Cultivating a Sustainable Mindset in Undergraduate Engineering through the Engineering for One Planet Framework

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ABSTRACT:
Sustainability is an intersection of environmental, social and economic perspective. A sustainable mindset finds solutions to restore nature and its resources to help local, regional and global communities while aiming to reduce economic and environmental burden on an establishment. Engineering and manufacturing units have recognized the importance of sustainability and life cycle assessment (LCA) of a product. Aspects such as design, material choice, manufacturing technique, packaging selection, energy efficiency, emissions and waste disposal are critical elements of design decision making to comply with regulations. In order for industrial sustainability goals to be realized, it is important to foster a sustainable mindset among the new generation of engineers. They will help to motivate the use of sustainable materials, and implement design and manufacturing changes for future engineered products. To accomplish this goal of educational training, four sustainable manufacturing mini-class modules (2-3 class hours) were designed and implemented using problem-based learning strategies in undergraduate engineering classrooms from first-year through senior year. Student learning outcomes were mapped to the Engineering for One Planet (EOP) Framework. First-year engineering students created 3D parts with cultural or historical inspiration in designs for additive manufacturing (DfAM). Sophomores designed sustainable prosthetic feet and proposed a novel eco-friendly manufacturing process for developing countries. Juniors focused on waste management in the medical industry, pollution data related to the disposal of non-biodegradable medical waste and federal regulations. Seniors inspected single-use medical devices and explored concepts such as circular economy and lean manufacturing. The impact of these modules were assessed using both formative and summative assessment strategies such as quizzes and an Institutional Review Board (IRB) approved pre- and post-surveys. Students demonstrated at least 50% improvement in technical knowledge and improvement in core sustainability concepts in all modules. In addition, students self-reported improved sustainability skills related to EOP learning outcomes such as environmental literacy, material selection, systems thinking, social responsibility and sustainable design. This study impacted 84 students in the College of Engineering with 15% to 80% improvement in EOP skills measured across the curriculum.

Keywords: sustainability, engineering education, curriculum, systems mapping, light-weighting, circular economy, lean manufacturing, linear economy, diversity, equity, inclusion (DEI)

1. INTRODUCTION:

There is a race to meet the ever-growing demand for consumable products that improve quality of life which has led to indiscriminate use of limited natural resources and production of waste [1, 2]. Waste such as electronics, packaging from single-use products, construction materials, manufacturing scraps contribute to ever-growing landfills [3, 4]. Manufacturers resist implementation of sustainable manufacturing practices because it takes time, resources and money to overhaul current engineering systems and practices. Sustainable manufacturing can be realized through extended product lifespan, increased practice of repair and reuse, and reduction of overproduction. However, this can negatively impact yearly profit margins of a company. For example, single-use disposables are favored in the medical device industry as it is less expensive to dispose of a contaminated device after single use rather than reprocess it [5]. Similarly, low-cost electronics that are obsolete with a short life cycle will result in more materials that end in landfills but will lead to more units sold by the industry [6]. Additionally, the reprocessing method to recover waste from scrap material such as ceramics, tires and waste glass can be a cost burden for a manufacturer. Since the adoption of 17 Sustainable Development Goals (SDG) by the United Nations in 2015, conventional engineering practices are being called into question [7]. Manufacturers and consumers are challenged to reduce their carbon footprint and reduce the burden on natural resources by adopting zero-waste and sustainable practices [8].

Aspects such as design, material choice, lean manufacturing, packaging, energy efficiency, emissions and waste disposal are discussed within organizations to comply with regulations. These topics aim to strategize how to incorporate best sustainability practices into corporate culture and manufacturing methods. This makes it critical to train the new generation of engineers who foster a sustainable mindset with skills that enable them to make informed sustainable choices when designing and manufacturing new products [9]. In response, engineering universities across the globe are now including sustainability education for undergraduate students [10]. This effort has been fueled by Lemelson Foundation and VentureWell who established the Engineering for One Planet (EOP) framework with feedback from over 100 stakeholders [11, 12]. The EOP framework consists of 9 focused topics (**Fig.1**) such as systems thinking, environmental literacy, material selection, responsible business and economy, critical thinking, communications and teamwork, and social responsibility [13]. Each area consists of carefully formulated core and advanced learning objectives that serve as a guideline for educators to incorporate sustainability into engineering education curriculum [13].

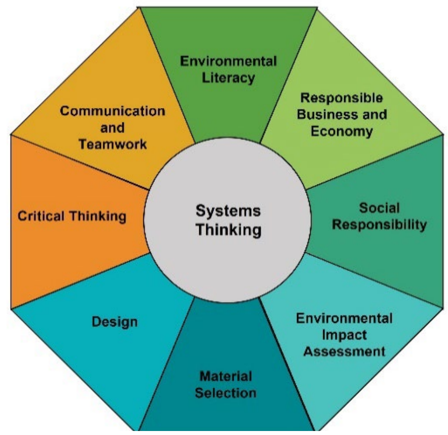


Figure 1: **Engineering-for-One-Planet Framework.** Nine focused topics with Systems Thinking at the center of the sustainable practices [13].

Western New England University has been successful in developing an "entrepreneurial and design thinking" ecosystem using design courses from each year within the engineering curriculum: first-year through senior year with extracurricular entrepreneurial design activities such as Golden Bear Innovation Jam to supplement these high-impact practices [14, 15, 16]. Using this successful framework as a model, four sustainability modules were designed and mapped to select EOP learning objectives and delivered to students throughout the 4-year College of Engineering (COE) curriculum, one course module per grade from first-year to senior year. The overall goal of this work was to create interdependent learning activities designed around the EOP framework to provide sustainable practices using targeted, hands-on problem-based learning.

2. METHODS:

The process of developing individual modules included identifying ABET learning outcomes associated with the courses for each year in the curriculum, aligning 3-4 EOP focused topic areas with the course and creating activities that would target specific learning objectives. The EOP framework has 9 focused topics, and each topic consists of a set of core and advanced learning objectives. To maintain clarity in this article, the list of learning objectives under each core or advanced category was labeled with the first bulleted learning objective numbered as '1' and so on [13]. The focused topics and the intentional overlapping themes between consecutive modules has been mapped (**Fig.2**). In general, 'Social Responsibility' and 'Design' were included in both first year and sophomore courses. 'Material Selection' and 'Systems Thinking' were included in sophomore and junior courses. 'Environmental Literacy' and 'Material Selection' were included in junior and senior courses. In addition, leadership skills such as 'Communication and Teamwork' were assessed across all four courses.

We hypothesized that (1) problem-based learning activities mapped across the EOP framework would improve student's knowledge about sustainable engineering practices and (2) students' skills in identifying sustainable manufacturing technique would improve after exposure to the modules. Both formative and summative assessment methods were used. Summative assessment of student learning was conducted through homework assignments, exam questions, quizzes and graded elevator pitch presentations. Technical knowledge was assessed using graded pre- and post-technical quizzes. Throughout this work, student artifacts were collected from all four courses. A formative assessment tool included a pre-and post-self-perception of knowledge survey based on EOP learning objectives covered by respective modules. The assessment tool was approved by Western New England University's Institutional Review Board prior to the start of the modules. The survey data was coded for student identification and tabulated by the administrator in the College of Engineering to maintain student anonymity. A total of 84 engineering students participated in at least one of the sustainability modules. All student responses to the survey were voluntary.

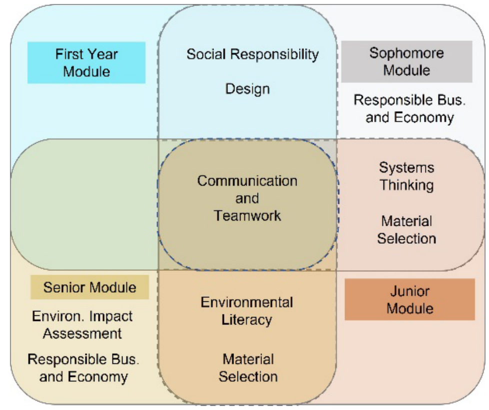


Figure 2: **Modules Delivered to Students in first-year through Senior Year.** Measurements were mapped on EOP

2.1 *First-year Module: Design for Additive Manufacturing (DfAM) and Culture Sustainability Module*

First-year engineering students in an introduction to engineering course participated in a 2-day workshop, ~3 hours/day, focused on DfAM that incorporated cultural sustainability. The DfAM workshop highlighted the opportunities and the restrictions of additive manufacturing processes. Students worked in groups to create 3D parts with cultural or historical perspective. Students searched for art forms, traditions, social habits, and rituals from the chosen cultural background or a significant time in history and used it as inspiration to create unique CAD designs and then 3D printed models. Students were required to incorporate the best DfAM practices required to successfully design a part using additive manufacturing. Each student group prepared a poster that was shared in a gallery walk [17]. Everyone explored the variety of culturally and historically inspired projects during the gallery walk and self-reflected on the information in an essay. Students were encouraged to include thoughts on unconscious bias, norms, habits, challenging/disruptive beliefs, and expectations that highlight problems behind oppressive worldviews and social insight/imagination on other cultural influences on design. A short quiz that assessed student knowledge on sustainability, the role of social responsibility and environmental justice in the engineering profession and design considerations for diverse groups was given to students before and after the DfAM workshop. The EOP learning objectives assessed include Design Core 1, Communication and Teamwork Core 1, and Social Responsibility Core 2 and Core 6 [13].

2.2 *Sophomore Module: Sustainable Design of Prosthetic Feet for Developing Countries*

Sophomore engineering students were exposed to a semester-long design project to develop a sustainable prosthetic foot. The design constraints included design size and weight restrictions, requirements on materials used and manufacturing technique implemented when made directly in a low-resourced country. Students considered the use of recycled materials and down-stream effects to marginalized people affected by material choices like recycled plastics [18]. They developed knowledge in various manufacturing processes such as the Jaipur foot as a labor-intensive method in low-resourced areas [19] and learned of the

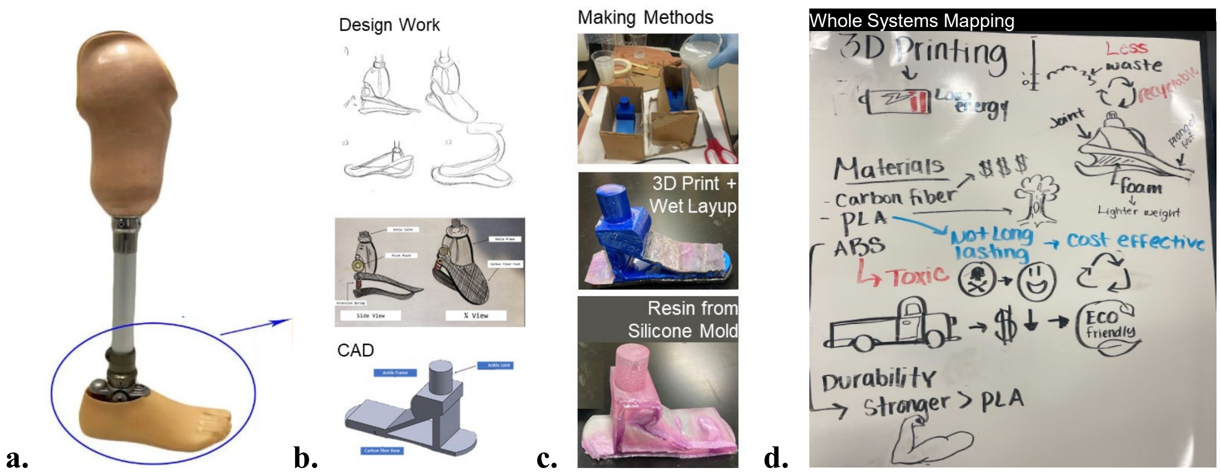


Figure 3. Sustainable Prosthetic Feet Manufacturing. The students were A) required to build a prosthetic foot (blue circle) B.) ideated with iterations of hand sketches and a final CAD model C) explored various making methods: 3D printing, wet layup and form molding D) used Whole Systems Mapping to explore several aspects of sustainable choices that could influence their design considering material choices, manufacturing, location, and delivery methods.

lack of available prosthetic technology and its societal impact in countries such as Rwanda [20]. Throughout this activity, students discovered and modeled corporate behavior of non-profit prosthetic technology organizations such as Legs4Africa, Limbs International and Amputee Coalition [21-23]. Each student designed a prosthetic foot in CAD which was 3D printed. Next, students considered the number of parts within their designs, and features of the foot that could be light-weighted [24]. Working in teams of 2 or 3, students with similar concepts teamed up to create a Systems Map to consider all avenues of sustainable implementation of their design from material choice, delivery, to manufacturing process [25]. Students prototyped final designs using wet layup lamination and form resin molding techniques using various supplies sustainable materials such as flax, coconut fibers, rice paper, fiberglass scraps, etc. (**Fig.3**). Designs were scored using a Pugh Matrix to identify the best sustainable design (**Appendix 1**). Students tested the functionality using a compression load to failure test, where output load was normalized by device mass (kg) benefiting those who had light-weighted their design effectively.

To assess student learning outcomes, students were asked technical questions related to their knowledge of prosthetic technology components, manufacturing techniques, and sustainability prior to the start of the project and again at the end of the semester. Additionally, this module assessed EOP learning objectives (1) Systems Thinking, Core 3, (2) Responsible Business & Economy, Core 2, (3) Material Selection, Core 5 and Core 6 (4) Social responsibility, Core 4, (5) Design, Core 1 and Core 2, and (6) Communication and Teamwork, Core 6 [13].

2.3 Junior Module: Waste Reduction in Medical Devices

Junior engineering students were exposed to a sustainability module focused on medical waste management and alternate sustainable solutions. The module was divided into two 50-minute class periods: (1) medical waste and disposal mapping and (2) developing an elevator pitch to propose alternative solutions to reduce medical waste using a storyboard proposal. On day 1, each group was given a medical product such as band-aid, gauze, dental fixing kit and fracture cast material. Students created a connections map with sub-topics: materials used in the product, degradation time, environmental impact, distribution streams, disposal regulations and common disposal methods. Next, they researched and identified sustainable natural materials that could be used for their medical product without compromising the functionality. Finally, they reported out their findings with the rest of the class. On day 2, each group created a story board using art supplies and pitched a novel sustainability design idea to a group of investors. Here, the rest of the groups in the class were acting as investors who could invest up to $1000 towards their favorite sustainable idea. In addition, each group was assessed by the instructor on the following criteria: relevant data on waste produced by existing technology, suggested sustainable material and communication skills. This module assessed EOP learning objectives (1) Systems Thinking, Core 3, (2) Environmental Literacy, Core 5, (3) Material Selection, Core 5 and (4) Communication and Teamwork, Core 1 [13].

2.4 *Senior Module: Design for Manufacture in Medical Device with a Sustainable Focus*

Senior engineering students were exposed to a sustainability module that was 3-lab periods in duration (3 hours/lab). The module focused on 1) Linear and Circular Economy, 2) Lean Manufacturing, and 3) Design Pitch Presentations for sustainable changes to design for manufacturing. Each team (2 students per team) was provided with a small medical device to deconstruct and determine aspects that could benefit from design changes to promote a more sustainable product. During the first workshop, students conducted an environmental impact assessment of their devices while mapping the product's life cycle. They inspected various components of the device such as packaging, material, function of the device, and design under the lens of sustainability. Next, students implemented the concept of linear economy to assess the fate of the medical device and formulated a plan to make it more sustainable using circular economy [26].

In the following week, students were instructed on lean manufacturing practices and where these principles align with sustainability. Students learned about working on an assembly line to increase production efficiency, scrap reduction, and how mass production could be modified when considering overstocking, i.e., push vs pull systems and inventory management. They researched distribution methods such as B2B, B2C and D2C to determine when medical devices implemented which delivery routes. They explored disintermediation and how that can save on environmental costs related to shipping and transportation. Students engaged in a hands-on module to track motion economy, manufacturing line efficacy and accuracy. The class was separated into two teams and given roles. One student served as the Manufacturing Supervisor, responsible for timekeeping and tracking their team's progress. The rest of the students created an assembly line and took responsibility for completing one step on the assembly line. The instructors utilized the 18-in-1 STEM Building Construction Learning toy to simulate the assembly process. Any time a part was acquired from the spare parts bin the Supervisor documented an opportunity (+1 point), and then if it was placed properly to the assembly another point was awarded (+1 point). However when a worker took the wrong part from the bins or placed the part incorrectly, it was an error (-1 point deduction). The teams raced to compile as many assemblies as possible within a 20-minute time block. (**Fig.4**). Afterwards, the class discussed how motion economy and organization of the assembly space can improve the manufacturing process and reduce costs by proper manufacturing design.

In the final week, senior engineering students developed an elevator pitch using a slide presentation. Working with their original teams and the medical device product they had been assigned, they proposed a sustainability design change to the device or the manufacturing process. They pitched their ideas to the course instructors and a R&D Manufacturing Engineer from a local medical device manufacturing company. Students wrote an Executive Summary and were assessed on new technical knowledge using a pre- and post-online quiz (**Appendix 3**). This module assessed EOP learning objectives (1) Environmental Literacy, Core 5 and Core 2, (2) Environmental Impact Assessment, Core 1, (3) Material Selection, Core 6, (4) Responsible Business and Economy and (5) Communication and Teamwork, Core 1 [13].

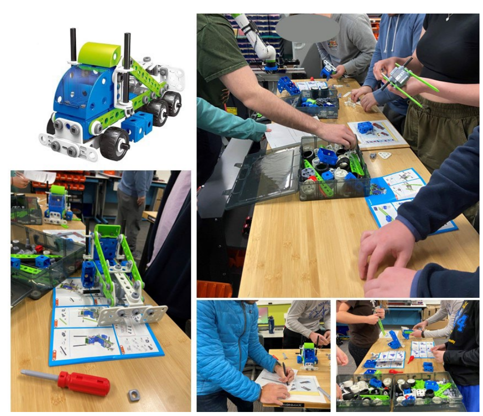


Figure 4: **Students Experience Lean Manufacturing through Assembly Line.** Students worked in 2 assembly lines to assess how many toy trucks could be assembled with accuracy in 20 minutes.

3. RESULTS:

IRB-approved pre- and post-surveys were used to assess the impact of the modules on students' perception of knowledge related to sustainable manufacturing practices in engineering. Their overall improvement in EOP learning objectives was seen across the curriculum, each bar showing a percentage of increased perception of knowledge in different topic areas (**Fig.5**). EOP topics such as design thinking related to minimizing environmental and social impact, recognizing local and indigenous practices and use of locally sourced materials was improved by 75% and 38% for first-years and sophomores, respectively. Likewise, recognizing the ethical implications and describing the negative and positive impact of design work on society, a skill in social responsibility, was improved by 25%.

Sophomores (31%) and juniors (22%) showed an improved systems thinking by recognizing social and environmental impact while solving a real-world problem. Student's ability to select sustainable materials with low environmental impact was improved in sophomores (30%), juniors (40%) and seniors (44%).

During the junior and senior modules, students spent considerable time learning about waste management of medical devices, mapping the life cycle of devices and analyzing the global and local impact of the waste produced by the medical industry. As a result, juniors (33%) and seniors (78%) improved their environmental literacy.

Across the curriculum, there was a significant improvement in students' communication skills and ability to work as a team. As the students pitched a sustainable novel design idea and communicated its social and economic benefits, they demonstrated increased communication ability: first-year (21%) sophomores (21%) juniors (29%) and seniors (70%).

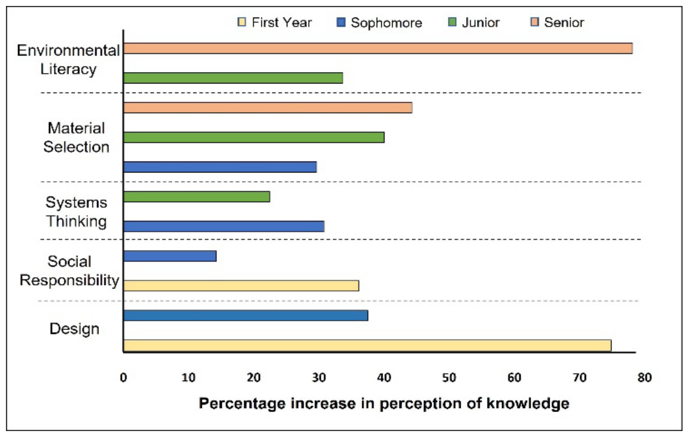


Figure 5: Overall student's perception of achievement of EOP Learning Outcomes. Students increased across all four years. Overlap in the modules created a continued knowledge base to build upon the next sustainability concept.

3.1 First-Year Assessment of Design for Additive Manufacturing with Sustainability

First-year engineering students learned DfAM while considering cultural influences. Students were given a short quiz before and after the first-year module to assess their knowledge of sustainability and social responsibility. They had a 12-point increase in the average quiz score with the pre-quiz (49%) compared to a post-quiz (61%, Student's t-test, $p<0.009$). The quiz showed no significant change in students' ability to explain the necessary considerations for designing for a diverse group (Student's t-test $p<0.069$). However, significant increases were seen in student's perception in knowledge in all the EOP learning objectives. Students created artifacts for the gallery walk inspired by Roman, Polish, and Egyptian culture which elicited conversations about how sustainable materials were used in these cultural designs (**Fig.6**).

Students wrote individual reflections after viewing the posters and artifacts from other teams which highlighted the impact of the gallery walk on student views toward sustainability and culture in design. The following example highlights a student's experience:

> *"It is always important.. to reflect on how your actions will affect others. As an engineer, you must consider how the projects you work on will affect all demographics of people.. You can form a connection with peers or coworkers from common culture and consider the knowledge of their background or culture when forming new ideas with them."*

A common thread among the first-year engineering student reflections was that they recognized and empathized with the ethical implications relative to social impact. The students reflected on the role of social responsibility in the engineering profession (**Appendix 2**).

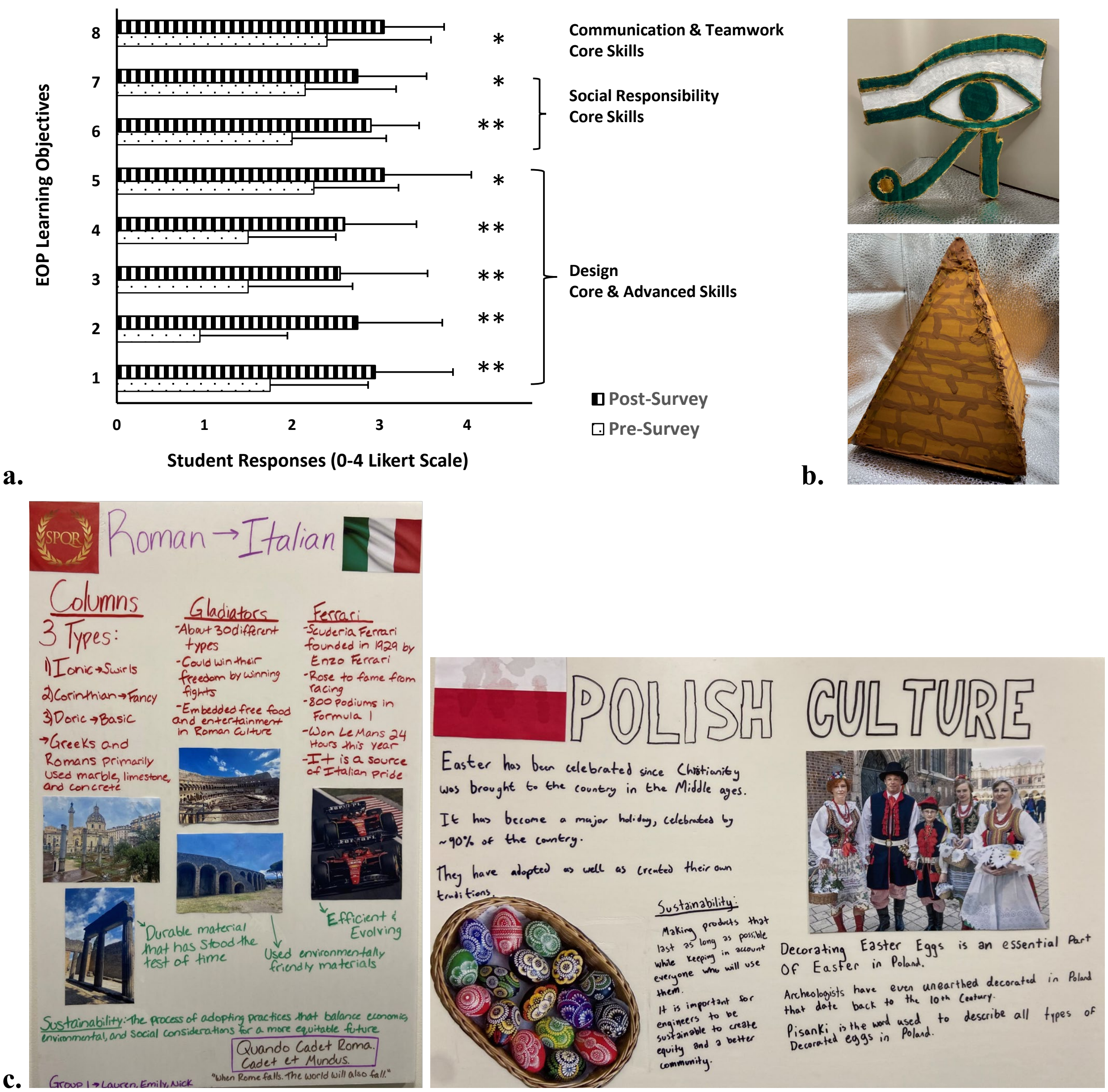


Figure 6. First-year Module on Culture and Design for Additive Manufacturing: Assessment and Student Artifacts. A) First year survey results. B) Roman culture is highlighted with an associated 3D printed column. C) Poster highlighting Polish traditions. Students made low-fidelity rapid prototypes of artifacts that demonstrated structures inspired by cultural perspectives.

3.2 Sophomore Assessment of Technical Knowledge of Sustainable Design of Prosthetic Feet

Sophomore engineering students developed prosthetic feet in a semester-long design project. They gained knowledge related to prosthetic technology, understanding of manufacturing practices, and technical concepts related to sustainable design. Specifically, comparing pre- and post-quiz scores, students had 61% higher scores in identifying parts of a prosthetic devices (Student's t-test, $p<0.001$). Student's ability to explain sustainable processes and make material selection that improves environmental impact increased by 44% (Student's t-test, $p<0.001$). Acumen of manufacturing techniques when building prosthetic sockets increased by 35% (Student's t-test, $p<0.01$). Articulating which populations that are negatively affected by recycling processes, and limited access to prosthetic technology was assessed; student's understanding improved by 56% (Student's t-test, $p<0.001$)

Student response to pre- and post-surveys related to their perception in knowledge of the EOP framework demonstrated improved in all measured topics except Social Responsibility. The sustainability module provoked the largest gains in perceived knowledge in topics of Materials Selection, Core 5 (36%), Design, Core 1 (36%) and Design, Core 2 (39%) of the EOP framework (Student's t-test, $p<0.001$, **Fig.7**)

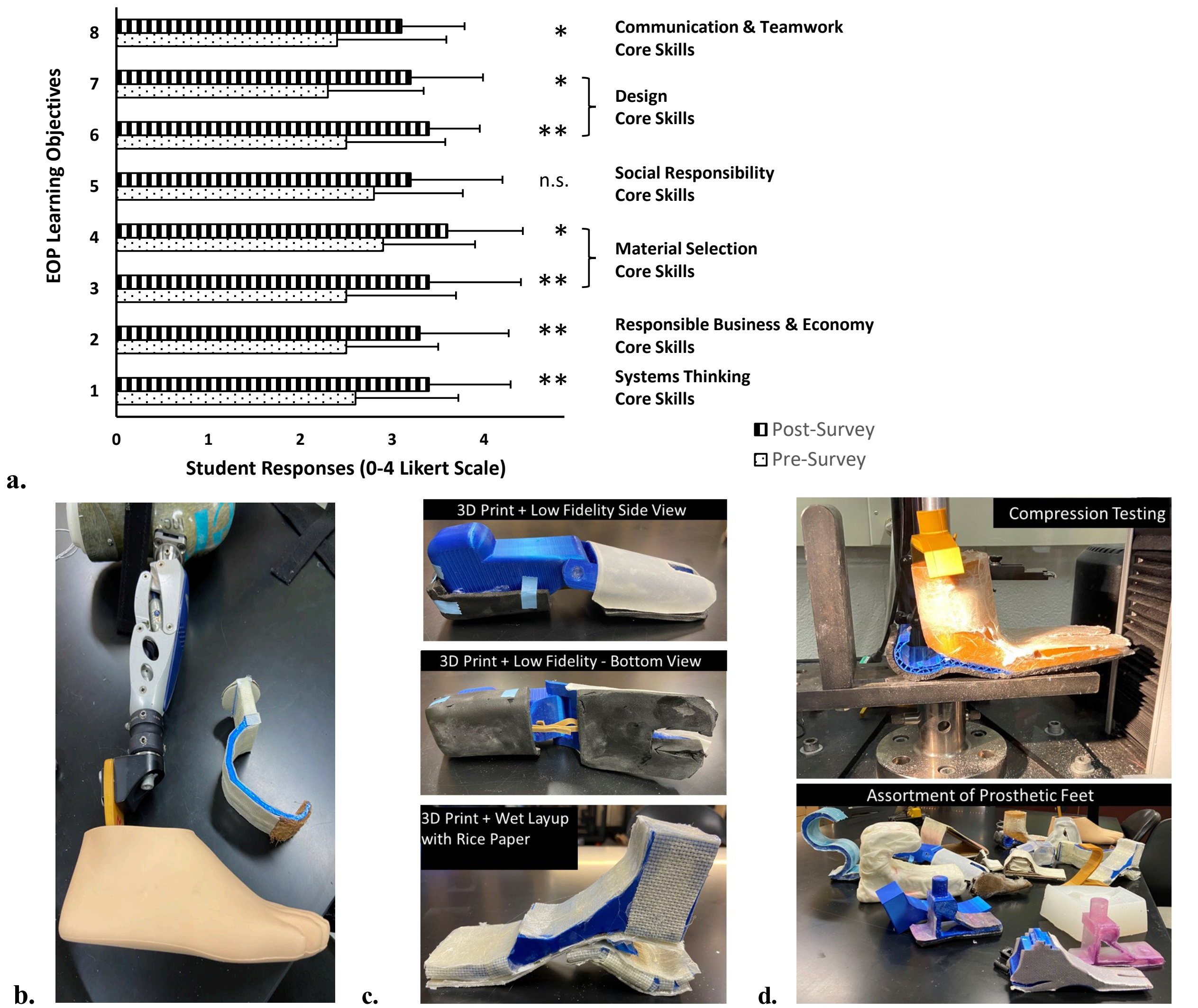
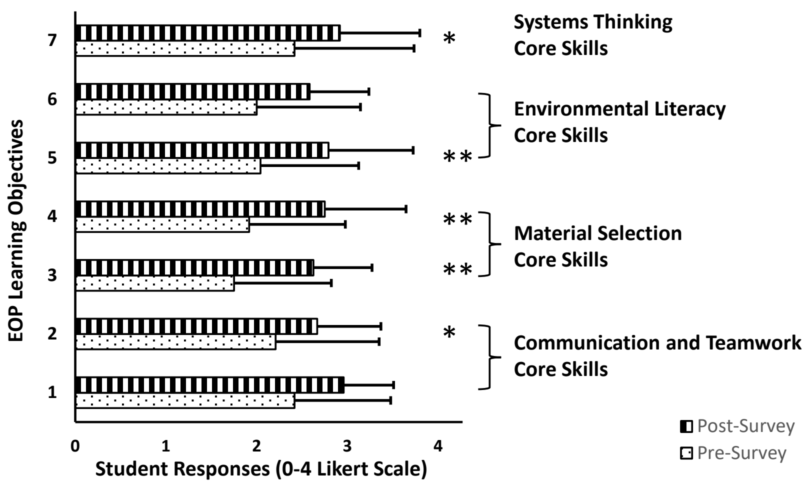


Figure 7. Sophomore Module on Prosthetic Feet: Assessment and Student Artifact. A) Sophomore survey results. B) A prosthetic simulator with a rice paper and coconut fiber-coated design next to it C) Examples of prosthetic foot designs. D) Compression testing to failure a prosthetic foot design and an assortment of various student projects.

3.3 Junior Year Assessment of Waste Management of Medical Devices

Junior engineering students learned about medical waste management and alternate sustainable solutions for packaging in medical consumables. Students scored an average grade of 80% on their knowledge regarding medical waste, material degradation and sustainable materials during the pitch. Student's ability to apply engineering and sustainability concepts to a real-world medical problem improved by 22% (Fig. 8A, Student's t-test, $p < 0.05$). There was a 33% improvement in student's awareness of how to research data regarding waste disposal, management, and regulations (Student's t-test, $p<0.005$). Students' response to the survey showed 40% improvement in making sustainable material choices that would degrade faster or make the device reusable for long term use and reduce waste (Student's t-test, $p<0.005$). The students had a 25% improvement on their ability to communicate social and economic benefits to stakeholders to achieve funding for their novel approach (Student's t-test, p-<0.005). Student artifacts show the Sustainability Concept Map created for a medical bandage and story board created for investor's pitch (**Fig.8**).



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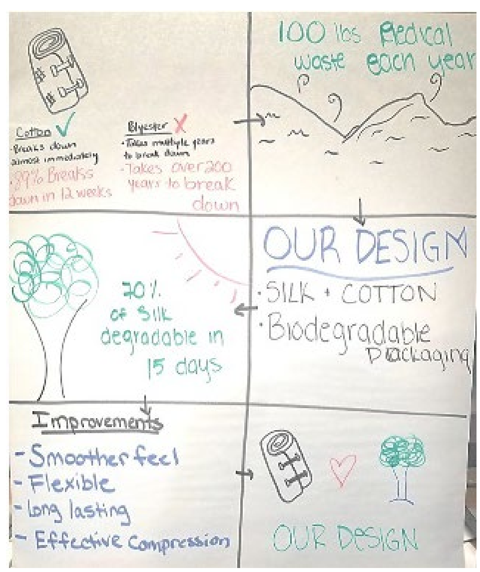


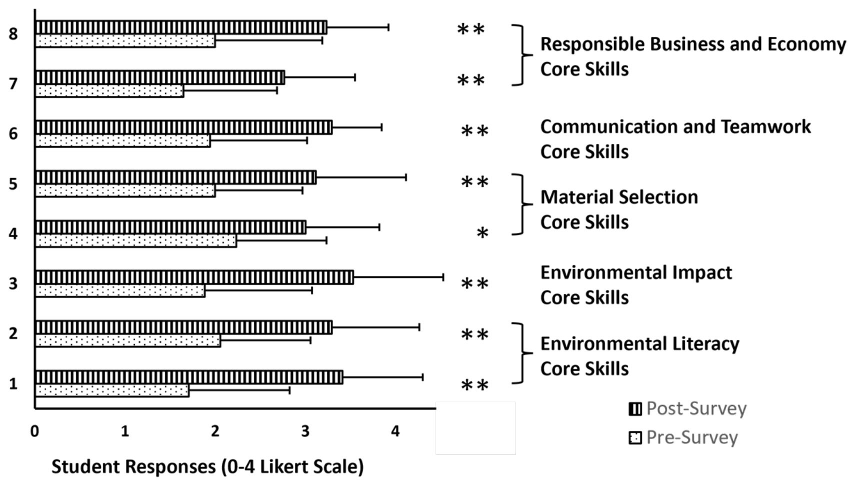
c.

Figure 8. Junior Module on Medical Waste Management: Assessment and Student Artifact. A) IRB approved survey show improved Systems Thinking and Environmental Literacy among students. Student artifact depicts the B) concept connections map for Band-Aid and C) pitch story board created for stakeholder presentation.

3.4 Senior Year Assessment of Connections between Sustainability and Lean Manufacturing

Senior engineering student's exposed to a 3-week design for manufacturing module were highly engaged in lab-based activities focused on circular, linear and lean manufacturing. Student's technical knowledge related to linear and circular economy and lean manufacturing was assessed using pre- and post- in-class quizzes. After the module, student's showed 167% improvement in their ability to identify non-sustainable components in a medical product and strong articulation in explaining linear and circular economy (Student's t-test, $p<0.005$). There was a 96% increase in technical knowledge related to lean manufacturing (Student's t-test, $p<0.01$, **Fig.9, Appendix 3**).

Students realized connections between sustainable manufacturing and lean manufacturing by understanding how to minimize waste and scrap, and to assess system performance and operator efficiency. Students' self-perception of knowledge from the EOP framework using pre- and post-surveys showed significant improvement in student's ability to apply concepts of sustainability in engineering practices (Student's t-test, $p<0.05$). There was a 60% improvement in student's ability to map the life cycle of a device and 100% improvement in the ability to analyze the sustainability of a product based on the waste and toxins added to the environment during its use and at end-of-life (Student's t-test, $p< 0.005$). The training in linear and circular economy helped students to find sustainable material alternatives that could be applied to concepts of lean manufacturing (34% increase, Student's t-test, $p< 0.005$, **Fig.9**).



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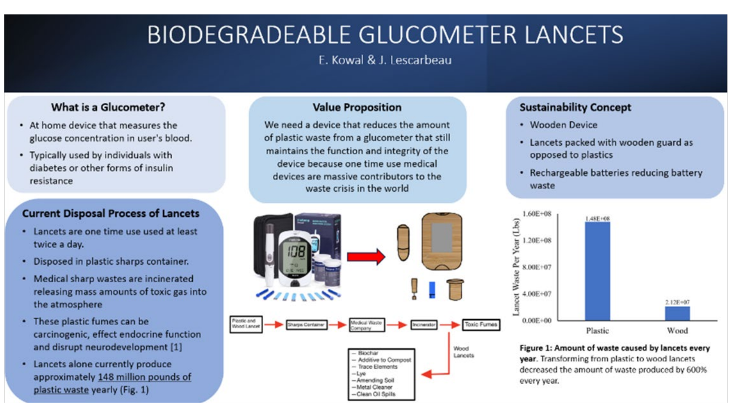

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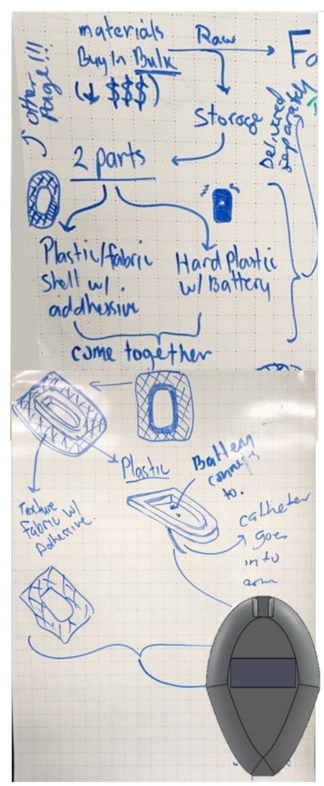

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Figure 9. Senior Module on Linear, Circular and Lean Manufacturing: Assessment and Student Artifact. A) Senior survey results. B) Redesign of a wood-based lancet for glucometer blood glucose monitoring for elevator pitch poster. C) Brainstorming circular manufacturing of a medical device with CAD model of medical device completed for elevator pitch posters (**Appendix 4**).

4. DISCUSSION:

This work developed four individual sustainability modules run in classrooms across the engineering curriculum. It represents the first step towards implementing EOP learning outcomes on a systemic level to help embed sustainable engineering training within the College of Engineering curriculum at Western New England University. The study design accomplished a method of providing overlapping sustainability themes between consecutive modules (**Fig.2**) to consolidate student learning and bring sustainable engineering practices into undergraduate education (**Fig.5**).

In each module, students were presented with unique environmental problems. These problems included use of additive manufacturing based on diverse cultures, prosthetic foot design in low-resourced countries, medical waste excess and optimization of materials used in common bandages and medical device redesign for life cycle assessment and lean manufacturing. Each activity had an open-ended solution that allowed exploration of the problem. This made students curious about the underlying reason behind the current product designs, material choices, packaging and waste created when designing or manufacturing these devices [27]. At the end of each module, results from the formative assessments (Fig. 5-9) supported the second hypothesis as students were successful in identifying the current need for a sustainable manufacturing practice and suggested a well-researched data driven solution. Student's comment such as '*this activity provoked thinking about bigger societal impact*' and '*it is important for engineers to reflect on how their actions will affect others*' shows a deeper connection with the new content, that support students Systems Thinking and Social Responsibility. The inclusion of diverse cultures in the DfAM and prosthetic foot modules provide a natural way of inculcating a DEI (Diversity, Inclusion and Equity) perspective into design projects. This was evidenced by student's reflection comment "*I believe using culture as a bridge is a powerful tool for enhancing inclusivity in future collaborations.*"

Engineering institutions across the globe recognize the need for training future engineers to develop a stronger Systems Thinking approach along with an environmental and societal perspective [28, 29]. Using Systems Mapping in conjunction with sustainable design changes during ideation process can help students develop a sustainable mindset. Jam boards and early brainstorming in each module helped to not only build a foundation of systems thinking, but provided an opportunity to share and intentionally incorporate sustainable ideas into the final designs.

It is challenging to change an already existing undergraduate engineering course or program while following strict ABET (Accreditation Board for Engineering and Technology) guidelines, and this can be a daunting task for faculty. These modules serve as a tool to inspire small- to medium-level implementation that help to engage undergraduate engineers with sustainability. Four ways to implement sustainability in higher education are (1) university makes no effort (2) 'bolt-on' accommodation in already existing curriculum, (3) 'built-in' system reform and (4) systemic redesign [30]. For this work, 'bolt-on' approach was found to be most feasible to introduce a stand-alone module in already existing courses. However, these modules would be better served towards a more global population, such as through general university requirements or a first-year engineering class that reaches all students within a program. Yet this requires buy in from several collaborating faculty who co-teach courses within the college. Future work will focus on the importance of this work through faculty training. Further course-specific development could support a more systematic integration of sustainability within the College of Engineering.

Some universities such as Carnegie Mellon University, Arizona State University and University of Texas at Austin have come together to create a Center for Sustainable engineering to promote a curricular change [31]. Efforts are being made to create sustainability modules or activities that can be inserted into an already existing course or create a new class that can be used as an elective or general university requirement. Rowan University and Clarkson University started a sustainability focused Research Experience for Undergraduates (REU) to promote future engineers to learn about pollution and sustainable practices [9]. To unify these individualized efforts, Engineering for One Planet initiative developed EOP framework that included a set of sustainability learning outcomes. This study aims to contribute to this knowledge as it used student-centered, problem-based and collaborative learning techniques to test the EOP learning outcomes in each classroom (**Fig.6-9**). These are highly effective interactive and constructive learning tools that promote student learning [32, 33]. The modules were collaborative, and students paced their own learning while the instructor created an environment for each group to explore and find creative sustainable solutions. Based on the summative assessment results, the first hypothesis was accepted that the student-centric learning activities mapped on EOP framework improved student's technical knowledge about sustainability manufacturing. As evidenced in the sophomore module, students' knowledge about prosthetic foot, manufacturing techniques and sustainable solutions improved by more than 50%. Similarly, juniors scored more than 80% for their knowledge about medical waste and landfills, common medical bandage's life cycle and material properties. Similar impact was recorded for seniors who improved their knowledge about linear and circular economy and lean manufacturing.

5. CONCLUSION:

Incorporating sustainability into the engineering curriculum is an important aspect of a wholistic engineering education. As engineering educators look to prepare students for the future of work, it is critical to expose students to more aspects of sustainability and manufacturing processes. Becoming culturally, socially, and environmentally aware helps to promote a workforce that can protect and advocate for the planet. Engineers are needed to help find solutions to the world's most complex and critical challenges. Engineers will be at the forefront of these challenges and need to have better educational training to prepare them for their role in society, modules like these offers a pathway to higher education in sustainability.

6. ACKNOWLEDGEMENTS

We would like to thank ASEE's Engineering for One Planet Mini Grant Program, for funding this work, with special thanks to our mentors Cindy Anderson and Bayo Ogundipe. Thank you to WNEU's College of Engineering administrative staff, Patty Reiley, for tabulating data from the IRB-approved surveys.

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8. APPENDICES:

Appendix 1.

Table 1: Pugh Matrix used for Design Scoring the Final Prosthetic Feet. A number of measurements used to assess sustainable design were assembled by the class in an Excel spreadsheet. On the final day of testing, using Instron compression loading, each device was assessed together by the student and faculty using the matrix.

Design of a Sustainable Manufacturing Process to Make Prosthetic Limbs

	Design Concept 1	Design Concept 2	Design Concept 3	Design Concept 4	Design Concept 5	Design Concept 6	Design Concept 7	Design Concept 8	Design Concept 9	Design Concept 10	Design Concept 11	Design Concept 12
	Student 1	**Student 2**	**Student 3**	**Student 4**	**Student 5**	**Student 6**	**Student 7**	**Student 8**	**Student 9**	**Student 10**	**Student 11**	**Student 12**
Weight (grams)	284	181	233	287	135	114	71	80	187	150	25	160
Max Force (kg)	539	172	647	178	200	41	127	298	203	341	57	172
Max Force (N)	5288	1687	6347	1746	1962	402	1246	2923	1991	3345	559	1687
Max Force / Weight (N/g)	19	9	27	6	15	4	18	37	11	22	22	11
How eco-friendly is it?												
Uses renewable materials (i.e. bioresin, rice paper, flax fiber fabrics etc.	0	1	1	-1	-1	1	-1	1	1	-1	-1	0
It minimizes waste through intentional design	0	1	1	1	1	1	1	1	1	1	1	1
It uses light-weighting	-1	1	1	-1	-1	1	0	1	1	1	1	1
Cost (Materials, Equipment)												
Cost of raw materials	1	1	-1	-1	-1	1	-1	0	-1	1	0	-1
Cost of equipment to manufacture	0	-1	-1	-1	1	1	-1	-1	1	1	-1	-1
How many parts does it include? Several parts/steps requires more assembly time, space, resources	0	1	-1	0	0	-1	1	0	-1	1	1	-1
Difficulty to mass produce	0	1	-1	1	1	0	1	0	0	1	1	0
Materials are stable under different temperature conditions	1	1	1	1	1	-1	1	-1	1	1	1	1
Cost of repair parts (availability - McMaster or custom made)	-1	-1	-1	1	0	-1	-1	0	-1	-1	1	0
Complexity of design and/or assembly	1	1	0	1	0	1	1	1	-1	1	1	-1
Cost (Labor, workforce, travel..)												
# of workers needed to make it?	1	1	-1	1	1	1	1	1	0	1	1	0
Labor costs associated with delivering it to clients	1	1	-1	1	1	1	1	-1	-1	1	1	0
Specialists travel cost (i.e. prosthetist needed for adjustment on site)	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
Eco-Friendly												
LIttle Waste Discarded	-1	0	-1	1	1	0	1	-1	0	1	1	1
Ease of recylcability	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0
Made from recycled parts	0	-1	-1	-1	-1	1	-1	1	-1	-1	-1	1
Can the waste be reused?	-1	-1	-1	-1	-1	-1	-1	-1	1	-1	-1	1
Ease of disgarding waste	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0
Circular Manufacturing												
Availability: where does the manufacturing have to happen?	-1	-1	0	1	1	-1	-1	1	-1	1	-1	-1
Availability: Does the country have the materials needed for a quality device	-1	-1	-1	1	-1	0	-1	-1	0	-1	-1	-1
Durability, how long the device and its components would last?	1	1	1	0	1	1	1	1	1	1	0	1
Design for viability, can a bad part quickly be switched out?	-1	-1	1	1	0	-1	-1	0	0	-1	1	1
Design for servicability, can the changes be made on site or sent back to the shop?	1	0	1	1	-1	-1	-1	-1	-1	0	1	1
Societal Impact												
Product Use: Ease of use by client	1	-1	1	0	0	1	1	0	0	1	-1	0
Product Use: Ease of adjustability by clinician	-1	-1	1	0	0	1	1	0	0	1	-1	0
Product Use: how accessible it is to the end user (Amazon delivery, or doctors office)	1	1	1	1	1	0	1	-1	1	1	1	1
Product Use: Customized to different sizes to meet customers of different age and/or K-levels	1	1	1	1	1	1	1	1	0	0	1	1
Cosmetic materials	0	1	1	1	0	1	1	0	1	1	1	1
Level of customization for individual choice	-1	1	1	0	1	1	1	0	1	1	1	1
Visibility: is the device aesthetically pleasing? What is the psychological impact at delivery?	0	1	1	1	0	1	1	0	1	1	1	1
Transport/Portablity (People and Goods)												
Ease of handling/shipping/assembly	1	0	0	1	-1	0	1	1	0	-1	-1	-1
Portability of materials (Shipping whole legs, bulky and hard to pack with restrictions on packaging or shipped in components and assembled on site)	0	0	0	-1	0	1	1	1	1	0	0	0
Portability of equipment used to make it (can the equipment be moved from place to place?)	-1	-1	-1	-1	1	-1	-1	-1	-1	1	-1	-1
Source of the raw materials (are they locally sourced?)	0	-1	-1	-1	-1	0	-1	0	0	-1	0	-1
Weight (are the devices heavy? Will it cost more to ship?)	-1	1	0	0	0	1	1	1	0	0	1	1
Production of material at the desired location? (Can the devices be made on site using locally established practices?)	-1	-1	-1	1	1	-1	-1	-1	-1	1	-1	0
Set up of equipment/process (is it user-friendly)	1	0	-1	1	1	-1	0	-1	-1	1	-1	-1
Design Features												
Has an ankle to support compression/absorption during impact (3 pts)	0	3	3	0	1	3	2	0	3	1	3	3
Strongest Foot	1	0	3	0	1	0	1	3	0	3	3	0
Score	**0**	**5**	**2**	**7**	**5**	**8**	**6**	**1**	**1**	**15**	**9**	**7**
	Design Concept 1	Design Concept 2	Design Concept 3	Design Concept 4	Design Concept 5	Design Concept 6	Design Concept 7	Design Concept 8	Design Concept 9	Design Concept 10	Design Concept 11	Design Concept 12
	Student 1	**Student 2**	**Student 3**	**Student 4**	**Student 5**	**Student 6**	**Student 7**	**Student 8**	**Student 9**	**Student 10**	**Student 11**	**Student 12**

Scoring Compared to Standard Manufacturing Practice of a Prosthetic Foot:

-1 = Does Not Meet

0 = Meets Compared to Standard

+1 = Exceeds Compared to Standard

Appendix 2.

Students Reflections from the DEI Module

“Moving forward, I believe using culture as a bridge is a powerful tool for enhancing inclusivity in future collaborations. When actively seeking out diverse cultural perspectives and incorporating them into projects, we not only celebrate differences but also create a more enriching and inclusive environment.”

“I think it is important to use culture as a bridge, not only to create impressive projects but also to build bridges of understanding and inclusivity in all our future endeavors.”

“I gained insight into cultures in general throughout the gallery walk. This insight was gathered particularly around the similarities and differences of the diverse ancient or modern cultures of the world.”

“It was interesting to see what each culture values, as that was shown well in the groups’ choices of which relevant piece of the culture to recreate. Some creations were related to architecture, traditions, and more. This helped me form a new perspective on how to improve inclusion in collaborations using culture as a bridge to do so.”

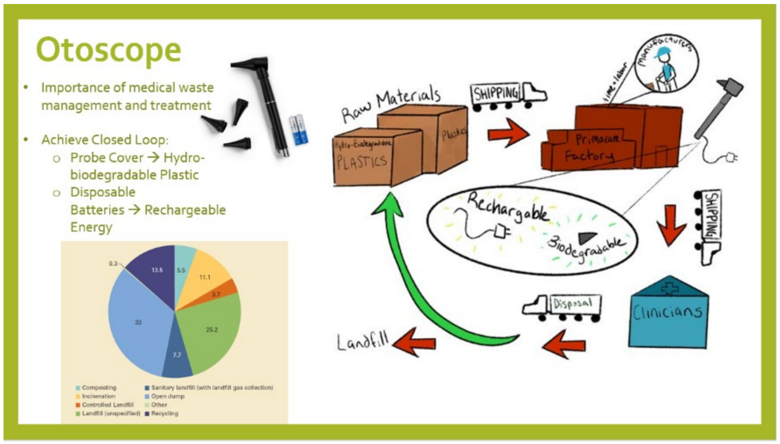
“It is always important, especially for engineers, to reflect on how your actions will affect others. As an engineer, you must consider how the projects you work on will affect all demographics of people. In collaborative projects, every member’s input matters. You can form a connection with peers or coworkers from common culture and consider the knowledge of their background or culture when forming new ideas with them.”

Appendix 3.

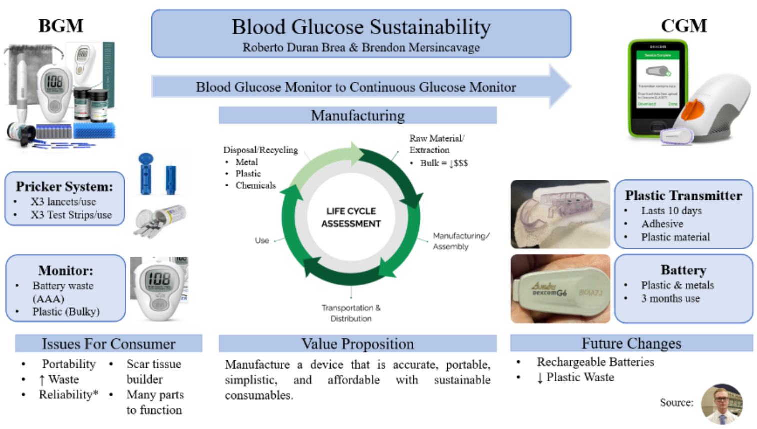
Pre- and post- Knowledge Quiz for Senior Module on Linear, Circular and Lean Manufacturing Practices.

Question 1. Name the 4 R's applicable to sustainable manufacturing.
Question 2. Name two toxic elements that pollute the environment after plastic incineration.
Question 3. What do you understand about circular manufacturing?
Question 4. Name three agencies that regulate medical waste disposal.
Question 5. Name the 5 S's in LEAN manufacturing.
Question 6. Fill in the blanks: A Gage R&R analysis determines the variation in the _____ and _____.
Question 7. Provide 3 explicit examples of how you can make a manufacturing process lean.
Question 8. Fill in the blanks: Six Sigma is a tool or set of statistical analysis techniques that are used to minimize ____ per ____. It is used to assess compliance of ______.

Appendix 4.



a.



b.

Appendix 4. Examples of Senior Posters to Support the Sustainability Pitch. Sustainability Pitches were delivered to an R&D Engineer and the course instructors, to convince them to implement more sustainable designs in the manufacturing process of medical devices. A.) Redesign of otoscope consumables. B.) Conversion to a digital port for real-time blood glucose monitoring.