Gotta Catch 'Em All: Teamwork, CAD, and Rapid Prototyping. Learning Graphical Communications Through an Introductory Hands-on Design-Build-Test Project

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Anna Wang[1] and Lelli Van Den Einde[2]

[1]Graduate Student; Dept. of Structural Eng., University of California, San Diego; e-mail: ahw001@ucsd.edu

[2]Professor; Dept. of Structural Eng., University of California, San Diego; e-mail: lellivde@eng.ucsd.edu

Introduction

The maker movement combines creative makers and advanced technologies such as the Arduino microcontroller and personal 3D printing to drive innovation in manufacturing, engineering, industrial design, hardware technology and education [1]. Through the process of making, students learn deeper. 3D printing and rapid prototyping allows students to practice the iterative design process [2] to produce a functional, aesthetic, and viable product [3].

Hands-on projects provide students with a "real world" engineering experience that enhances learning over standard course work. They allow students to experience a design-build-test process with well-defined design goals and cost and time constraints. Students learn the importance of creating a schedule and meeting deadlines, communication and coordination, cost implications, manufacturing and tolerancing issues, and documenting their design process [4, 5]. Providing clearly defined rules and requirements are integral to the success of the project. Design competitions should provide performance targets but include flexibility in how the students can achieve the performance goals [4].

3D printing and computer aided design (CAD) can be used in design-build-test projects for introductory courses to enrich student experiences [5]. They provide a realistic opportunity to explore the nature of the engineering design process [6] and promote student engagement [7]. The inclusion of 3D printing allows students to see what works and what does not work, forcing them to make required design changes [7].

Design-build-test challenges also provide opportunities to educate next generation engineers in practical concepts such as design reviews, technical communication, and teamwork. Design reviews have been recently incorporated into design challenges because they are recognized as an important element in delivering a quality product for a customer [8, 9]. They provide a mechanism to determine if the design meets the customer's specifications and fosters communication between the customer and student teams. Additionally, they improve the quality of the design through feedback from the customer and other technical experts. Design reviews can focus on technical aspects as well as testing of the product [9].

Technical communication skills can be incorporated by including a design presentation and/or report to ensure that students can communicate their design intent and understand the impact of their decisions in the design-build-test process [1]. Poster presentations are a form of technical communication that benefits students by allowing them to prepare exhibits (i.e., posters), participate in a dynamic learning environment that simulates a technical conference and "provides an alternative assessment method for students who may not excel on written quizzes and exams" [10].

The design-build-test challenge environment is also effective in promoting academic motivation. Students feel more motivated to complete an assignment if it is relevant to their career goals, and the increased motivation is partially associated with higher engagement in learning and improved group and communication skills [11]. A design-build-test project allows students to work together towards a tangible outcome and develop the critical non-technical skills that are not explicitly taught in engineering curriculum [12].

The ongoing COVID-19 pandemic has also introduced challenges for hands-on engineering learning. While many courses have experienced varying degrees of success with moving hybrid or completely remote, students still experience obstacles such as internet connectivity issues and finding quality learning spaces and technology [13]. CAD and other engineering software have also replaced the maker space as primary tools for the design-build-test project, and students are more focused on developing simulation skills. Therefore, students are lacking the in-person makerspace experience which has shown to improve confidence in engineering design by demonstrating the realities of prototyping and manufacturing [14]. Remote students have also reported feeling a lack of "relatedness", a sense of belonging and value within a team. Opportunities to form relationships with their peers in hybrid or in-person courses can increase feelings of relatedness and lead to higher academic performance [15].

A design-build-test project called the Pokémon Challenge was implemented in a freshman Engineering Graphics course at the University of California, San Diego. The primary learning objectives for the project were to develop spatial visualization and reasoning skills, understand the power and precision of computer-aided modeling, construct accurate complex 2D and 3D shapes, organize and deliver effective verbal, written and graphical communication, and apply relevant sketching, 2D and 3D techniques using modern engineering tools in a team-based setting to design parts of a larger system. The 8-week project started during week 4 of the 10-week quarter and provided detailed performance specifications, required students to undergo design reviews and work in teams, and provided multiple opportunities for teams to communicate their design process. This paper introduces the design challenge and describes some of the implementation challenges faced during the pandemic related to teamwork, motivation, and the ability to ensure all students were able to participate even if remote. Based on student survey data, recommendations for improved implementation practices for future design-build-test projects are presented.

Pokémon Challenge

The purpose of the Pokémon Challenge was to allow students to use the engineering design process while building upon their prototyping and graphical communication skills through hand-sketching, CAD, and manufacturing techniques. The project theme, which was selected to engage students, tasked them to develop a mechanism that would help Professor Oak catch all the Pokémon in the Kanto region to help him fill his Pokédex and further his research. Students were asked to optimize their Pokémon catching method and create a design that would be creative, aesthetically pleasing, fit within Prof. Oak's grant budget, and be able to catch the rarest Pokémon. Teams of 3-4 engineers were commissioned to develop a machine that could move a mass (the Pokéball) from the Start Zone to the End Zone. Each machine started from rest and was triggered by a pre-programmed Arduino and servo motor.

Scoring was determined by a Performance Index which penalized cost and rewarded accuracy, height, and distance from the End Zone (equations 1-3). Accuracy was weighted the most followed by height and distance, respectively. Machines were also tested over three rounds for precision to ensure that teams did not get "lucky" during testing. Teams with a unique design or those that exceeded expectations in creativity and aesthetics were also awarded a bonus factor. The highest PI possible was 110. If a team did not land in a Zone/Tier (ex: landing on the base of the End Zone or the floor), the Catch Rate for that round was zero.

$$PI = \left(1 + \frac{A}{100}\right)\left(\frac{1}{k}\sum_{n=1}^{k} R_n - 0.015C\right) \quad (1)$$

where,

A = aesthetic, creativity, and design score (0-10)

k = number of rounds = 3

$$R_n = 3T_n + 5Z_n + 2D_n = \text{Catch Rate for round } n \quad (2)$$

T_n = Height (tier) score for round n (0-10)

Z_n = Accuracy (zone) score for round n (0-10), included a 50% penalty for hitting the backboard

$$D_n = (10pts)\frac{d-6"}{42"} = \text{Distance score for round } n \quad (3)$$

d = distance from front edge of start zone to end zone in inches (min of 6" and max of 48")

C = Cost in Pokédollars

Teams competed individually as well as part of a conference: Valor, Mystic, and Instinct, with each conference led by a Teaching Assistant. To incentivize students, the winning individual teams and the winning conference received extra credit on their final term project grade.

A. *Competition Format*

Fig. 1 shows the complete test set-up. A crocheted hacky sack with a mass of approximately 41 g and a diameter of 2" was used as the "Pokéball" (Fig. 2).

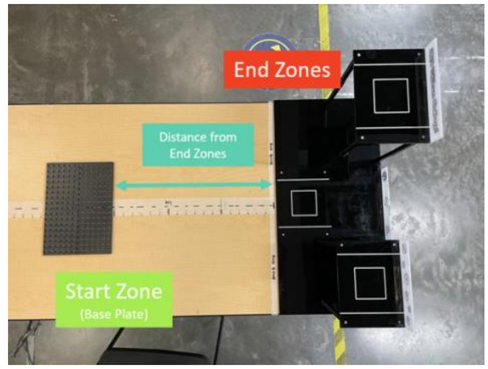


Fig. 1 Test Setup

Fig. 2 Pokéball

Start Zone: Each team received a Base Plate that acted as the foundation for their machine. Base Plates measured 10.1"x7.3", and had cutouts spaced at 0.59" apart for attaching Fischertechnik or custom parts.

End Zone: The End Zone consisted of three platforms (Tiers) at varying heights with each Tier separated into three Zones, like a target (Fig. 3). Each Zone had a 2-inch-tall backboard. The Pokéball was permitted to bounce off the backboard, but teams would receive a penalty on their accuracy score for doing so.

Arduino & Servo Motor: Fig. 4 shows the given Arduino and servo motor controller used to trigger the machines. Teams could use a potentiometer to adjust the duration that the servo motor rotates in a range from 1 sec to 10 sec.

B. *Project Requirements*

Each machine had to meet certain engineering requirements or risk being disqualified. The machine had initial dimensional constraints of 10.1"x7.3"x14" (i.e., the machine must fit within the footprint of the Start Zone and be no more than 14" tall). However, there were no boundaries for the machine after being triggered. The Pokéball was not permitted to touch the floor at any time. The centerline of the base plate must also be in the center of testing set-up and orthogonal to the edge of the End Zone. Therefore, aiming for the higher tiers required a custom connection to angle the mechanism relative to the base plate while still staying within the footprint of the Start Zone. The servo motor was also required to be within the Start Zone (so students had to design a mount or holder). However, the Arduino and wiring could remain outside. Machines were required to be at rest prior to starting the servo motor using the Arduino. Teams also had a 3-minute time limit to set-up their machine.

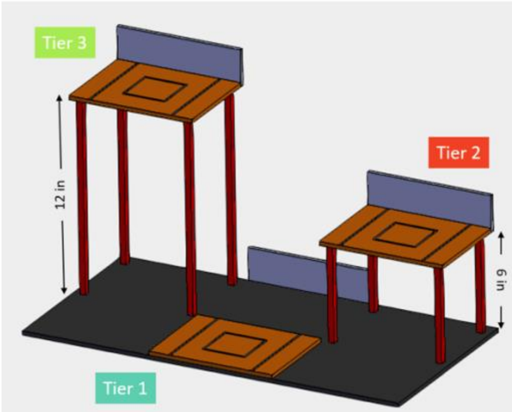


Fig. 3a End Zone

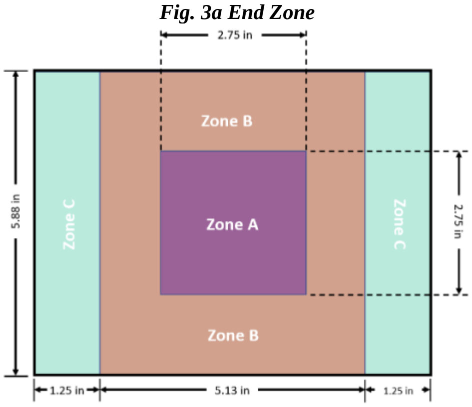


Fig. 3b Tier Close-up and Zone Numbering

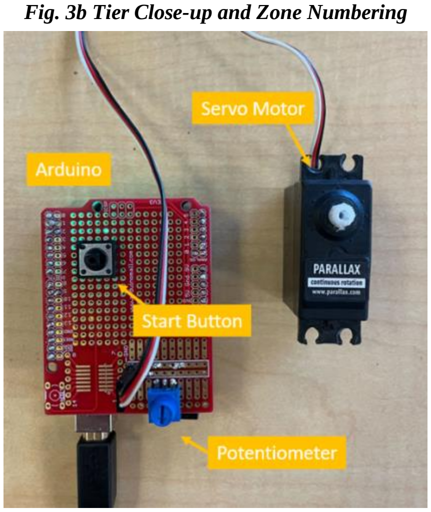


Fig. 4 Arduino and servo motor set up

In addition, each machine was required to have at least one unique 3D printed part per team member, one unique laser cut acrylic part per team member, and one type of connection. A connection is described as any feature that joins two or more pieces together. At least one 3D printed part had to be larger than 1"x1"x1". These requirements were set to ensure that every student had experience using both the 3D printer and laser cutter. All required parts had to actively contribute to the mechanism of the machine; however, one laser cut piece was allowed to be decorative.

Each team member was not only responsible for the CAD and fabrication of their required 3D printed and laser cut parts but was also responsible for a sub-assembly. Their individual required parts may have been a component of a teammate's sub-assembly, requiring collaboration between team members during all stages of the design process.

Aside from the above constraints, the project was left very open-ended to allow for creative engineering solutions. While many teams opted for a simple, rubber-band powered catapult, other teams created scoping or scissor mechanisms, cannons, and trebuchets. Some teams incorporated mechanisms to easily adjust the angle and rotation of their launch. Since the instructions only identified the constraints and objectives of the project, students could experience the engineering design process from start to finish.

C. Materials

Teams were provided with rental and consumable materials and a budget of 1500 "Pokédollars". No other materials were permitted including adhesives such as glue or tape. This was to ensure that students would work on tolerancing to connect their pieces during the manufacturing process.

Rental materials included Fischertechnik parts, various sizes of rubber bands, and stainless-steel balls which could be used as weights. Rubber bands and stainless-steel balls were priced higher than other materials due to their potential energy. Therefore, teams who relied more on gravity and the servo motor as energy sources would incur a lower cost.

Consumable materials included a generous allocation of acrylic (12"x24" sheet at a random thickness) and 3D printing funds (40 hours per team). Additional acrylic and 3D printing funds could be purchased at a low cost. This was to encourage teams to develop more custom parts rather than relying on the more expensive rental pieces. Spectra fiber (a specialty fishing line used for pulley applications), one 18" aluminum rod, and #4-40 screws, nuts, and washers were also provided at no cost with no limitations.

D. Deliverables

The project consisted of several weekly milestones, called Team Design Reviews, to pace the students throughout the quarter. Prior to each Team Design Review, teams were required to submit an entry in their "Engineering Notebook" (a slide deck). Teams would present their Engineering Notebook slides to the teaching team, similar to how they would present project updates to a client. This was not only for the students to document their engineering design process, but also for them to practice verbal and visual communication skills and get feedback from the teaching team. During each Design Review, teams were evaluated on teamwork, effective communication, and meeting the project requirements.

All students started with individual hand-sketching and brainstorming prior to sharing their ideas with their teammates (Fig. 5). Teams were also required to designate roles such as Project Manager, CAD Manager, Manufacturing Lead, and Drawings Coordinator to ensure that all students held leadership responsibilities in at least one aspect of the project. They were also required to create a detailed schedule of their project plan and modify it weekly as needed to adjust for unforeseen circumstances.

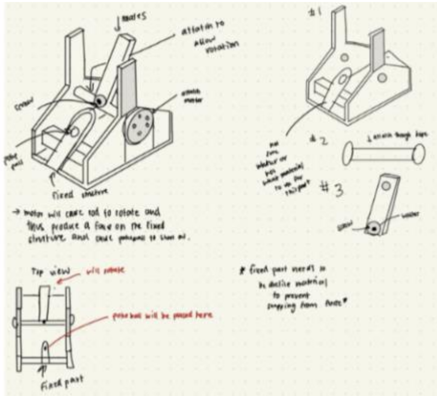


Fig. 5 Sample Conceptual Sketches

After deciding on an initial design, teams started to develop a SolidWorks assembly of their machine. A completed CAD model, including all parts, fasteners, and the servo motor, was required by the fourth week of the project (Fig. 6). This was required prior to manufacturing for students to identify issues with connections and dimensioning. Students were introduced to hand-sketching, SolidWorks, and AutoCAD in parallel with these stages of the project and were able to develop their skills through these practical objectives.

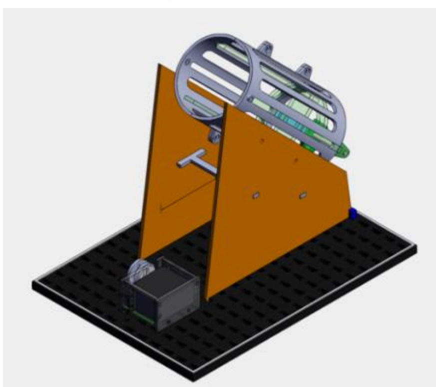


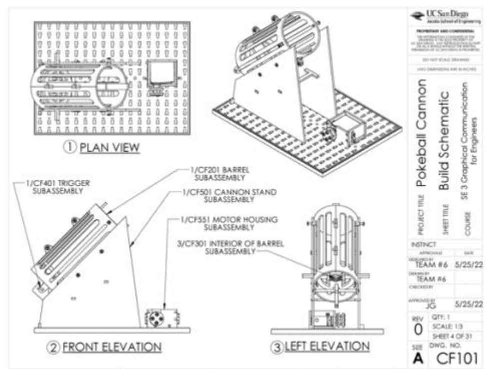
Fig. 4 Sample CAD Model

A conference design review was held halfway through the project to replicate a "peer review" and encourage collaboration and idea sharing between teams in the same conference (lab section). Each team presented their cumulative Engineering Notebook slides to their peers and provided constructive feedback to each other.

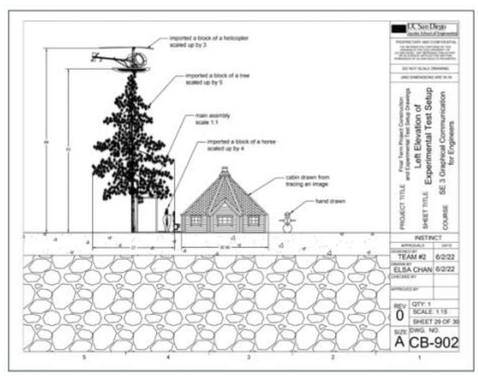
During the fifth week of the project, all teams demonstrated their prototypes in the first round of testing. Teams were permitted to manually deploy their machine or only demonstrate the working sub-assemblies. Only 9 teams (out of 46) had a complete mechanism that was able to be triggered using the motor during this stage. Students had a huge wakeup call about the importance of tolerancing as many parts did not fit together as expected. A week later, teams demonstrated their improved prototypes during testing round two. This round of testing served as a dry run of the final competition, and 38 teams had a working mechanism with the motor, showing significant improvement in just one week. The remaining two weeks were dedicated to iterating their design and completing the drafts of their drawing sets.

In addition to a physical prototype, students were required to submit a complete engineering drawing set to demonstrate their graphical communication skills (Fig. 7). All drawings were required to be compiled on sheet size A using ANSI standards, and title blocks, fonts, leaders, sheet numbering. They had to be consistent across all sheets and between software programs (SolidWorks and AutoCAD).

Drawing sets were composed of a Title Page, General Notes Sheet, Bill of Materials, Build Schematic, Exploded Views of sub-assemblies and full assembly, sub-assembly placements, and custom part drawings completed in SolidWorks. Teams also included creative experimental test setup plan and elevation views drawn in AutoCAD using imported, traced, and hand-drawn blocks. Drawings were required to be detailed enough so that their parts could be replicated exactly. Therefore, students needed to include dimensions, detail callouts, and section views where necessary.



a. Sample SolidWorks Drawings



b. Sample AutoCAD Test Setup

Fig. 7 Sample Construction Drawings

The term project culminated in a final competition during their final exam block (Fig. 8). Teams presented their technical posters as well as demonstrated their final prototypes. Technical posters included SolidWorks model and drawing images, AutoCAD experimental setup images, a project overview, and the design approach. Teams highlighted key design features as well as challenges and learning points.

During the final exam block, teams had 15 min to set-up and run their prototype over three rounds. While not competing, students were required to be with their posters to present to their instructors and guests as well as check out posters made by their peers. Teaching Assistants helped with running the testing stations as well as grading the poster presentations.

Fig. 8 Final Competition and Poster Fair

Competition Results & Assessment

A. Competition Results

The winning team achieved a PI of 62, well above the class average of 11.1. Second and third place earned 35.9 and 35.1, respectively. 21 out of the 46 teams earned a PI of 0. The top two teams both had an extendable scoping or scissor mechanism, used mostly custom-made parts, and obtained consistent scores throughout all three rounds (Fig. 9). Although both teams did not reach the higher tiers, the PI rewarded them for their precision and accuracy, a consequence of their complex design.

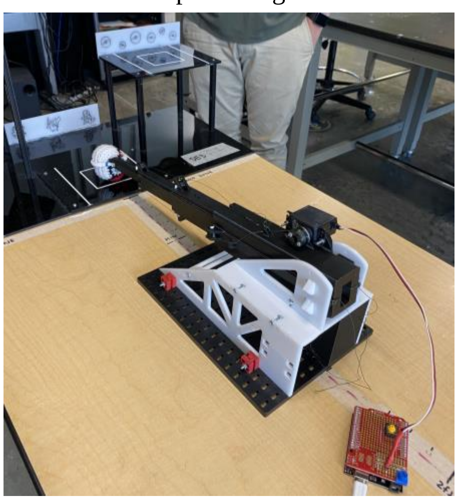


Fig. 9a First Place

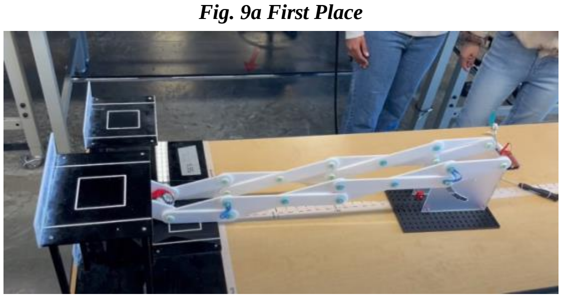


Fig. 9b Second Place

Many teams were also successful using a launching mechanism (Fig. 10), which was easier to construct, but not as precise. These teams were successful in reaching the higher Tiers. However, they were less consistent and had a higher cost due to the use of rubber bands and stainless-steel balls.

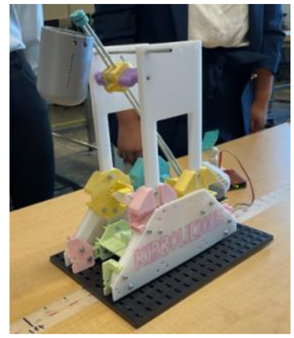


Fig. 10 Example Trebuchet

B. Survey Results

The teaching team conducted a survey at the end of the term project to understand the students' perspective on their learning outcomes and experience. 156 of the 176 students completed the survey. Out of these 156 students, 97% of students agreed that the term project was helpful in applying course content. Furthermore, 95% agreed that the term project was effective in teaching them rapid prototyping and 86% agreed that the engineering notebook was an effective way to document their project status.

When asked what part of the term project they enjoyed the most, 42% of students said they enjoyed rapid prototyping using the laser cutters and 3D printers. Many students also expressed that they enjoyed seeing their CAD models come to life. One student commented "What I enjoyed most was making the prototypes and testing them because it gave us all a sense of how life as an engineer could possibly be". 82% of students also indicated that they enjoyed working in teams, including one student who commented "I enjoyed spending time with my groupmates and building friendships with them" and another who responded "I enjoyed the opportunity to work with others during the term project. Having different roles and dividing work to complete the project makes us feel proud of what we created". Students also acknowledged the benefits of the open-ended nature of the project, "I liked the creativity aspect of being able to take unique approaches to solve the given problems".

Students also expressed challenges and concerns about the project. Only 61% of students agreed that the amount of individual work for the project was reasonable. However, 81% of students agreed that the level of difficulty of the design-build-test project was reasonable. Many students mentioned that the workload was too high, with one commenting "I think it was too heavy on the work as it was taking over all of my other classes". Others expressed that it was difficult to find an available 3D printer or laser cutter, especially during peak hours and prior to a deadline. The Maker Studio's only large laser cutter was also down for maintenance during the final week of the project. Students also criticized the clarity of the term project directions and felt that the amount of information given was overwhelming.

C. COVID Accommodations

One of the biggest challenges for engineering education during the era of COVID is the implementation of hands-on activities. While CAD and hand-sketching are critical skills in the engineering toolbox and can be taught remotely, the in-person makerspace experience cannot be replaced virtually.

During the 2021-2022 academic year, UC San Diego courses were permitted to be up to 50% remote with masks required in all in-person classroom environments. Students in this class were required to attend all labs and lectures in-person. However, accommodations were made for those who were ill or quarantined by allowing them to attend via zoom for Team Design Reviews and testing. Although these students were unable to participate in the makerspace, teams were still able to share updated CAD files through GrabCAD and update their Engineering Notebooks with their remote peers. This allowed students to work on flexible communication and collaboration, which is valued by employers, especially as industry becomes more globally connected.

From the student surveys, 80% agreed that the hybrid delivery of the term project (with some students sometimes on zoom) did NOT impact them in successfully getting work done. The entire class was also virtual for one week during the CAD stage of the project due to an increase in COVID cases. When asked about the remote portion of the class, 41% of students expressed that attending lab remotely was very convenient, especially while completing software heavy assignments. Many students also appreciated that the instruction team prioritized their health and safety with one commenting that "the benefit [of remote lab] was that if someone got COVID, they were still able to fully participate in lab. It was really kind that [the instructors] did this, and it helped many groups".

D. Assessing Teamwork

The instruction team surveyed the students at the midpoint of the term project and asked them to provide specific, constructive feedback of their peers. This anonymous feedback was sent to each group so that teams could address their issues and improve their team dynamic prior to wrapping up the project. One student told their teammates "I think we had a few setbacks with our design… but I appreciate the flexibility that you guys have had in quickly changing designs. … Achieving our deadlines is the only way that we'll be able to effectively complete this project so let's work together and support each other in the last few weeks of this project's culmination".

Students filled out the same team evaluation at the end of the term project, which instructors used to adjust final term project grades as needed, depending on contributions from each member. Survey questions included rating the degree to which their team had high levels of cooperation and mutual support, took initiative to resolve issues between themselves, and how much they appreciated one another's unique capabilities. In addition, 87% of students agreed that team problem solving resulted in effective solutions, and 81% agreed that communication in their group was open and honest. These surveys were important not only for instructors to identify red flags early on, but also for students to communicate constructive feedback to their peers and for resolving internal conflicts professionally.

Conclusions

Developing a design-build-project that meets desired learning objectives while recognizing the varying skills and knowledge that students bring to the table is challenging. A balance must be found between providing enough details about the project without over constraining students from being creative. The workload must be appropriate, and all deliverables must meet the learning objectives. Furthermore, implementing a maker hands-on project during a pandemic presents additional complications with supporting rapid prototyping, teamwork, and fostering engagement.

Overall, students found the Pokémon Challenge to be a rewarding experience and recognized that student learning outcomes were met. They were grateful at the ability to join remotely if they had to quarantine or were sick, which allowed them to participate effectively in their team project. Teams had to adjust to changes in personnel, a skill required in the practical world. Students did complain about the amount of individual work required for the project. While some teams struggled with team dynamics, for the most part students enjoyed the team experience and were pleased with how far they had come in their designs.

Many lessons were learned from this first implementation of the Pokémon Challenge. Specifically, running an elaborate hands-on design-build-test experience is labor intensive. The design reviews alone took 8 hours once a week to review the 46 teams even with two members of the teaching team working simultaneously. However, these design reviews held teams accountable to meet milestones and provided an opportunity for the teaching team to mentor them to be successful. Many students waited until the day before a deadline to work on their projects leading to issues with availability of the 20+ 3D printers and two laser cutters. Other areas for improvement include finding ways to streamline the deliverables and assist students with time management so they do not feel so overwhelmed with the deadlines.

In future implementations, the performance index would be adjusted so teams would not feel discouraged, and more teams could be successful. This would include not penalizing them for hitting the backboard, and awarding points for landing in the End Zone even if not directly on the target. Furthermore, the term project would likely be started earlier in the quarter despite students not having any CAD skills yet, to spread the workload and get them rapid prototyping earlier.

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