to design custom designed instructional science kits for a school district while employing small scale production techniques to manufacture kits in an efficient manner). Making enables students to better understand STEM concepts by providing students direct engagement with materials and applying said materials for personally relevant projects. As students develop expertise in working with materials, they develop intuition and self-efficacy towards STEM, as an active practitioner of STEM. Finally, in consideration to the dynamics between expansive learning and self-concept, students are actively integrating their varied knowledge bases amongst themselves and with one another, requiring students to form generative solutions and deepen their own knowledge as they negotiate with the challenges of connecting different forms of knowledge and develop understanding of limits and potential for how they can be interrelated.

Study Context

We conducted our study as a cross-institution collaboration between Tier-1 research university and a school district next to our university's location. The school district had recently established a career and technology education complex (CTEC). The CTEC is designed in a high school level, academy-style, with the intent of preparing students for the intermediate step in their education or career goals. Among the course groupings, the CTEC offered to include automotive technology, industrial engineering and robotics, construction technology, and welding. Of interest to the premise of this paper, the courses were aligned with presently identified high-skilled and high wage careers as identified by the school district's own CTE advisory council. The school district considered our standing interest in creating flexible, production environment production scenarios and agreed to have our research team conduct part of the classes within the CTEC's own coursework, specifically under their industrial engineering and robotics courses. Our research team was given an allotted amount of time out of the CTEC's own classes to conduct our studies, with two classes, each with a duration of 2 and a half hours, conducted all 5 days of the week, for 2 semesters.

For the fall semester, we emphasized the development of skills pertaining to Making and production engineering (Figure 1). For Making related subjects, we supplied our partnered classes with a fully stocked Makerspace, replete with electronic components, soldering stations, micro-controllers, sensors, motors, wires, and assorted hand tools. We taught students how to use the various materials and equipment through a series of daily hands-on activities that combined

	Making Concepts	Manufacturing and Production Concepts
Fall Semester	High-level introduction to electronics (e.g., Ohm's law). Students use tools such as breadboards, multimeters, power supplies, wires, or soldering irons. Basic programming concepts include variables, control structures, and functions. Programming concepts are combined with electronics through microcontroller based projects.	Manufacturing systems, Master Production Schedule, Material Requirement Planning, Inventory Management and Control, and Introduction to Lean Production. Students are taught theoretical concepts and given practice assignments to apply knowledge (e.g., Master production schedule is practiced through students making a schedule to complete a production run of 100 electronic switches).
Spring Semester	Basic shop/power tools and 3D printers. Instructors teach students basic CAD CAM skills (e.g., camera space manipulation, model transformation, boolean modeling techniques, and consideration of real-world dimensions for eventual fabrication)	High-level introduction to production management including quality management, sales and operations planning, forecasting, customer service, and basics concepts of supply chain management.

Figure 1: *Adaptations* instructional science kit in use.

elements of programming and elemental electronics, in varying proportions based upon the emphasis of a given 6 week period. A similar approach was conducted for the production engineering concepts including introduction to manufacturing systems, master production schedule, material requirement planning, inventory management, and lean production.

The spring semester was characterized by a focus on the interweaving of the Making and production related concepts covered in the fall semester, alongside with the introduction of subjects digital fabrication and production management. Essentially, the spring semester served as the inter-disciplinary horizontal expertise development phase of our study. During the spring semester, students were given weeks-spanning assignments that focus on the development of a production line to produce several artifacts.

We organized course content delivery, by way of horizontal expertise development, through the active use of de-scaffolding[12]. In de-scaffolding, students' initially develop expertise in a given 'in-focus' activity while supportive 'out-of-focus' concepts adjacent to the activity are scaffolded through pre-completed material. As students progress through the class, more and more 'out-of-focus' topics are incrementally de-scaffolded as students learn how to establish connections between different content . For example, students initially learn how to create an interactive paper-LED grid that is controlled by an Arduino. Initially, students are only taught the concepts pertaining to the immediate electronics (e.g., Ohm's law, LEDs, soldering, bread-boarding) while the other elements that support the activity are provided as-is. As students engage with a similar activity, students focus on concepts that were previously provided as-is (e.g., students create a different type of paper LED grid but are now expected to develop skills to program it and combine that knowledge with electronics) until they are completing the activity as a whole (e.g., students combine knowledge of programming and electronics with 3D printing knowledge to design and create housing and buttons for the electronics and micro-controller for the LED grid).

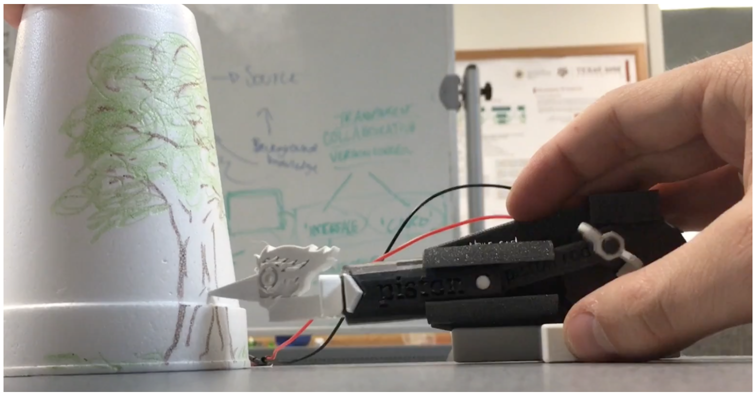

Figure 2: *Adaptations* instructional science kit in use.

Instructional Science Kit Production

Students were asked to design and implement a production environment to mass-produce a low-volume amount of instructional science kits for use within 5th grade elementary schools of the same school district. We chose to use these instructional science kits as a necessary production scenario because they were products that were intended to be used in a real-world scenario and carries the expectation of quality of production and proper sourcing of parts for the assemblies. The kits themselves are the product of a separate research project that we conducted to understand how Making can be used as a vehicle for STEM concept development for elementary school education[37].

The specific instructional science kit that we selected was the “Adaptations” kit. The *Adaptations* kit consists of a mix of 3D printed parts and basic electronic components. The instructional science kit is used in the content of a 5th grade science class where the concept of adaptations are represented by a 3d-printed bird beak attached to a motor-powered rack and pinion to perforate a styrofoam cup (Figure 2). The kits are meant to be used in multiple sessions where 5th-grade students would use TinkerCAD[38] to modify the existing beak design for use in the following classes to observe how changes in animal physiology, as modeled by the kit, can influence how they can operate under different environments. We have characterized the sub-assemblies that represent the kit in figure 4.

Pre-Study

Students were given the study brief to and consent forms to review. Two pre-study surveys were administered; details of the measures in the questionnaires are noted in the upcoming subsection “Measures”.

Study

The studies were conducted for a period of 3 weeks, with each week focusing on a particular sub-assembly for the instructional science kit. Since our study was conducted in the Spring semester, the students were engaging more in the management side of the production and less on

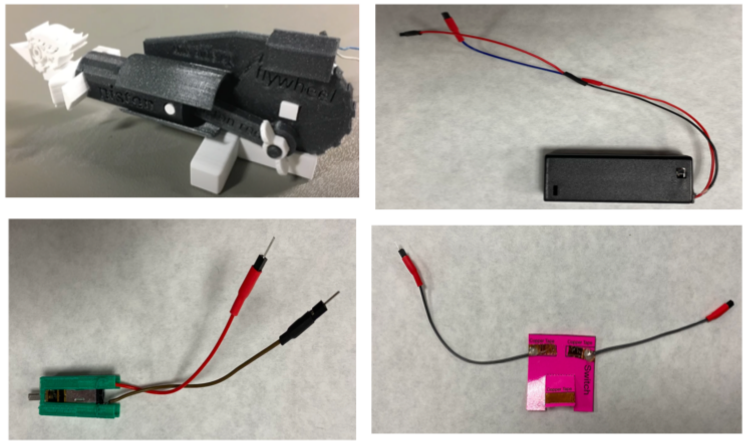

Figure 3: Sub-assemblies for *Adaptations* instructional science kit. Top-left: 3D printed parts for bird-beak control. Top-right: Battery case with soldered jumper wire ends. Bottom-left: Rotational motor with 3D-printed housing with soldered jumper wires. Bottom-right: Paper-button with jumper wire soldered to copper-tape connection.

Battery Case		Electronic Paper Button Switch		Rack and Pinion Assembly			
Part	Quantity	Part	Quantity	Part	Quantity	Part	Quantity
Battery Case	1	Paper Switch	1	clean_gear_dowel.stl	1	birdBeak.stl	1
AA Batteries	2	Laminate	1	Motor_Dowel_Adaptor.stl	1	rotational motor	1
Hot Glue	N/A	Hot Glue	N/A	gear_track.stl	1	Hot Glue	N/A
Jumper Wire	1	Copper Tape	3	Base.stl	3	Male Jumper Wire Half	1
Shrink Wrap Segment	3	Female Jumper Wire Half	1	push_clamp.stl	1		
Solder	N/A	Male Jumper Wire Half	1	motor_case_bottom.stl	1		
		Solder	N/A	motor_case_top.stl	N/A		

Figure 4: List of parts for each sub-assembly of the *Adaptations* of the produced instructional science kit.

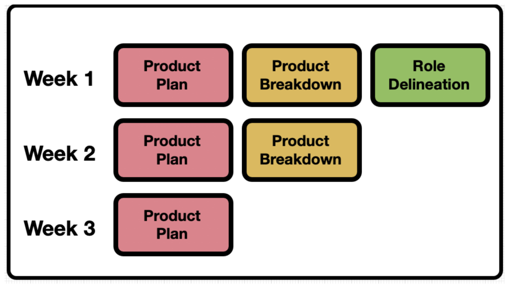

Figure 5: Schedule of production for sub-assemblies for instructional science kit

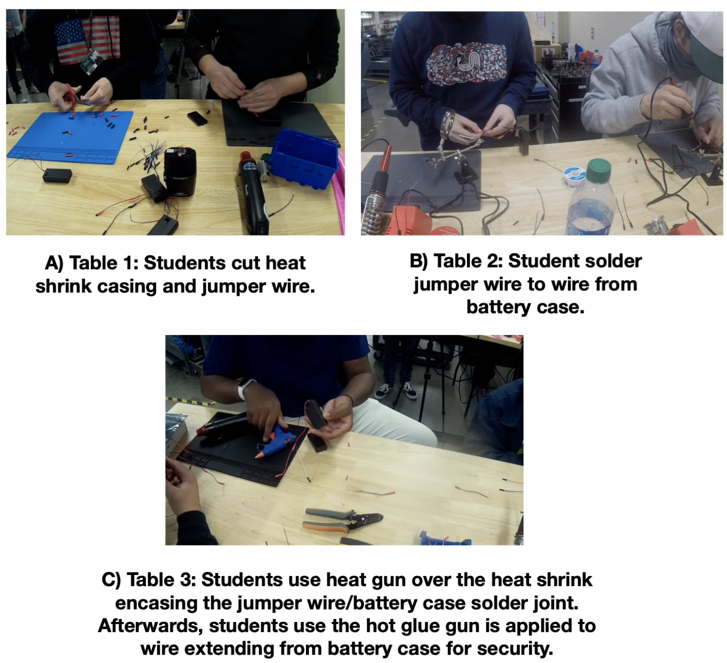

Figure 6: Individual production desks for battery sub-assembly

the supportive skills. In an interest to understand how students iteratively connect concepts across Making and production, we had two conditions represented by the different classes of our study. In the *Scaffolded* condition, the class was conducted where the instructor provided support across product planning (*i.e., What are we making and the means of making it?*), breakdown (*i.e., How is the product understood in terms of its components?*), and role delineation (*i.e., How are roles for product assembly designated?*) In the *Descaffolded* condition, the instructor gradually takes support away as students assume more and more responsibilities over time. By week 3, students are responsible for product breakdown and role delineation, given only a general plan by the mentor (Figure 5).

Study Participants

A total of 17 high school students participated in the study. Participants were recruited via the school district's existing CTE course. There were 10 students in the *Scaffolded* condition and 7 for the *Descaffolded* condition. All students were male. Students' ranged in age range 14 to 18.

Measures

A single pre-post measures was administered before the start and end of the 3-week class project. The Academic Self-Description Questionnaire II (ASDQ-II)[39] includes a sub-scales based on particular subjects of interest and self-efficacy towards them including computer studies, mathematics, industrial arts, science, and general day-to-day self-efficacy. Each sub-scale composes of 8 items that assess identification with and perceived efficacy in academics, for example for the case of ”Computer Studies”, items would include assessment statements such as "Compared to others my age I am good at COMPUTER STUDIES classes"). The ASDQ-II follows a 8-point Likert scale where participants are asked whether or not they believe the statements are true or not where "1" corresponds to ”Definitely False” and 8 to ”Definitely True”.

Results

RQ1:

We summarize our results where we compared the *Scaffolded* and *Descaffolded* classes. Of the ASDQ sub-scales, we only found significance in general self-efficacy and school self-efficacy. A Wilcoxon signed-rank test showed that there was a statistically significant change for the *Descaffolded* group from pre-test to post-test for general self-efficacy ($Z = 0$, $p = .04$) with a mean rating of 4.14 for pre-test ((*"More false than true that I am good at most things."*) to a post-test of 4.79 ((*"More true than false that I am good at most things."*) (Figure 7). We also saw a statistically significant change in the *Scaffolded* group for the sub-scale, school self efficacy ($Z = 0$, $p = .04$) with a mean rating of 5.24 (*"More true than false that I am good at most school subjects"*) for the pre-test and 6.36 (*"Mostly true that I am good at most school subjects"*) for the post-test (Figure 7). There were no statistically significant change in pre-post scores for the other sub-scales for the ASDQ-II for both groups.

RQ2:

We reviewed our collected video data and uncovered the following themes that characterize how the students differed in their performance between the two *Scaffolded* and *Descaffolded* classes. Our analysis of collected video and audio was through a qualitative coding approach known as grounded theory.

The approach involves three phases. In phase 1, 'Open coding', we determine descriptive categories of observed events. In phase 2, 'Focused or axial coding', we employ the use of categories to derive more refined themes. Finally, in 'Selective coding', we identify new themes and observations that are applied to further refine the analysis[40]. The coding procedure was by two coders. After completion of open coding by a single coder, the other coder reviewed codes generated. The inter-rater agreement was at 78%.

Organizational Decision Making by the Scaffolded Group

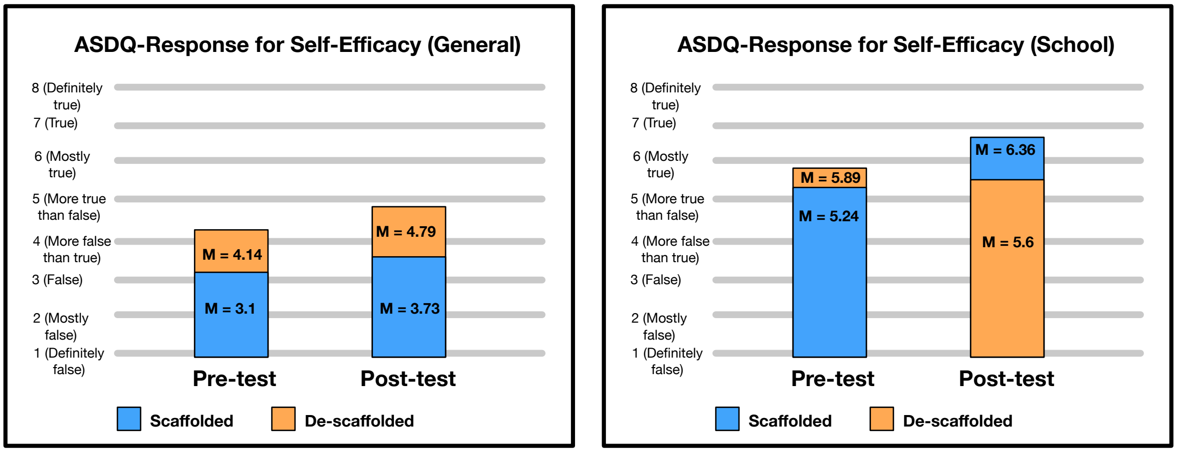

Figure 7: ASDQ Response Results for self-efficacy (general) and school self-efficacy

The *Descaffolded* group was differentiated from the *Scaffolded* group where they were gradually given more responsibility by way of self-organization (i.e., roles and workstation designation) and product breakdown. The students highlighted that their decision making was influenced by time constraints such as identifying what process would take the longest time and placing individuals to a process based on their recognized speed of completion. Another factor for organization was in terms of manpower, where the exact challenge of the task and skills available in members present, determined how many individuals would be placed at a given workstation.

Challenges Common and Unique to Sub-assemblies in Production: From the videos, students noted challenges that were common to all sub-assemblies of production, these characterized by inherent organizational issues. Students characterized organizational issues by how they remarked on the difference between making an individual product versus scaling the same steps for multiples under time pressure. The *Descaffolded* group differed where they recognized how certain workstation tasks were asymmetrical in their time requirements (i.e., task for cutting materials took significant less time than soldering materials directly to motor) leading to delays in production cycles and individual workstations standing in idle.

Students also recognized inherent challenges unique sub-assembly of the overall kit. Paper switch, recognized by both groups as the easiest sub-assembly to complete, was challenged by the initial step of removing copper tape from its paper lining, representing a time sink when the task is repeated at scale. The main challenge in the battery case, as identified by the *Scaffolded* group, was in splicing soldered wires directly onto the pre-connected wires of the battery case, a step that requires deft in applying solder to both sides of the small wire connection than that of the solder joint present in the paper switch. Finally, the motor case, the *Descaffolded* group noted analogous challenges in soldering, this time between the jumper wire and the terminals of the motor itself, again attributing this challenge to the small size of the terminals themselves.

Discussion

The *Descaffolded* group saw increases in general self-efficacy whereas the *Scaffolded* group saw a similar increase in school self-efficacy. We believe that such a result arose due to how the two groups differed in how involved they were in the active horizontal integration of skills and generating solutions from said integration. In the case for the *Descaffolded* group, for each class week, students encountered unique problems for the part of production they were responsible for (as seen at the start of week 2 where students took on the responsibility of role delineation for the production schedule (Figure 5)). While students described issues in their production when given responsbility of its design and implementation, the *Descaffolded* group were just as likely to create solutions based on encountered errors and adjusting based in skill level of specific students in group and constraints in terms of process time.

For the *Scaffolded* group, students followed the production line procedures under guidance by the instructor, akin to that of a apprentice-to-master relationship. The increase in the school self-efficacy by the *Scaffolded* group could be attributed to the students' own completion of the whole of the production experience, believing that having the experience in of itself is sufficient to engage in the practice of production. With the *Descaffolded*, we saw a distinction where there was no such increase in school self-efficacy but rather, in general self-efficacy. Perhaps the increase in this facet of self-efficacy could be attributed to the students' having experienced personally derived setbacks in their production and deriving solutions based on encountered problems and creating solutions based on the interface between the different skills they've accrued.

Conclusion

The future of work will require a new kind of worker, one that is capable to integrating various skills across different disciplines as information and manufacturing technology continues to advance. At present, we recognize that our education system does not currently prepare students for the future of work, opting for a siloed model of vertical development of skills within a given domain. Based on the interplay between expansive learning, self-efficacy, and Making as a vehicle for STEM learning, we sought to understand how we could create a class curriculum that could enable students to actively horizontally integrate their skills in practice-based scenarios. Through a partnership with a high-school CTE class, we performed a study that examines how students' can engage in horizontal integration of CTE aligned skills and its influence on students' own self-efficacy, observing an increase in students' own general self-efficacy. As a limitation for the current work, we acknowledge that the study could use a comparison with another comparable CTE class, not involved with the program that we have developed. In addition, there is a limitation in the time span of the study that we described here for our analysis. Future work will address these limitations by drawing comparisons with different CTE groups based on program involvement as well as longer term development of students' own practices in the CTE classroom.

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