Sustainable Product Design: Designing for Diversity in Engineering Education

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Abstract

Current and future engineers will need to address sustainability's triple bottom line, simultaneously addressing financial, environmental, and social goals. There is also a need to improve diversity in engineering, both in the communities served by new technology and the representation of gender and ethnic minorities among engineering professionals. We present data gathered from "Engineering 10: Introduction to Engineering Design and Analysis". This freshman course included a six-week Mechanical Engineering module entitled "Sustainable Human-Centered Design", and aimed to teach both Human-Centered Design techniques as well as the principles of Sustainable Design. We investigated these students' experiences, confidence, and goals, particularly focusing on aspects that are unique to gender and ethnic minorities. We suggest that enrollment diversity in engineering could be improved by teaching engineering in a manner that both complements the previous engineering and design background of all students, as well as emphasizes the learning goals most important to underrepresented engineering students. We also recommend offering sustainability and service learning projects that appeal to gender and ethnic minority students, to pique their interest and encourage their pursuit of an engineering career.

I. Human-Centered Sustainable Product Design

In Spring of 2008, the Department of Mechanical Engineering at the University of California at Berkeley launched a new course module around the theme "Human-Centered Sustainable Product Design" in order to show that mechanical engineering research and practice had much to offer in solving the world's grand challenges in sustainability. An additional goal was to foster a welcoming environment for female and ethnic minority engineering students. Our premise was that introducing sustainability could be a means of attracting and retaining engineering minority enrollment, and that the

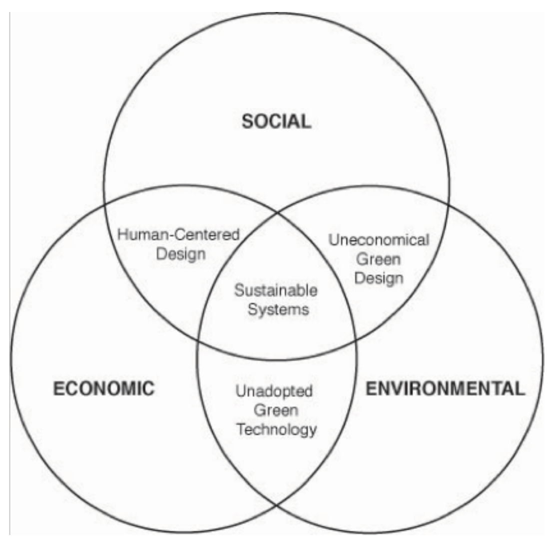

Fig. 1: *The Design of Sustainable Systems as the sum of the triple bottom line of Social, Economic, and Environmental goals.*

additional level of social benefit would be an added draw for all students.

For this paper we define "sustainability" as "meet[ing] the needs of the present without compromising the ability of future generations to meet their own needs" [1]. Previous years' experiences in teaching sustainable design to teams attempting to meet the three-part goal of sustainability [2, 3] have built upon the framework presented in Figure 1, based on the concept of sustainability as the intersection between the environment, the economy, and the social system [4]. This definition, not only emphasizes the environmental impact of products, but also includes economic viability and the social impact that engineering can have on society as a whole, as well as underserved communities.

In order to investigate differential impacts by gender and ethnicity, we investigated the experiences, confidence, and goals of the engineering students who took the course. We suggest that enrollment diversity in engineering could be improved by teaching engineering in a manner that complements the previous engineering and design background of all students, as well as emphasizing the learning goals most important to women and underrepresented minorities.

II. Related Work

This paper builds on previous research on integrating sustainability, social values and engaging content into freshman engineering, design curricula and even analysis courses [5,6]. Most notable of these is the work of Terpenny et al. [7], investigating the learning outcomes from traditional (e.g., egg drop) and sustainability-themed freshman engineering projects.

Several other universities have also used sustainability as a theme in freshman design courses. However, these design courses often focus on detailed design or design specifications as opposed to needfinding and conceptual design. Lau [10] describes a freshman class at Penn State that uses a multi-interpretational approach to "green design" that includes life cycle analysis (LCA), biomimicry, industrial ecology, and "green design". Kemppainen et al. [11] describe a freshman sustainable design course where first-year students were introduced to engineering through a sustainability-themed design project that focused on developing a green manufacturing process for a specific material (timber) in a specific region (upper peninsula of Michigan), as opposed to the design of a product that interfaces directly with an end user.

There is evidence that appropriate technology and sustainability-themed student-led design projects are disproportionately appealing to women. For example, Al-Khafaji and Morse[8] describes a student-led design course connected with the Stanford's chapter of Engineers for a Sustainable World. Zimmerman and Vanegas present a case study of Engineers Without Borders having an increase in the proportion of women in leadership roles [9].

III. Testbed

In this paper, we present data gathered from "Engineering 10: Introduction to Engineering Design and Analysis", in Spring 2008 and Spring 2009 at UC Berkeley. E10 is an introductory engineering course designed to help entering freshmen transition into college and connect to engineering research and practice during their first year. The course is co-taught by four faculty from different engineering departments in the College of Engineering. In Spring 2008, the departmental modules included those from Industrial Engineering and Operations Research (IEOR), Nuclear Engineering (NE), Civil and Environmental (CEE) Engineering, and Mechanical Engineering (ME). In Spring 2009, we had the same offerings except there was no Nuclear Engineering module.

Course Description: E10, *Engineering Design and Analysis*, is an introduction to the profession of engineering and its different disciplines through a variety of modular design and analysis projects. Hands-on creativity, teamwork, and effective communication are emphasized. Common lecture sessions address the essence of engineering design, the practice of engineering analysis, the societal context for engineering projects and the ethics of the engineering profession. Students choose two modules to develop design and analysis skills, and practice applying these skills to illustrative problems drawn from various engineering majors. [12].

The structure for the fifteen-week course was:

- A three-week introduction to the course and general themes that were to be addressed in each module.
- A six-week module in one of the engineering areas
- A six-week module in a different engineering area.

The ME module was entitled "Sustainable Human-Centered Design", and aimed to teach both Human-Centered Design techniques as well as the principles of Sustainable Design.

This paper presents data gathered from two surveys in Spring 2008 and 2009: one of all E10 students, and one of the students who participated in the ME module. In the survey of all E10 students, question topics included the students' previous experiences in engineering or design, including summer or after-school involvement in engineering-related programs or design competitions, and enrollment in high school courses in sewing, computers, shop, art, design, or drafting/CAD. We also asked the students to rank their abilities on engineering skills described by ABET program requirements [13].

- Analytical Skills
- Creativity and Practical Ingenuity
- Develop Designs that meet needs, constraints and objectives
- Ability to identify, formulate, and solve engineering problems
- Communication skills with multiple stakeholders
- Team skills with people from diverse backgrounds and disciplines
- Leadership and management skills
- High ethical standard and a strong sense of professionalism
- Dynamic/agile/resilient/flexible
- Ability to learn and use the techniques and tools used in engineering practice
- Ability to recognize the global, economic, environmental, and societal impact of engineering design and analysis

Table 1 lists the number of students, including women and under-represented minorities, participating in the full E10 course, as well as in the ME modules during semesters where the Sustainable Human-Centered Design module was offered.

		2008			2009		
		Class	**Module 1**	**Module 2**	**Full Class**	**Module 1**	**Module 2**
Total Students		174	65	58	142	58	52
Gender	**Women**	45	17	12	34	13	12
	Men	129	48	46	108	45	40
Ethnicity	**African-American**	1	1	0	2	1	1
	Chicano	18	6	6	14	2	9

Table 1: Number of students, including women and underrepresented engineering minorities, participating in E10 course, and specifically in the ME module.

In both years, the ME module proved to be the most popular module for all students. The most striking statistic, however, is that it was also the module with the highest precentage of women students (67% in 2008 and 73% in 2009), even though mechanical engineering nation-wide and at UC Berkeley has the lowest enrollment of women of all of the disciplines. This supports our hypothesis the content and the nature of projects matters in students choices about engineering. Although too small in numbers to be statistically significant, it is interesting to note that all of the African American students chose to take the ME module and 67% and 79% of Chicano/ Latino/ Hispanic (hereafter referred to as "Chicano") students took the ME module in 2008 (with four choices) and 2009 (with three choices), respectively.

Within the ME module, students were given a choice of projects to work on – sustainable design problems as well as ones that additionally address the needs of underserved communities such as migrant farm workers in Central California and Native American communities. To form teams, the students were asked to rank their top three project choices and were usually awarded their first or second choice. The proposed projects are provided in Table 2. Because complete data were not available for the Spring 2008 Module 1, it is not included in the analysis that follows:

2008 Module 2	2009 Module 1	2009 Module 2
▪ Smart Lighting ▪ Seguro Materials Testing for Pesticide Protection ▪ Pinoleville Pomo Nation (PPN) Sustainable Building ▪ Dorm Room Furniture ▪ Bicycle Transportation ▪ Humanizing Hesse Hall ▪ Composting at Cal	▪ Smart Lighting ▪ Seguro Materials Testing for Pesticide Protection ▪ PPN Solar Thermal Energy ▪ PPN Renewable Electricity ▪ Greening Your Dorm ▪ Black Cloud – Art and Technology for Sustainability ▪ Mobile Learning	▪ Smart Lighting ▪ Seguro Materials Testing for Pesticide Protection ▪ Pinoleville Pomo Nation (PPN) Sustainable Building ▪ Greening Your Dorm ▪ Black Cloud – Art and Technology for Sustainability ▪ Mobile Learning ▪ Wind Energy in Golden Gate Park

Table 2: Project options from 2008 Module 2, and 2009 Modules 1 and 2.

The Seguro Materials Testing project addressed pesticide protection of the migrant farm worker community, and all Pinoleville Pomo Nation (PPN) projects focused on the energy and culturally-sensitive housing needs of this Northern California Native American community. All other projects focused on the more "mainstream" users catered to by engineering designers, including college students.

In the rest of the paper we review significant results by gender that distinguish self-perception of skills and self-selection of projects for the female students relative to that of their male counterparts. Due to so few African-American students and Chicano students enrolled, we were only able to find significant differences between underrepresented ethnic minority and non-minority populations in a few cases of the module surveys. However, these few students still provided valuable anecdotal information about their experiences in engineering.

IV. Engineering Experience

In the course entrance survey, we asked all students to mark whether or not they had participated in a variety of engineering-related experiences in high school. These experiences are shown in Fig. 2.

In 2008, a significant number of women in E10 had participated in design competitions in high school, in comparison to men. This could be an indicator that these design competitions are succeeding in encouraging women to pursue engineering; hopefully this shows that targeted outreach works. The women had less experience with shop courses, however, indicating that providing them hands-on shop experience in a female-friendly environment might boost their confidence level to that of their male counterparts.

The Chicano students' backgrounds before arriving at engineering had significantly more design competitions, as well as art or shop classes. This indicates that engineering interest could be sparked by other creative, hands-on courses in addition to the traditional math-and-science pathway to engineering (Fig. 3).

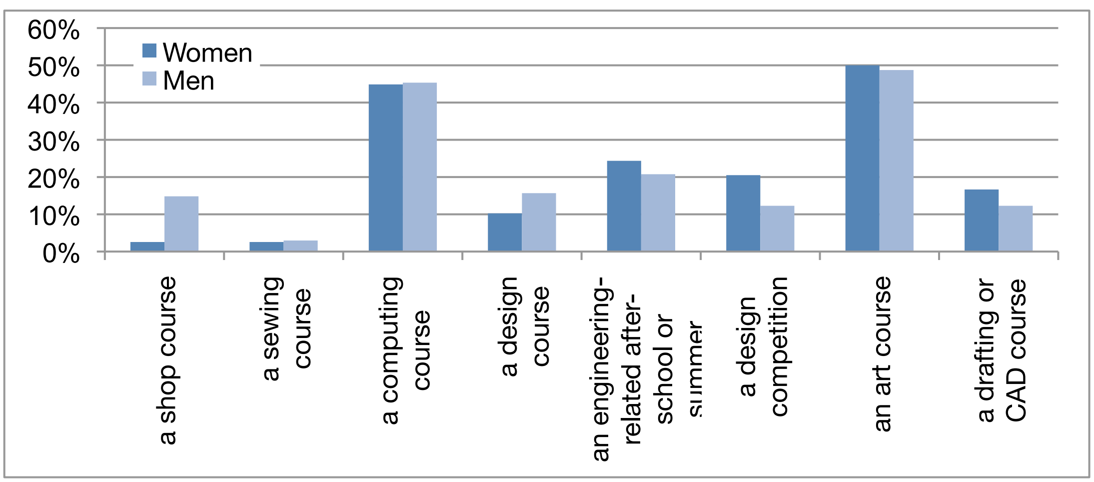

Fig. 2 : Percent of students who had high-school engineering experience, by gender, combining results from both Spring 2008 and Spring 2009.

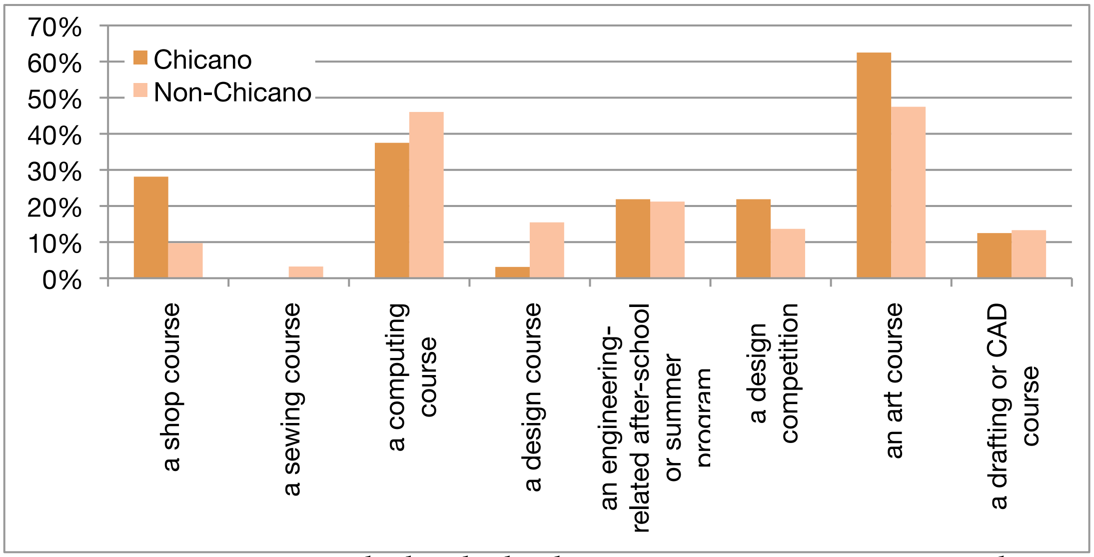

Fig. 3: Percent of students who had high school engineering experience, by ethnicity, combining results from both Spring 2008 and Spring 2009.

V. ABET Engineering Skill Confidence Initial Self Assessment

As part of the survey at the beginning of the E10 course, we asked the students to self-assess themselves (using a 5-option Likert scale) on a variety of engineering skills, based on the ABET requirements [13]. The results by gender are shown in Fig. 4. The students self-assessment followed gender trends where the men self-rated their analytical skills over the women's self-assessment (p=0.001). Men also rated their ability to use the tools of engineering practice as well (p≤0.0001). The women on the other hand, self-rated their skills higher in communication, teamwork, leadership and ethical/ professional skills (p=0.14, ≤0.001, 0.45, 0.001, respectively). The women also rated themselves higher in 2008 (p=0.054) for their ability "to recognize the global, economic, environmental, and societal impact". The gender difference in this last skill was displayed in 2009 as well, but was not statistically significant, however. This pattern is consistent with previous studies that have demonstrated women's lack of confidence in their analytical math and science skills [1124604925], however these results add the potential for using women's higher confidence in "people skills" to attract more women into engineering as they are key skills for success.

Chicanos were the only underrepresented ethnic minority in large enough numbers for analysis. The only skill with a statistically interesting difference in this population was in the "team skills with people from diverse backgrounds." They rated themselves at 4.25 on average using a 5-point scale; whereas the majority students were at 3.94 (p=0.07).

VI. ABET Engineering Skill Confidence: Before and After ME Module

At the end of the first Mechanical Engineering Module in Spring 2009, the students in the module were asked to rate their confidence in skills again. The overall improvement for that class was statistically significant in the students' confidence in their ability to solve engineering problems, to recognize the global and environmental impact of engineering and design, and to develop designs that meet needs, constraints and objectives (Table 4). Team Skills were on the borderline of significance.

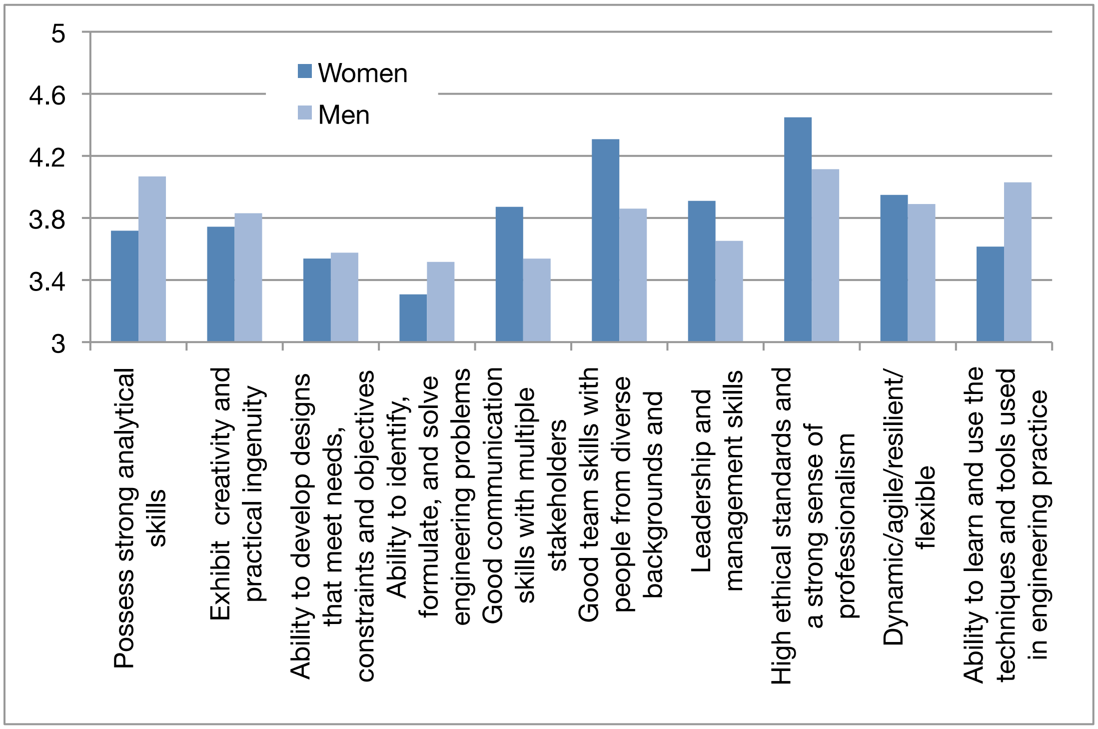

Fig. 4: Skill Confidence by Gender for both years combined at start of class.

ABET Eng. Skills	Avg. Confidence		p
	Before	After	
Strong Analytical Skills	4.116	4.15	0.815
Creativity	3.983	4.083	0.477
Develop Design	**3.75**	**4.066**	**0.0315**
Engineering Problems	**3.683**	**4.133**	**0.003**
Communication	3.483	3.65	0.347
Team Skills	**3.766**	**4.083**	**0.058**
Leadership	3.666	3.9	0.181
Ethical	4.05	4.183	0.437
Dynamic/Agile/	3.983	3.983	1
Use Techniques and Tools of Engineering Practice	4.116	4.1	0.913
Recognize Global Impact	**3.616**	**4.033**	**0.022**

Table 3: ME Module course ABET Engineering Skills Confidence Values, for all students. Statistically significant results shown in **bold (including borderline cases)**.

ABET Eng. Skills	Avg. Confidence (Men)		p
	Before	After	
Strong Analytical Skills	4.271	4.167	0.518
Creativity	4.042	4.083	0.791
Develop Design	3.771	4.021	0.139
Engineering Problems	**3.750**	**4.083**	**0.059**
Communication	3.458	3.563	0.594
Team Skills	3.750	4.042	0.118
Leadership	3.625	3.813	0.335
Ethical	3.958	4.104	0.468
Dynamic/Agile/	3.938	3.875	0.720
Use Techniques and Tools of Engineering Practice	4.146	4.021	0.476
Recognize Global Impact	3.583	3.958	0.080

Table 4: ME Module course ABET Engineering Skills Confidence Values, for all male students. Statistically significant results shown in **bold (including borderline cases).**

ABET Eng. Skills	Avg. Confidence (Women)		p
	Before	After	
Strong Analytical Skills	**3.500**	**4.083**	**0.026**
Creativity	3.750	4.083	0.303
Develop Design	**3.667**	**4.250**	**0.055**
Engineering Problems	**3.417**	**4.333**	**0.005**
Communication	3.583	4.000	0.328
Team Skills	3.833	4.250	0.295
Leadership	3.833	4.250	0.295
Ethical	4.417	4.500	0.764
Dynamic/Agile/	4.167	4.417	0.275
Use Techniques and Tools of Engineering Practice	4.000	4.417	0.196
Recognize Global Impact	**3.750**	**3.958**	**0.055**

Table 5: ME Module course ABET Engineering Skills Confidence Values, for all female students. Statistically significant results shown in **bold (including borderline cases)**.

Tables 4 and 5 show respectively how men's and women's confidence levels in engineering skills changed from before the ME module to after the ME module. Both men and women identified that they had become more confident in their ability to identify, formulate, and solve engineering problems. However, the women in the class showed significantly more improvement in confidence. Fig. 5 shows the amount that the men's and women's confidence changed over the course of the Mechanical Engineering module. While the Mechanical Engineering module helped boost the confidence of the female students in their engineering abilities, the sustainability-themed projects improved all students' confidence in their ability to solve engineering problems in the broader global context.

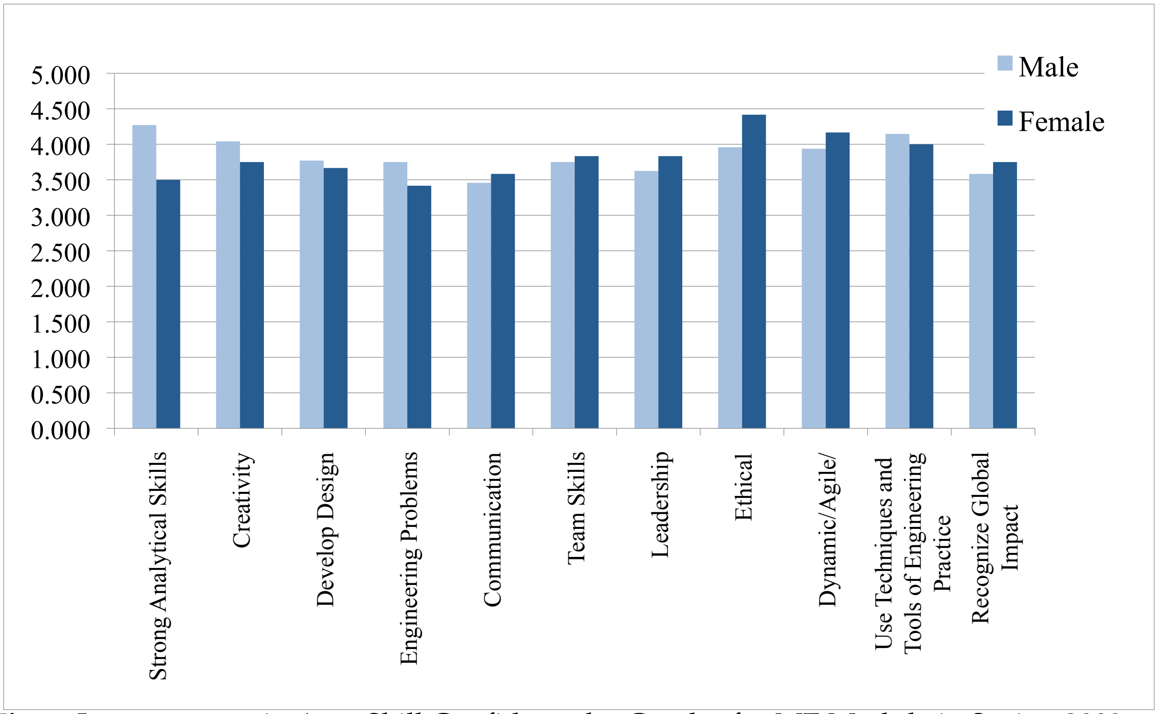

Fig. 5: Improvement in Avg. Skill Confidence by Gender for ME Module in Spring 2009.

VII. Gender and Project Preferences

At the beginning of each ME module, we asked the students to rank their project preferences. The selection of projects varied from year to year, and was adjusted between modules. Table 6 shows the percentage of men and percentage of women who included a given project in their top three preferences.

2008 ME Module 2			
	% Women	% Men	p
Smart Lighting	50.0	56.5	0.561
Bicycle Transportation	*8.3*	*41.3*	*0.141*
Portable Electronic Devices	33.3	50.0	0.368
Dorm Room Furniture	58.3	54.3	0.319
Hesse Hall	25.0	30.4	0.538
Seguro Materials Testing	*58.3*	*30.4*	*0.134*
Composting at Cal	25.0	13.0	0.292
Pinoleville Pomo Nation Buildings	*41.7*	*23.9*	*0.134*
2009 ME Module 1			
	% Women	% Men	p
Smart Lighting	53.85	62.22	0.518
Black Cloud	38.46	20.00	0.175

PPN Solar Thermal Energy	30.77	46.67	0.739
PPN Renewable Electricity	30.77	44.44	0.451
Mobile Learning	*61.54*	*44.44*	*0.135*
Greening Your Dorm	38.46	35.56	0.397
Seguro Materials Testing	46.15	44.44	0.721
2009 ME Module 2			
	% Women	% Men	p
Smart Lighting	41.7	60.0	0.517
Greening Your Dorm	25.0	25.0	0.598
Wind Energy in Golden Gate Park	41.7	67.5	0.081
PPN Sustainable Building Design	25.0	37.5	0.414
Black Cloud	33.3	30.0	0.543
Seguro Materials Testing	*58.3*	*35.0*	*0.131*
Mobile Learning	**75.0**	**45.0**	**0.013**

Table 6: Percent of Women/Men who ranked a project in their top three choices. Significance values are in the far right column. Statistically significant results are in **bold**; statistically interesting results are *italicized*.

Women were more interested than men in the Seguro project for pesticide protection of migrant farm workers. Women also seemed to show more interest in the mobile learning project; this could be due to women's interest in education issues, as evidenced by the high percentage of women in education as a discipline and profession. Women were more interested in the Pinoleville Pomo Nation (Native American community) project in 2008, but less so in 2009. We believe this may be due to the framing of the problem in 2009 as one that focused on energy calculations and less on community needs-finding.

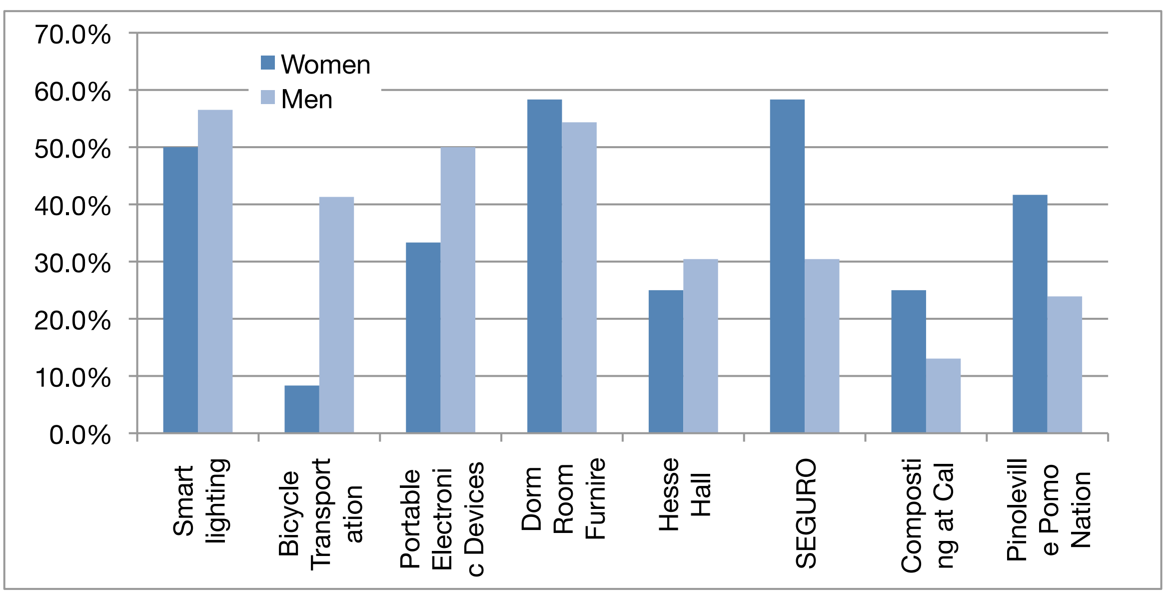

Fig. 6: 2008 Module 2 Project Preferences, by Gender. Bars represent percent of Men/Women who included a given project in their top three choices.

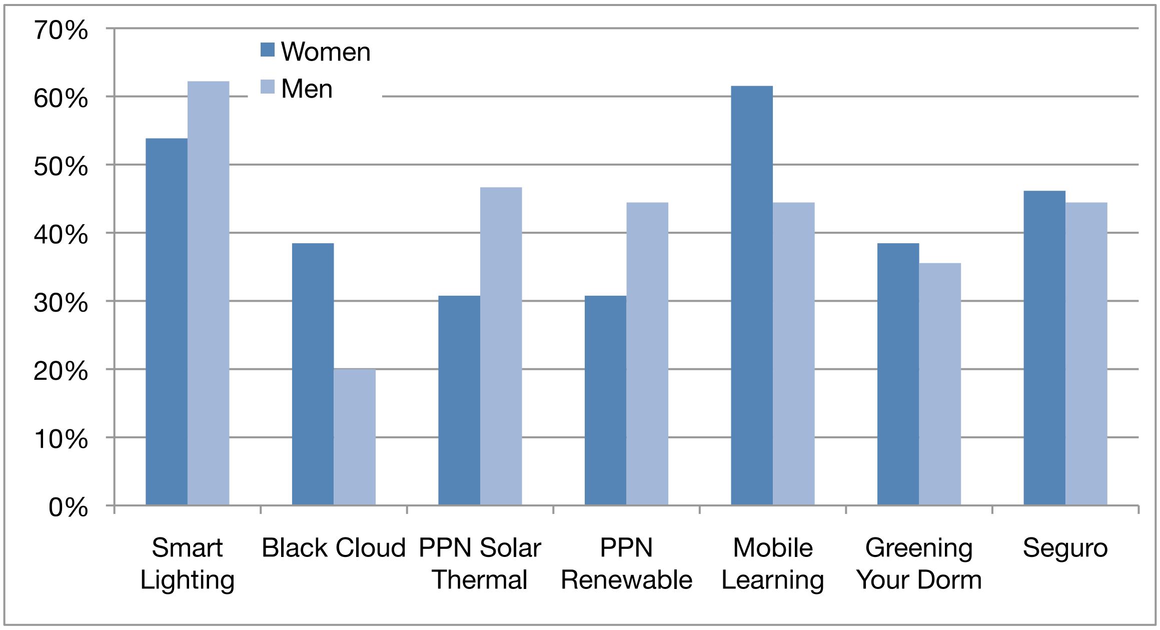

Fig. 7: 2009 Module 1 Project Preference by Gender. Represents percent of Men/Women who ranked a given project in their top three choices.

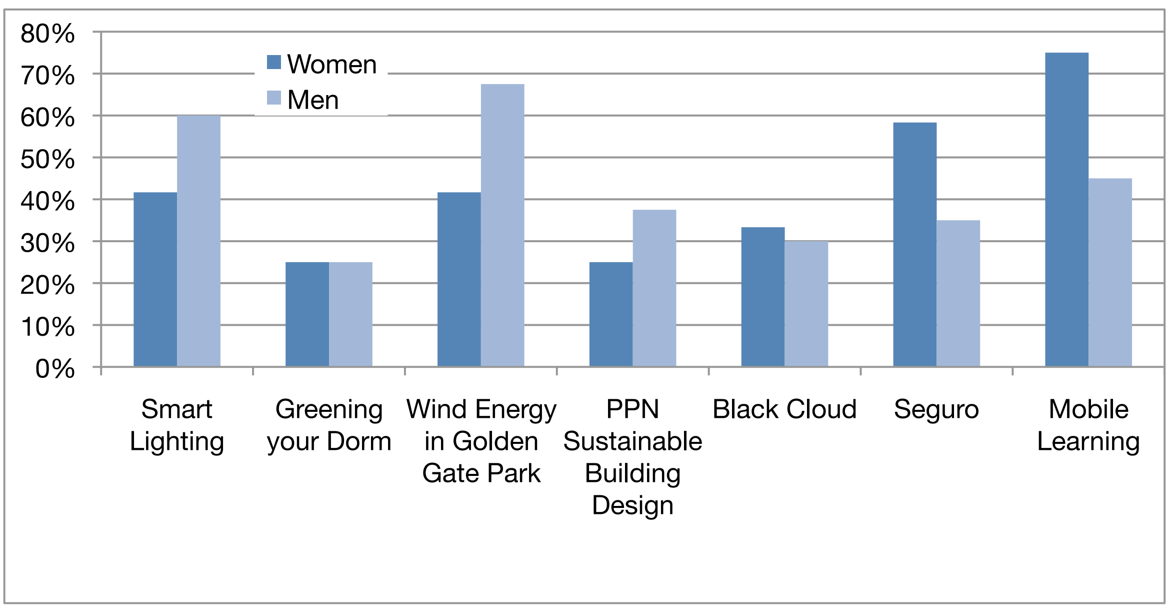

Fig. 8: 2009 Module 2 Project Preferences, by Gender. Bars represent percent of Men/Women who ranked a given project in their top three choices.

VIII. Ethnicity and Project Preference

The only revealing significant results for Chicano students was a preference for mobile learning and the "humanizing Hesse Hall" projects. Although not at the statistically significant threshold ($p<0.05$), there was a trend for the Chicano students to want to work on the Pinoleville Pomo Nation projects, wind energy, and the "black cloud" indoor air quality monitoring project.

IX. Qualitative Comment Analysis

A qualitative analysis of student's comments provides insights into some of the choices made. For example, one Chicano student, whose first choice was the Seguro Materials Testing project, provided this reason for his project choices:

> *"I chose the material testing because I know people who would actually be affected by these suits. It would be a great opportunity to aid them in anyway. I chose the mood lighting second because my room already has lights that are specifically just to set a tone, and not for any other purpose. The last choice is because renewable energy is important for our future and it could be interesting to see how wind turbines work."*

One female student, whose first choice was the PPN project, provided this reason for her project choice:

> *"I liked the Pomo Nation project the best because I thought it would be really interesting to design an entirely green building; there are so many options it would be fun to come up with the best options that would best fit the needs of the nation. […] I also liked the Seguro Materials Testing Materials Testing a lot because it seemed very hands on and I like that. When I work on a project I like to be physically and mentally engaged. It helps me be more creative. I really do not want to work on a project that is going to be mostly theoretical because I do not find that interesting or engaging"*

Five of the twelve female students in the second module of 2009 brought up environmental themes (care about the environment, interest in renewable/alternative energy, etc.) as their rationale for selecting their project.

A female student from one of the PPN teams stated:

> *I absolutely loved this class and I wish that both modules had been structured like the ME Module. I enjoyed learning and practicing the design process. I absolutely loved being able to be creative and feeling that I could make a difference in the world around me.*

Another female student from one of the PPN teams stated:

> *The class was very useful in getting students' creative natures to come out. It showed how design is a very important part of engineering. I like the whole design project.*

This student found the Mechanical Engineering module as a bridge between design and engineering, as a link back to the students' "creative natures".

One female student from the second module in 2008, who participated in the PPN project, has continued to work with the project and is now switching her major from Civil Engineering to Mechanical Engineering based on her experiences.

It was reassuring to see positive comments by majority students as well. One male, Asian-American student wrote in his design journal:

> *Today was essentially the kick-off for our human-centered sustainable design project. To be hones, I'm rather excited about it. I was assigned to my first choice project - solar electricity generation for the Pinoleville Pomo Indian tribe. I've been interested in alternate forms of energy for a long time, and am eager to learn more about, not to mention have the chance to work on my first genuine engineering project.*

Today, we had our innovation workshop at the PPN reservation in Ukiah. Man-where to begin! Overall, I'd have to say the experience was a positive one. I mean yes, it was a bit of a hassle getting there and it was certainly a very long day, but I feel that the knowledge gained about the PPN people and their needs . . . It was a productive/ informative day, and I look forward to beginning the design process with my team mates.

Although the teaching evaluations were high and most comments were positive, this variant of "the exception that proves the rule" example indicates that one majority male student in 2008 felt the course was not reaching him.

I hated this module. From my understanding of E10, it should communicate to people what the different types of Engineering are about. To me, it failed abysmally at doing that. It communicated what Human Centered Design is, but that is not what all of Mechanical Engineering is. I would actually be turned away from Mechanical Engineering if this module was my first introduction to it and I hadn't competed in over 20 robotics seasons and had years of experience in outside of High School that taught me what Mechanical Engineering can be.

This highly accomplished student did not connect human-centered design with mechanical engineering. He views the discipline as one that can be defined as building robots to compete. The comment does raise the question about how we are communicating engineering to K-12 students. Whereas the dueling robots can be engaging to many students, we should do a better job of communicating the societal impact and benefits of engineering as well. Perhaps by neglecting to emphasize the human side of engineering, where societal and ethical problems frame and motivate the engineering practice, we're also forgetting to emphasize the part of engineering that appeals most to underrepresented minorities in engineering (women and some ethnic minorities). We did bring this student in to help us redesign the modules for the 2009; although we want to attract diverse students, we do want to have options that appeal to traditional engineering students as well.

X. Conclusions

Women and underrepresented minorities are attracted to projects where the beneficiaries are underserved communities. By better integrating service learning, sustainability, and issues in underserved communities we can potentially improve recruitment and retention of these underrepresented engineering students.

Perhaps through the example of human-centered design, where engineering students are more engaged with the communities they have the ability to affect, we can attract and keep a more diverse set of engineering students. This not only includes gender and ethnic minorities in engineering, but diversity in ways of thinking about engineering.

In many ways, we are hoping to appeal to a different type of student; while many students self-select for engineering due to their own confidence and proficiency in analytical math and science skills, some are drawn to engineering's potential to benefit society as a whole. The socially responsible engineer of the future needs to have a place in today's engineering education system. By providing students with open-ended design projects that address human needs and societal problems such as sustainability and social justice, the socially responsible engineer is reassured that their engineering skills will eventually lead to opportunities for engineers to positively impact the world.

XI. Acknowledgements

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Author Biography

Lora Oehlberg is a doctoral student in mechanical engineering at UC Berkeley. She has an MS in mechanical engineering from the University of California at Berkeley and a BS in mechanical engineering from Stanford University. She is interested in how new media can be used to help designers in new product development teams document their design process. Her background includes both corporate product design and development and human–computer interaction research.

Ryan Shelby is a 3rd year Alfred P. Sloan Ph.D. Student Fellow in the Department of Mechanical Engineering at the University of California at Berkeley. Mr. Shelby received his M.S. in Mechanical Engineering from the University of California, Berkeley in 2008 with a concentration in design, and his B.S. in Mechanical Engineering from Alabama Agricultural & Mechanical University in 2006 with a concentration in propulsion systems. His doctoral research focuses on the macro- and micro- decisions that minorities, underrepresented/underserved groups, and rural area residents make concerning sustainability and renewable energy technologies.

Alice Agogino is the Roscoe and Elizabeth Hughes Professor of Mechanical Engineering from the University of California at Berkeley. She served as Chair of the Faculty Senate; Associate Dean of Engineering; Faculty Assistant to the Executive Vice Chancellor and Provost in Educational Development and Technology; and Director for Synthesis, an NSF-sponsored coalition of eight universities with the goal of reforming undergraduate engineering education, and continues as PI for the ENGINEERINGPATHWAY project. Prof. Agogino received a B.S. in Mechanical Engineering from the University of New Mexico (1975), M.S. degree in Mechanical Engineering (1978) from the University of California at Berkeley and Ph.D. from the Department of Engineering-Economic Systems at Stanford University (1984). Prior to joining the faculty at UC Berkeley, she worked in industry for Dow Chemical, General Electric and SRI International.

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