Transformation of Design Instruction in a Low-Resource Setting

Matthew Petney, Rice 360 Institute for Global Health
Mr. Samuel Gonthako Ng’anj, University of Malawi, The Polytechnic

Samuel-an Industrial Engineer works as lecturer in Mechanical Engineering Department at The Polytechnic, a constituent college of the university of Malawi. He has over 20 years of experience in teaching Drawing and design, Manufacturing Technology, Quality control and Ergonomics. Samuel was head of Mechanical Engineering Department and in 2017 was appointed National judge for the 2017 National Innovation competition. Samuel studied professional Production Engineering at Malawi Polytechnic, Bachelors in Industrial Engineering at Nelson Mandela Metropolitan University (NMMU) in South Africa and Masters in manufacturing at Swinburne University of Technology (SUT) in Australia.

Mr. Joseph Chikaphonya Phiri, University of Malawi, The Polytechnic

A staff associate at The Malawi Polytechnic, a constituent college of The University of Malawi, under the Electrical Engineering department.

Coordinator of final year projects in the department and an enthusiast of Innovation.

Dr. Matthew Wettergreen, Rice University

Matthew Wettergreen is a Lecturer in Engineering at the Oshman Engineering Design Kitchen at Rice University. He is also the Assistant Director for the Rapid Prototyping Program at the School of Science Technology.

Dr. Ann Saterbak, Duke University

Ann Saterbak is Professor of the Practice in the Biomedical Department and Director of First-Year Engineering at Duke University. Saterbak is the lead author of the textbook, Bioengineering Fundamentals. Saterbak’s outstanding teaching was recognized through university-wide and departmental teaching awards. In 2013, Saterbak received the ASEE Biomedical Engineering Division Theo C. Pilkington Outstanding Educator Award. For her contribution to education within biomedical engineering, she was elected Fellow in the Biomedical Engineering Society and the American Society of Engineering Education.
Transformation of Design Instruction in a Low-Resource Setting

Abstract

Engineering schools in low-resource settings typically do not have access to makerspaces, which are common in engineering schools in the USA. Without tools or materials to build and iterate prototypes, instructors often assign paper-only design projects. Students in low-resource settings move through the first half of the design process, including understanding the problem, defining design specifications, generating solution ideas and selecting a solution. But, due to resource constraints, students “stop” the design process with a dimensioned sketch and a description of the materials needed to build the device.

Through a long-term collaboration between Rice University and the University of Malawi Polytechnic, we have established a makerspace that is appropriate and sustainable in a low resource setting. The PIDS, or Polytechnic Innovation Design Studio, was established in 2016 with a grant from the Lemelson Foundation. PIDS houses electrical and mechanical prototyping tools such as Arduinos and Raspberry Pi, 3D printers, a laser cutter, a CNC machine, and various hand tools. Prototyping materials include supplies that are readily available in markets in Malawi. PIDS is open to all students across the school of engineering, faculty, recent Polytechnic graduates, and members of the Entrepreneur Hub, and it has become a true innovation hub where over 700 students have participated in hands-on workshops, class work and independent projects since its inception.

In conjunction with establishing the PIDS, the required first-year drawing course was modified to include design projects scoped at a district hospital. The projects selected were a traction system for femoral fractures and a manual cast-cutting device. With the curricular modifications, all first-year students completed several steps in the engineering design process and created dimensioned drawings as well as low-fidelity prototypes of their design solutions in the PIDS. The final-year capstone design courses in mechanical and electrical engineering have also been transformed to emphasize prototyping. Final-year students with access to the PIDS completed more steps in the engineering design process, with time allocated to prototyping, testing, and iteration. In the final-year course, students now build projects such as a monitoring system for remote telecommunication sites and a neonatal respiratory rate sensor.

In this paper, we discuss the impact of the PIDS and its transformation of the capstone design course. Using pictures of sketches, CAD drawings, and physical prototypes documented in student reports, the number of iterations, the quality of the final products, and the number of type of tools used to produce the final prototype are noted. Comparing before and after the opening of the PIDS, there are clear improvements in the number of department-specific tools used by student teams as well as the quality of the prototypes. In summary, this paper discusses the creation of a makerspace in a low resource setting and the impact the facility has had on the design education at the University of Malawi Polytechnic campus.
Motivation

Engineering schools in low-resource settings typically do not have access to makerspaces, which are common in engineering schools in the USA. For example, FabLabs, makerspaces coordinated by the Fab Foundation, are unequally distributed, with only 46 of the 1215 (<4%) recorded FabLabs based in Africa, and half of these in three countries (Egypt – 9, South Africa – 8, and Morocco – 6) [1]. In a university setting, without tools or materials to build and iterate prototypes, instructors often assign paper-only design projects, or the burden of finding prototyping material is placed upon the academic mentor. Students in low-resource settings move through the first half of the design process, including understanding the problem, defining design specifications, generating solution ideas and selecting a solution. But, due to resource constraints, students “stop” the design process with a dimensioned sketch and a description of the materials needed to build the device. When a prototype is constructed, it is rarely tested fully, or improved upon. Without prototyping, students do not experience the shortcomings or need for design iteration. This leaves projects unfinished or untested and students’ education about the design process incomplete. Additionally, designing projects on paper presents less of a challenge than making prototypes and testing them in the real world. Thus, students fail to receive real-world experience successfully completing the design process for a client. At worst, they are unable to proceed in projects that require structure and iteration because they have not learned a structured design process.

In Kenya, Donaldson describes that even in markets where products are constructed locally, no coherent design process is used and almost no original design is undertaken because they do not have the required expertise [2]. Building the design capacity of engineers and technicians using a local design facility can address some of these shortcoming for industry. This is consistent with the government’s strategy in Malawi, which has adopted a national export strategy that includes increased manufacturing for export [3].

While there are many NGOs and other organizations targeting the needs of communities in low income countries, new product development that occurs in developed settings often does not address needs of low resource settings [4]. Even with a virtual and field immersion, the design process students undertake is necessarily linear, without significant opportunity for iteration with end-user feedback, until the next annual visit to the low-income country [4]. Local designers have regular access to end-users and other stakeholders. Improving students’ ability to produce functional original designs is a first step at addressing the lack of technical innovation. Even with access to design facilities, there are significant barriers for local designers to complete the new product development and deliver products into the market, as experienced by Vigyan Ashram design studio in western India [5]. In Malawi, lack of trust in locally manufactured solutions and limited access to capital present difficulties for new ventures. However, accessing the materials and support in the design studio improves the cost to benefit ratio for entrepreneurs [6]. Access to a makerspace can enable the university to adopt more modern educational techniques, such as problem-based and self-motivated learning [7]. These opportunities can lead to grant funding, addressing issues of startup capital and mentorship. PIDS students and graduates are positioned
to create high quality products that can lead to a change in public perception of locally developed solutions.

**Academic Setting**

The site of the work was undertaken at the University of Malawi Polytechnic. The Polytechnic is the technical university located in Blantyre, Malawi founded in 1965. The Polytechnic is organized around four traditional engineering departments: electrical engineering (including biomedical engineering), mechanical engineering, civil engineering, and mining engineering; 15 degree programs are offered. All programs of study feature a heavily theoretical curriculum. The Polytechnic’s academic calendar is broken into semesters and engineering degrees are awarded in a five-year program. The number of students in the electrical engineering (EE) and mechanical engineering (ME) departments are 309 and 210, respectively.

Blantyre is a city of 1 million located in southern Malawi, a southern African democratic republic. The city is the commercial and industrial capital of the country with several large construction, telecommunications, and processing facilities. This affords the faculty the ability to form partnerships with relevant and local industry partners.

**Final-Year Projects Pre-PIDS**

In their fifth year of studying engineering at the Polytechnic, students in all four engineering departments undertake a two-semester final-year project (FYP). This project is similar to the capstone experience in the United States required by ABET and is designed to challenge students to apply technical concepts learned up to that point in their education. Individual students or student teams apply a version of the design process to solve an open-ended problem. This paper focuses on FYP projects in the ME and EE departments because of their focus on engineering design and involvement in the PIDS. The mining department was recently established and does not yet have final year students, and the civil engineering department focuses primarily on research projects. Before 2016, the source of projects were proposals by members of the department based on their personal interests, or by students after they completed an internship at a local company. Mechanical Engineering students worked on projects individually, and Electrical Engineering students worked on projects in pairs. Each project is assigned an academic supervisor, and, if involved with an industry partner, also an industry supervisor. Over the course of two semesters, students work to solve their selected problems. The design process is introduced during the third year of study in a lecture-based course and is not rigorously covered during the final-year projects. In their FYP students proceed towards a solution based on their own initiative and guidance from mentors. Bi-weekly meetings with academic supervisors are encouraged, yet in practice, meetings between supervisors and students often occur less frequently. Milestones for the project include three written progress reports and two oral presentations over the course of the year (Table 1).
Table 1. Major Deliverables for First Year Projects

<table>
<thead>
<tr>
<th>Deliverable</th>
<th>Due Date</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project proposal report and oral presentation 1</td>
<td>End of First Semester</td>
<td>Problem definition and scope of the project</td>
</tr>
<tr>
<td>Interim progress report</td>
<td>Middle of Second Semester</td>
<td>Three solution ideas with drawings/circuit diagrams, the proposed solution, a detailed description, and a proposed budget</td>
</tr>
<tr>
<td>Final report and oral presentation 2</td>
<td>End of Second Semester</td>
<td>Solution, prototype, testing, results, conclusions, and recommendations</td>
</tr>
</tbody>
</table>

Project topics in the EE department generally revolve around automated systems (e.g., automated irrigation systems, automatic animal feeding systems) or monitoring systems (e.g., monitoring remote telecommunication sites, monitoring power theft). Many ME projects focus on food processing products that could be used by small scale farmers (grain threshers, grain mills, etc.), with others looking at water supply (various types of pumps).

In the first semester students do work that resembles the first half of the design process, including research and setting parameters (Table 1). Sections of the project proposal report highlight the activities encouraged during the first semester: problem statement, project objectives, literature review, approach to the problem, and outline of designs. In practice, students spend most time doing online research about the problem and potential solutions; they find or create three ideas to meet the minimum requirements for the Interim Progress Report without formally generating useful design criteria or brainstorming an exhaustive list of solution options.

In the second semester students typically work to construct prototypes (Table 1). Limited funding is available for these prototypes from the university. However, due to budgets constraints imposed by the Malawi government, departments may disperse the funding late (or not at all) during the second term, leaving insufficient time for students to purchase materials and construct prototypes. Students have access to all university lab facilities, including a machine shop with traditional lathes and mills, drill presses, welding machines (e.g., arc, MIG, and oxy acetylene). Lab technicians often assist with prototyping. In the past, due to these resource constraints some students/teams stalled in progress and finished with only a dimensioned sketch and a description of the materials needed to build the device.

**Modifications to Final-Year Projects Post-PIDS**

With the addition of the Polytechnic Innovation Design Studio in 2016, the Polytechnic has been gradually reforming the structure of final-year projects, starting with the ME and EE departments. One major shift has been in project sourcing and team makeup. For the 2016 and 2017 projects, Polytechnic lecturers visited industry to identify potential relevant project ideas; see an example prompt below from a Puma fuel station. In 2017, the ME department began...
assigning projects to pairs of students instead of individuals, and two interdisciplinary teams combined ME and EE students in groups of three.

**Automatic Measurement of Fuel Levels**

**Problem:** Fuel levels in reserve tanks and distribution tanks (filling station) of oil companies in Malawi need to be measured/checked to balance the off-loaded and the sold amounts, determine the amounts to be ordered, check the presence of contaminants (e.g. water), and evaluate if theft of fuel occurred. Currently the measurement of fuel levels is done manually using a dip stick, which is calibrated, to measure the levels of fuel in the tanks. The bottom end of a dip stick is coated with water finding paste, which changes colour when immersed in water. So the presence of water can be noticed by the paste. Manual measurement is inaccurate, is difficult to do, for example when it is raining, and incurs a risk on the user who must climb atop tanks to take the measurement.

**Overall Goals:** There is a need to design an automatic system that can measure the fuel levels in tanks, check the presence of water, calculate (measure) the density of the fuel, and display this information to the responsible people view so they can take the appropriate actions.

The curriculum of the FYP courses has also shifted to provide more structure and support for students in their projects. Now, in the first semester of the FYP course for ME and EE, two important concepts in the design process are taught to the students: problem definition and idea generation. Three in-class lessons cover stakeholder analysis, needs finding, setting design criteria, and brainstorming techniques. These topics were specifically selected to improve upon shortcomings in previous projects. As an example, previously teams would only ideate the required three solutions rather than brainstorming dozens. This resulted in a lack of divergent or innovative ideas from teams.

From one student’s report: “Different theories of operation of pumps which were sourced from the internet and engineering books were used to come up with the possible solutions.” Beginning in 2016 and expanding in 2017, we encouraged teams to dedicate adequate time to brainstorm individually and consider a wide variety of possible solutions in this process rather than designing a system and simply selecting the first three designs that come to mind. This curricular shift was facilitated by more teams making use of the new Polytechnic Design Studio, whose staff regularly encouraged more thorough brainstorming. With access to more materials, students were not limited to designs that they could build with very basic components.

**Polytechnic Design Studio**

Through a long-term collaboration between Rice University and the Malawi Polytechnic, we have established a makerspace for use by the students to assist in the fabrication of their design projects. The PIDS, or Polytechnic Innovation Design Studio, was established in May 2016 with a grant from the Lemelson Foundation. This is a physical makerspace located in the Physical Sciences building, in the same building as electrical engineering, and near to the
mechanical engineering block. The space is 900 sq ft and is open 45 hours/week, including 5 hours each Saturday. While PIDS is open to anyone to use, membership is marketed to students across the school of engineering, faculty, recent Polytechnic graduates, and members of the Entrepreneur Hub (a traditional co-working space for early stage entrepreneurs).

The design studio manages a suite of tools and resources to facilitate prototyping and experimenting. PIDS houses electrical and mechanical prototyping tools such as Arduinos and Raspberry Pis, 3D printers, a laser cutter, a CNC machine, and hand tools. Physical prototyping materials (like plywood, cardboard, and plastic sheets) are kept in stock from supplies that are readily available in local markets. Members can borrow Arduinos, National Instruments equipment, digital multimeters, and a wide range of electric components to take out of the studio. Within the studio, members are allowed to personally use the laser cutter, FDM 3D printers, the CNC machine, various hand tools (e.g., drill press, hot air gun, soldering irons, etc.) computers, and internet (100Mb per day per member). During day-to-day use, members problem solve together, organically form teams around specific design projects, assist each other in prototyping work, and share digital resources (software, tutorials, etc.). Since opening in May 2016, it has become a gathering place for individuals interested in working on technical design projects, especially final-year students who traditionally met in the university hostels where electrical blackouts are common.

The PIDS has become a true innovation hub where over 700 students have participated in hands-on workshops, class work, and independent projects since its inception. During 2017, excluding classes and formal workshops, the design studio had a total of 129 paying student members and 18 paying non-student members who borrowed materials and used the space to work on personal projects. During peak times of year such as the weeks leading up to FYP presentations, during the university holidays, or preceding other design deadlines, the studio operates above capacity; it can sit 24 comfortably, yet it often hosts 40+ members while others work in an adjacent room.

The activities that the studio supports go beyond simply providing space and tools. For example, in the studio final-year students assist each other with tasks outside their core skillset, designing mechanical components or simple circuits. This knowledge transfer is also available for the students in their first and second year to interact with students who are near graduation. Establishment of the studio was led by an adjunct faculty member of Rice University, who had engineering design and prototyping experience in electrical and mechanical disciplines. In the second year, operation of the studio was taken over by two Polytechnic graduates who divide their time between managing the space and designing their own products. With their experience as students at the Polytechnic and designing medical devices for small-scale production, they are well suited to provide technical and procedural guidance to FYP teams and PIDS members.

**Assessment Methods**

Membership records and sign-in sheets for the design studio were used to determine which groups used the studio for their projects. Pre-PIDS conditions are 2014 and 2015; post-PIDS conditions are 2016 and 2017. While there were many aspects that could have been measured,
we focused on only a few in this paper. In addition, the process of evaluating the impact of this instructional change on student performance was fairly unique, so the scope was limited to aspects that were more easily measured.

FYP reports from 2014 to 2017 were evaluated for the prototyping tools used and the overall quality of constructed prototypes. All reports are from the ME and EE departments. Evaluations were performed using photos and descriptions of the prototype, testing processes, and construction description contained within the reports. A few FYP project teams focus on research only (e.g., performance comparison, optimization) and do not create a prototype; these research projects were not included in the analysis for this paper. Not all project reports were available. Table 2 shows the number of project reports available and evaluated from each department and year.

Table 2. Number of project reports evaluated for EE and ME projects. Poor record-keeping, combined with an exclusive paper (i.e., not electronic) trail of papers, led to difficulty in retrieving reports for this study.

<table>
<thead>
<tr>
<th>Year</th>
<th>EE</th>
<th>ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>7 / unknown</td>
<td>3 / unknown</td>
</tr>
<tr>
<td>2015</td>
<td>0 / 13</td>
<td>6 / unknown</td>
</tr>
<tr>
<td>2016</td>
<td>10 / 11</td>
<td>6 / 20</td>
</tr>
<tr>
<td>2017</td>
<td>15 / 18</td>
<td>7 / 17</td>
</tr>
</tbody>
</table>

The projects were anonymized, with names and years removed. Order was randomized amongst projects from years 2014-2016. 2017 reports were evaluated when they became available at the end of the year. Three evaluators scored each report; these evaluators had a technical background, worked in the EE and ME departments at the Polytechnic, and were familiar with some of the projects. The three evaluators individually scored the projects for (A) prototyping tool usage, (B) prototype quality, and (C) prototyping level.

(A) Prototyping tool usage: Tool usage was assessed at a level from 0 to 3. Scores referenced the presence of a particular tool used to fabricate a design solution and the level of technical proficiency in using that tool. A score of a 3 meant that the tool was used to a high level of proficiency, a 2 meant a tool was used with an average level of proficiency, and a 1 meant that tool use was present, with a low level of proficiency. A score of a zero indicated that tool was not used. Definitions of levels were based on the context (namely a low resource setting) and were intended to differentiate student work. Each report was assessed for the use of all tools regardless of department, although due to the varying number of tools for each department (seven tools apply to EE, nine tools apply to ME), only change in department-specific tool use was assessed. Table 3 indicates the tools that were reviewed for each report.

Total prototyping tool usage was summed for each team across all department-specific tools. Summed scores were then averaged among each subgroup (e.g., EE pre-PIDS). We compared the mean pre- and post-PIDS scores using an independent t-test with a p value <0.05 considered
statistically significant. The scores cannot be compared between ME and EE because the number of tools evaluated in each department are different. In addition, the percentage of teams using each tool (number of teams using tool / total number of teams * 100) and average score among teams that used each tool were assessed to see which tools experienced the greatest change.

Table 3. Tools evaluated in each report

<table>
<thead>
<tr>
<th>EE</th>
<th>ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Analog circuit construction (breadboard, stripboard)</td>
<td>• Welding (arc, MIG, TIG, brazing)</td>
</tr>
<tr>
<td>• Microcontroller programming (or other digital electronics)</td>
<td>• Conventional Mill</td>
</tr>
<tr>
<td>• DMM, LabVIEW, oscilloscope or other measuring tools</td>
<td>• Conventional Lathe</td>
</tr>
<tr>
<td>• Computer programming (HTML, python, C++, etc.)</td>
<td>• CNC Milling</td>
</tr>
<tr>
<td>• Soldering</td>
<td>• 3d Printing</td>
</tr>
<tr>
<td>• Welding (arc, MIG, TIG, brazing)</td>
<td>• Laser Cutting</td>
</tr>
<tr>
<td>• Conventional Mill</td>
<td>• Basic Hand Tools</td>
</tr>
<tr>
<td>• Conventional Lathe</td>
<td></td>
</tr>
<tr>
<td>• CNC Milling</td>
<td></td>
</tr>
<tr>
<td>• 3d Printing</td>
<td></td>
</tr>
<tr>
<td>• Laser Cutting</td>
<td></td>
</tr>
<tr>
<td>• Basic Hand Tools</td>
<td></td>
</tr>
</tbody>
</table>

Relevant to both EE and ME

• Computer Aided Design, including circuit design (AutoDesk Inventor, EagleCAD, etc.)
• System Assembly – selecting and assembling prebuilt components into a functioning system

(B) Prototype quality and (C) prototyping level: Evaluators individually scored prototype quality and prototyping level on a scale of 0 to 5 (Table 4). Each subgroup (e.g., EE post-PIDS) was plotted in a box and whisker plot, and subgroup means were compared. Insufficient reports were available in the same year to compare prototyping quality and level between projects that used PIDS versus those that did not.

Table 4. Evaluation matrix used for evaluating prototype quality and level

<table>
<thead>
<tr>
<th>(B) Criteria for Prototype Quality</th>
<th>(C) Criteria for Prototyping Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 High quality prototype well-constructed with high precision, good quality joints (solder, welding, woodwork), system enclosure,</td>
<td>Functional, integrated prototype with tests and design improvements</td>
</tr>
<tr>
<td>4 A combination of high and medium quality elements described above and below</td>
<td>Functional, integrated prototype with tests to confirm some design criteria</td>
</tr>
<tr>
<td>3 Medium quality prototype, where joints are functional but not good quality, precision and performance occasionally meets design criteria, temporary fixtures/connections are used</td>
<td>Functional, integrated prototype with NO tests, OR tested components with NO integration</td>
</tr>
<tr>
<td>2 A combination of medium and low quality elements described above and below</td>
<td>Some functional components, no integration,</td>
</tr>
</tbody>
</table>
1 Low quality prototype where joints are poor, precision is insufficient to meet design criteria | No functional components, even of decomposed parts

0 No Prototype described in text or shown in photos | No prototype

The criteria used to evaluate prototype quality and level were developed to capture the full range of prototypes. The 0-5 scores were developed by the authors, based on evaluation tools used at Rice University.

**Differences in Prototype Development in FYPs Comparing Pre-PIDS and Post-PIDS**

Not every evaluated project utilized the design studio to create their prototypes. Utilization of the design studio among final-year students in the EE department was high from inception though, with 22/25 teams using it since the PIDS opening (Table 5). The adoption of usage by the ME students was lower (6/13) but did double between year one and two.

Table 5. Number of teams in evaluated design projects that used PIDS for their prototyping.

<table>
<thead>
<tr>
<th></th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>EE</td>
<td>8/10</td>
<td>14/15</td>
</tr>
<tr>
<td>ME</td>
<td>2/6</td>
<td>4/7</td>
</tr>
</tbody>
</table>

(A) **Prototyping tool usage**: Department-specific tool use in EE projects increased significantly from before-PIDS at 5.7 (SD 2.5) to after-PIDS at 9.6 (SD 2.6); t(9) = 3.63, p = 0.003 (Figure 1). Department-specific tool use among ME projects experienced a small, but significant increase from 6.8 (SD 2.0) to 8.9, (SD 2.1); t(17) = 2.45, p = .012 (Figure 1).

![Figure 1. Tool usage among department-specific projects.](image-url)
Within EE, the increase in tool use reflects an increase in both the number of tools used by each team and the proficiency of tool use. All tools were used by a larger percentage of teams after the design studio; the largest gains were made among microcontrollers (MCU), digital multimeters (DMM) and related tools, and software programming (Table 6). Pre-PIDS, 57% of teams used a microcontroller whereas 92% of teams used one post-PIDS. Scores for MCU and soldering proficiency increased the most among teams who used these tools, with the MCU scores increasing from an average of 1.9 to 2.4, and soldering increasing from 0.5 to 1.1.

Table 6. Percentage of EE teams using a specific tool, and the average proficiency score among teams who used the tool. Data is presented for tools with greatest change for EE teams.

<table>
<thead>
<tr>
<th>Percent of EE teams using tool</th>
<th>Average Proficiency Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MCU</td>
</tr>
<tr>
<td>Pre-PIDS</td>
<td>57%</td>
</tr>
<tr>
<td>Post-PIDS</td>
<td>92%</td>
</tr>
</tbody>
</table>

(B) Prototype quality: When rated on a scale of 1 to 5, prototype quality in EE teams increased from 2.9 (SD 0.57) to 3.8 (SD 0.46); t(8) = 3.95, p = 0.002, and in ME from 2.8 (SD 0.96) to 3.7 (SD 0.60); t(12) = 2.463, p = 0.015 (Figure 2). Thus, prototype quality increased for both ME and EE projects as a result of having the PIDS.

(C) Prototyping level: For EE and ME, respectively, scores for prototyping level did not experience a statistically significant change from 3.3 (SD 1.0) to 3.7 (SD 0.46); t(6) = 1.02, p = 0.172 and from 3.4 (1.06) to 3.7 (0.49); t(10) = 0.94, p = 0.187 (Figure 3). The criteria used for grading may not sufficiently differentiate projects that have started constructing a prototype, with most scores clustering around 3 and 4. More granularity in the assessment criteria is needed to assess the varying stages of prototyping achieved by FYP teams.
Figure 2 and 3. Quartile box and whisker plot of prototype quality and level for EE and ME before and after PIDS.

Prototype Case Examples

Example 1: Demonstration of low fidelity nature of Pre-PIDS prototypes.
One of the highest rated projects (Figure 4) from 2014 used cardboard and twisted wire to construct a prototype circuit. While this allows students to produce their functioning circuit in the same arrangement that they draw their circuit diagram, it does not allow students to improve the quality of their prototypes or construct more complex circuits. Nearly all EE post-PIDS projects constructed prototypes on a breadboard, and many transferred it to a stripboard.

![Figure 4. 2014 EE Prototype – Typical Pre-PIDS circuit prototype using cardboard as a backing and organizational structure for a circuit.](image)

Example 2: Demonstration of prototype evolution based on newly available tools/techniques
A comparison between two similar projects can illustrate some of the impact of PIDS. Teams worked on a soil moisture sensor in both 2015 and 2016; while the later team could use the previous team’s work, their prototypes illustrate improvements that were common among many projects. The 2015 team built their analog circuit on breadboards and formed the plaster of Paris sensor by hand (Figure 5). The 2016 team soldered their analog circuit to a stripboard and used an Arduino to add a display to the soil moisture sensor. The sensor was cast in a laser cut mold, which also served to evenly space the electrodes (Figure 6). These changes improved the quality and performance of the prototypes, improving repeatability of sensor manufacturing and reliability of the circuit. The improvements enable the team to present the project to outside partners.
Example 3: Growth in microcontroller use over time

Two EE projects and one ME project in 2014 and 2015 used microcontrollers (Arduino and Waspmote). These were purchased by the team or their mentor from outside of Malawi. Aside from these projects, the other projects in that year used basic analog circuitry mounted on cardboard, and connected with twisted wires, if any. Since PIDS, 21 project teams have used microcontrollers, which can enable teams to test important features of the solution more rapidly.
than a purely analog solution. For example, the behavior of a proposed solution can be altered quickly by reprogramming. After this rapid iteration, students still employ analog circuitry to condition the signals and interface with sensors, as seen in the soil moisture project.

**Many Needs Remain at PIDS as Design Instruction Evolves**

Over the past several years, many positive additions have been made to the design program at Malawi Polytechnic University. First, a greater focus has been placed on teaching students a structured process for design. Second, specific steps were highlighted in the education of students in the design process, for example, problem identification and brainstorming. Finally, the PIDS improved the quality of prototypes produced by teams and individuals. However, the design studio does not guarantee high quality prototyping. There are several teams that, while they used a microcontroller, breadboard/stripboard, and other tools available at the design studio, their prototypes remained very low quality. Overall, both the EE and the ME team prototypes improved in prototyping tool usage and prototype quality.

Usage of the PIDS has increased each year it has been open. Through the first two years we have learned many lessons about how to improve the design education in the coming semesters. There are still many observed gaps and opportunities for growth in the design education at the Malawi Polytechnic.

Mechanical Engineering would benefit from low fidelity prototyping before constructing a final prototype with higher fidelity materials. Most design work in ME is still performed theoretically, without much iteration or testing in the design. Very few reports discussed changing the design based on testing results, which may indicate a lack of reporting this type of information, or a lack of time to make alterations. From observation, many teams do not finish prototypes until near the end of the year, leaving little time for refinement. Including a low fidelity prototype review at the end of the first semester would require students to prototype and test earlier without requiring significant schedule alterations. This change may not require additional funding to be disbursed from departments because resources for low fidelity prototyping are available in the design studio. ME projects might be built at a small scale with low durability materials, and EE projects could include a breadboard prototype of the most critical pieces of the solution.

In seeking to push teams towards higher fidelity prototypes, the skills gap for many of the new ME tools is greater than for the EE tools available in the design studio. Moving from prototyping with hand tools or manual milling machines to prototyping with a CNC requires a greater investment (time plus education) than moving from wiring circuits on cardboard to using a breadboard. This is especially relevant at the Polytechnic where students are not yet instructed on creating CNC toolpaths or other practical skills required to use CAM devices. Until the curriculum is changed to include more CAM, this skills gap is being covered by teaching short practical workshops so students can 3D print and laser cut. Skills required to use the CNC remain prohibitive, with only two projects putting it to use. With increased access to the studio, course curricula can continue to include more practical elements.
Many ME projects result in a metal final product that is welded, so use of the studio for constructing the final products is limited. This indicates a need to collaborate between the welding/milling workshops and the design studio, not a need to incorporate more metalworking tools into PIDS itself.

The Polytechnic continues to improve the FYP course, including a transition to digital documentation, which should improve document retention. Based on work in the ME and EE FYP courses, lessons on problem definition and brainstorming are being applied to the civil engineering department.

The sustainability of PIDS requires a dedicated staff to manage the space. In January 2018, two recent engineering graduates and one dedicated technician began to manage the space. These design studio engineers are responsible for teaching workshops, mentoring students in design and prototyping, keeping the space operational, and developing new technologies to showcase the innovative capability of Polytechnic graduates. While they are not responsible for teaching normal classes, their expertise will be critical to the success in FYP and other design-build courses. The design studio engineers are funded through grants because a comparable position does not exist within the university hiring structure.

Overall, the Polytechnic Innovation Design Studio has been a great addition to the Polytechnic in Malawi. The team looks forward to future developments in design instruction and how to sustain a makerspace in a low resource setting.

References
[5] Kulkarni, Y. “Fab Lab 0.0 to Fab Lab 0.4 - Learning from running a lab in an Indian Village.” Fab12. 2016