AC 2008-1709: COMPARING THE DESIGN PROBLEM SOLVING PROCESSES OF PRODUCT DESIGN AND ENGINEERING STUDENT TEAMS IN THE US AND UK

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Comparing the Design Problem Solving Processes of Product Design and Engineering Student Teams in the US and UK

Abstract

The delivery of sustainable and innovative products and services in global marketplaces demands changes in the way engineers are educated. Identification of essential elements of global engineering education and development of global competencies in engineering design are key prerequisites to the development and delivery of emerging global engineering curricula. The goal of the research reported in this paper was to characterize how diverse design teams operate differently and what common methods they use despite the differences in their backgrounds. We analyzed the design problem-solving strategies and processes used by four student teams. Two of these teams consisted of senior product design students in the UK and two of them included freshman engineering students in the U.S. We used a cross case study analysis to compare senior product design and freshman engineering teams as well as mixed-gender and all-male teams. We asked all student teams to solve an engineering design problem on a fictitious street crossing issue occurring on their college campus. We video-recorded their discussions and collected the documents they produced during the protocol. A key characteristic of the product design teams was their use of drawings at every stage of the design process; in contrast the freshman engineering teams carried out more detailed information gathering activities. These differences between senior product and freshman engineering teams reflected the emphasis areas in their curriculum. All four teams frequently iterated between the different stages of the design process and project planning was a neglected area for all teams. Further research is needed to increase the number of team studies to explore the role of design drawings in supporting team communication, team information gathering and use processes, and the role of team diversity in supporting innovative design solutions.

Introduction

The study of design thinking attempts to discover three things: the processes designers follow in developing a design solution, comparison of designers with various levels of experiences, and how the quality of the design solutions relates to the problem solving processes. Given that design is a human activity involving both creativity and innovation, quantifying how designers think offers real challenges. In addition, teamwork, which has a considerable importance in engineering and product design, expands the complexities of design problem solving. In our study, we used mixed methods approach to explore design problem solving processes of engineering and product design students with an attempt to understand how students approach to and solve design problems.

Our sample includes student teams with diverse educational and cultural backgrounds, different geographical locations, and diverse team compositions. We predict that students with diverse backgrounds and educational experiences would use different approaches to solve their design problem and would produce diverse solutions. We wanted to document these differences; however, we also wanted to explore the similarities among these teams, despite these variances. We believe that our findings would guide future research and be a significant contribution to the design problem solving literature where there is a growing emphasis on global teams and international collaborations.

Research on Problem Solving and Design Processes

The majority of the research on design problem solving has focused on individual designers. For example, Atman et al.[1] used Verbal Protocol Analysis (VPA) to characterize first and fourth year engineering students as well as faculty and expert designers. Studies on problem solving highlight distinct differences between expert and novice problem solvers; Resnick (1985)[2], for example, found that experts approach problems differently than novices. Before starting the solution process, experts reinterpret and simplify problems and use drawings to clarify the relationships among the problem variables. In a more recent study, Atman and her colleagues[3] found that expert engineers spent more time on problem scoping than engineering students. In addition, experts gathered more external information to understand the problem than did engineering students. In addition, experts explicitly did and were better at monitoring their problem solving processes and planning than the novices[4]. Consequently, in our analysis we paid close attention to the strategies first-year and senior student teams used during problem scoping and information gathering.

There is also a rich body of research on team design processes. Both Cross and Cross (1995) [5] and Goldshmidt (1995)[6] studied the social processes and communication of expert design teams based on data collected during a Delft Protocols Workshop. Team based design thinking has also been studied with engineering students[7,8]. Other researchers who looked at the differences between individual designers and teams found that the individual designer spent more time gathering information about the task before starting to search for solutions[9,10]. The team of designers studied during the Delft Workshop, started producing alternative solutions earlier but had more step backs to the clarification of the task[9, 10]. These findings on the behavior of expert teams contradict with the research findings on the behavior of individual designers. The studies on teams are limited at this time; however, planning is one behavior that is observed in both individual and teams of designers. Experts who works individually plan and reflect on their processes while expert team of designers allocate team roles and monitor their problem solving processes.

Research Background and Purpose

The studying of teams in design can be categorized according to Figure 1 which has 3 axes: uni-disciplinary vs. multi-disciplinary teams, collocated vs. distributed teams and teams where members are at home in their own university vs. away in a different culture[11]. This figure can be used to categorize research on student design teams.

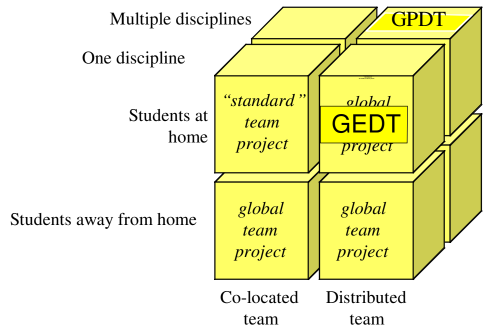

Figure 1. Types of Design Teams

The larger goal of this project is to use the globally distributed teams to study the category: Distributed, Multi-disciplinary and Students at Home (labeled GPDT in the diagram). However, in this study, we seek to identify differences in students at home as a first step before exploring global teams. This paper is based on baseline data from engineering students studying in the US and product design students studying in England.

Research Sample and Methods

Four student teams participated in this study. Two of these teams consisted of senior product design students in the UK (senior product design teams) and two of them included freshman-engineering students in the U.S. (freshman engineering teams). All four teams had previous teaming experiences and had worked together on design projects before. We selected the freshman engineering teams from a pool of seven teams based on two criteria. First, we wanted the freshman teams to match the gender distribution and team size of the senior product design teams. One of the senior teams and one of the freshman teams included two female and two male members. Each of the other two teams included three men (See Table 1). Second, we selected teams that produced feasible solutions that were closer to the quality of the solutions developed by the senior teams so that we can compare their processes rather than the quality of their solutions.

Table 1. *Categorization of Teams*

	Team Name	Team Description
UK Teams	❑ Senior Mixed Team ❑ Senior Male Team	❑ Mixed-gender Team (2 men, 2 women) ❑ All-male Team (3 men)
U.S. Teams	❑ Freshman Mixed Team ❑ Freshman Male Team	❑ Mixed-gender Team (2 men, 2 women) ❑ All-male Team (3 men)

We asked all student teams to solve an engineering design problem on a fictitious street crossing issue occurring on their college campus. The following problem description was provided to all teams although the street and building names were modified for the campus where the study was conducted.

> Street Crossing Problem: University campuses are often overcrowded with pedestrians crossing the streets, since walking is a popular form of transportation for college students. One busy intersection on campus is the crossing by the <*name of the first building*> building to the <*name of the second building*> across the <*name of the street*> Road. Students need to cross this intersection to get from their classroom to the lab. The university would like to design a cost effective method to cross this street, which would reduce the possibility of accidents at this intersection. Your teams' goal is to solve this engineering design problem. Please keep your design simple yet effective and document all of your design ideas. Your work should contain a detailed description of your design, diagrams, calculations, etc. When you complete your design, please submit all of the documents you created.

We video-recorded students' discussions and collected the documents they produced during the protocol. Verbal Protocol Analysis was performed on data collected from these four student teams. A modified version of Atman (2001)'s design steps and categories were used for coding team protocols (See Table 2). We used a modified version to capture some of the details we observed when analyzing design teams (e.g. modeling alternative solutions and modeling selected solutions). Senior product design students had 30 minutes to solve their problems in a quiet conference room. For the freshman engineering teams, the verbal protocol was a component of their introduction to design course and they were allowed to spend one hour to solve their design problem in a classroom setting.

Table 2. *Design Steps and Categories Used for Coding*

DESIGN STEPS	NEW CATEGORIES
Problem Scoping	❑ Problem Definition (PD) ❑ Information Gathering (INFO) ❑ Identification of Assumptions (ASSU)
Developing Alternative Solutions	❑ Generating Ideas (IDEA) ❑ Modeling Alternative Solutions (MODALT) ❑ Feasibility Analysis (FEAS) ❑ Evaluation of Alternative Solutions (EVA)
Project Realization	❑ Decisions (DEC) ❑ Modeling Selected Solution (MODSEL)

We used a cross case study analysis to compare senior product design and freshman engineering teams as well as mixed-gender and all-male teams.

Results

Anyone involved in team-working would agree that there are many variables that influence the effectiveness of a given team. In this study, we noticed both differences and similarities between groups of senior and freshman students as well as within groups. In this section, we will first present the characteristics of the design processes followed by the senior product design teams and then present the characteristics of the freshman engineering teams. Finally, we provide a comparison of these teams across grade level and based on gender composition.

Design Processes of Senior Product Design Teams

Problem Scoping Stage

A key characteristic of the senior product design teams was the use of drawings at every stage of the design process. Both teams used drawings when defining their problem. As seen in Figure 2 and Figure 3, their drawings are almost identical. They drew sketches individually to communicate their design ideas but also collaboratively as they prompted the person in charge of drawings to add components to the sketches. These drawings first started as a tool to define the problem but evolved as they identified their design solutions becoming a tool for modeling alternative or selected design solutions. For example, in Figure 3, the team drew one of their alternative solutions (island) and had rich discussions on the details of the island.

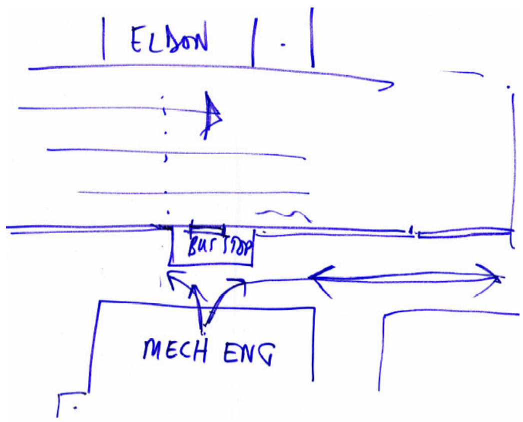

Figure 2. Mixed-Gender Senior Design Team

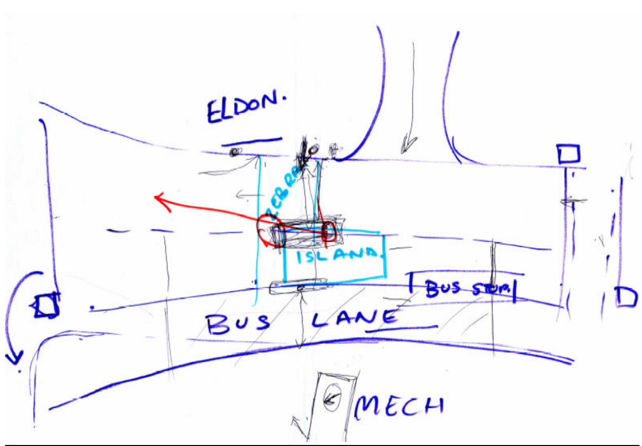

Figure 3. All-male Senior Design Team

In addition to the drawings, senior teams relied heavily on internal information (i.e. knowledge of team members) for the entire process. The only question they asked to gather external information was how much the budget was.

Alternative Solutions Stage

Among the senior product design teams, the all-male team started generating ideas earlier than the mixed-gender team. Figure 4 shows the design steps the two product design teams followed. The rows in these charts indicate the use of design steps that are listed on the left column. The columns represent time segments and each square is equivalent to 30-second time intervals (See Table 2 for the descriptions of the abbreviations used in these charts). According to these charts, both teams started their problem solving process by defining the problem. The senior mixed team did not start generating ideas and developing alternative solutions until after spending 4 minutes defining the problem and gathering information. They first focused on the given problem and discussed their knowledge of the location and problems associated with it. The male team started developing alternatives right after they finished reading the problem statement. In addition, both senior teams spent most of their time on problem scoping and generating alternatives while spending less than 10 % of their time on project realization.

We also calculated the number of iterations by counting the transitions teams made between problem scoping, alternative solutions, and project realization stages (See Table 3). Both teams made a significant number of iterations between problem scoping and alternative solutions and both teams re-read the problem statement frequently when solving their problem.

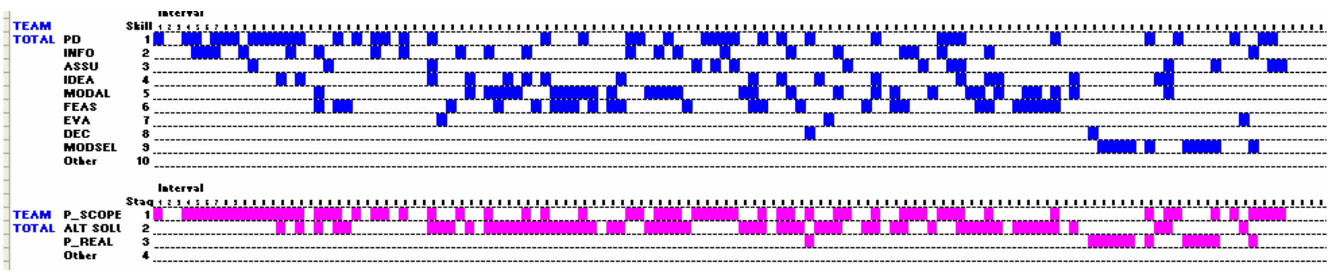

Figure 4. Senior Mixed Team (Iterations=48)

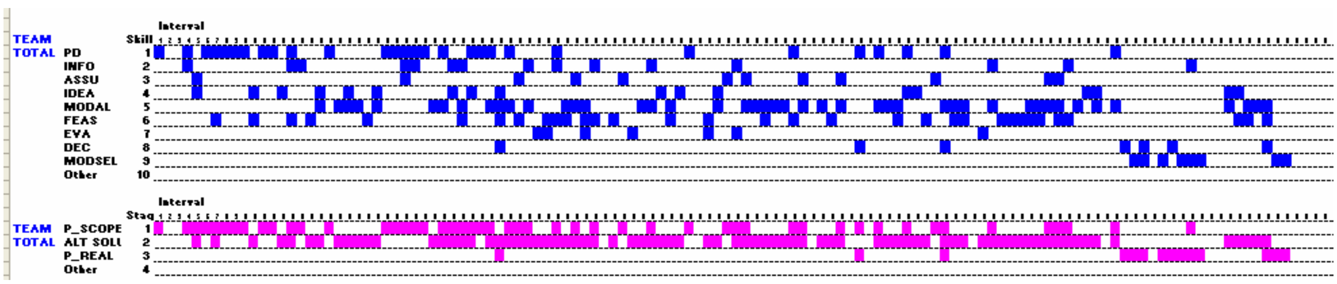

Figure 5. Senior Male Team (Iterations=54)

Table 3. Senior Product Design Teams

Team Name	Number of Iterations Between Design Stages	Percent Time Spent Before Idea Generation
Senior Mixed Team	48	13%
Senior Male Team	54	7%

The senior male team used a formal idea evaluation method to compare their alternatives (See Figure 6). The mixed team, however, evaluated their ideas through verbal team discussions and did not create any formal evaluation or a written documentation of their design evaluations.

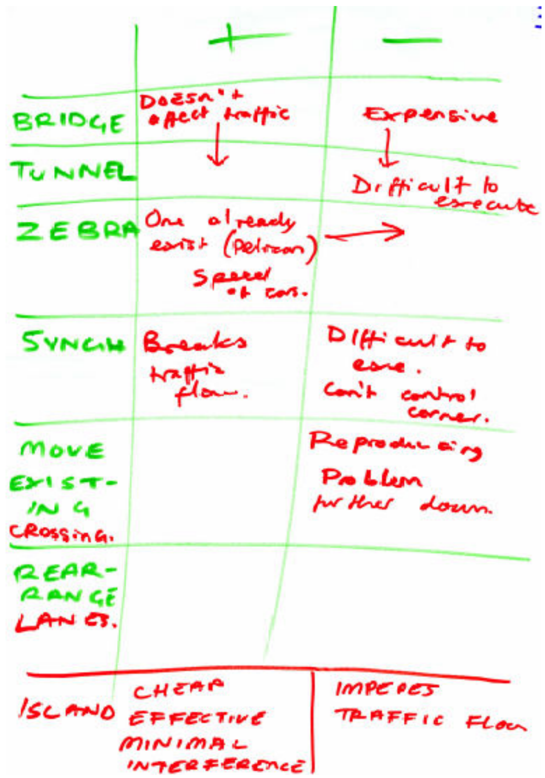

Figure 6. Pros/Cons Analysis by Senior Male Team

<u>Design Processes of Freshman Engineering Teams</u>

Problem Scoping Stage

Both freshman engineering teams started the problem scoping stage by defining the design constraints and criteria. They started this process by reading the given problem statement and gathering information. Figure 7 shows how the freshman male team documented this process. The mixed team used the same procedure to document their constraints and criteria.

A key similarity across the freshman teams was their focus on external information gathering. Both teams gathered information and used this information to define the problem. They asked questions about the meaning of words given in the problem statement (e.g. what do you mean by cost-effective?), time constraints, budget, problem location, traffic flow, construction costs, etc. Figure 8 shows a list of questions the freshman mixed team generated and asked to the faculty. The male team also asked questions to gather information; however, they did not document their questions and answers in writing.

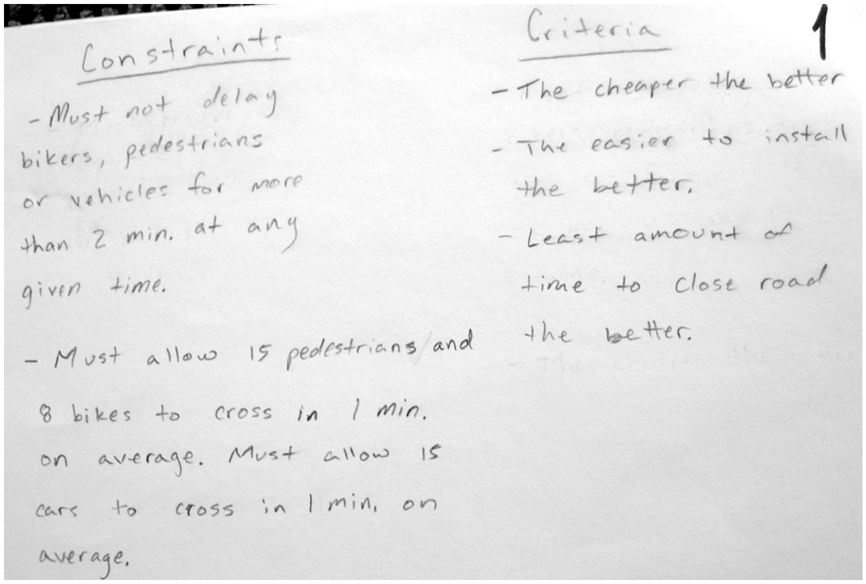

Figure 7. Problem Definition by Freshman Male Team

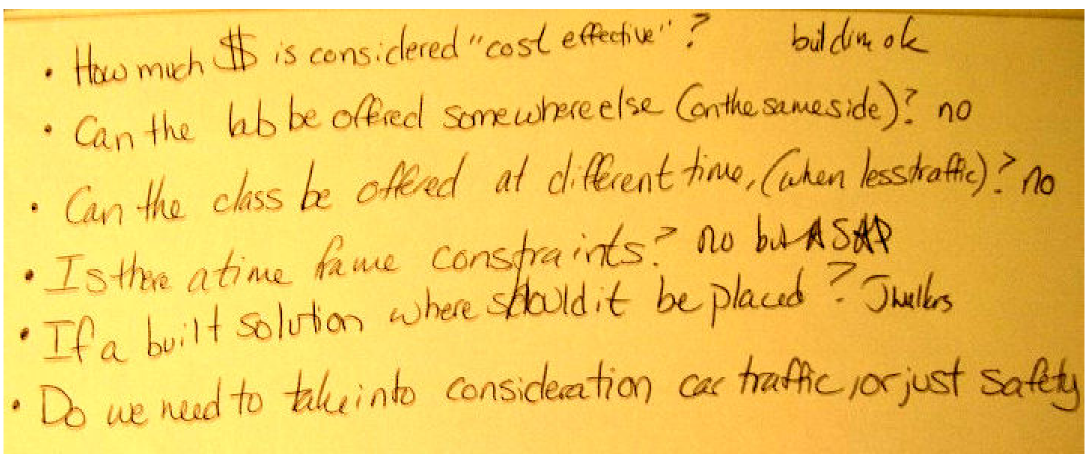

Figure 8. Information Gathering by Freshman Mixed Team

Alternative Solutions Stage

Both the freshman mixed-gender and male teams followed a formal brainstorming process to generate ideas. While the mixed team started generating ideas at the very beginning of their design process, the male team completed 44% of their time before starting to formally generate alternative solutions. As seen in Figure 10, the male team spent the first half of their problem solving process for problem scoping and showed less iteration between design stages compared to the mixed team (See Table 4).

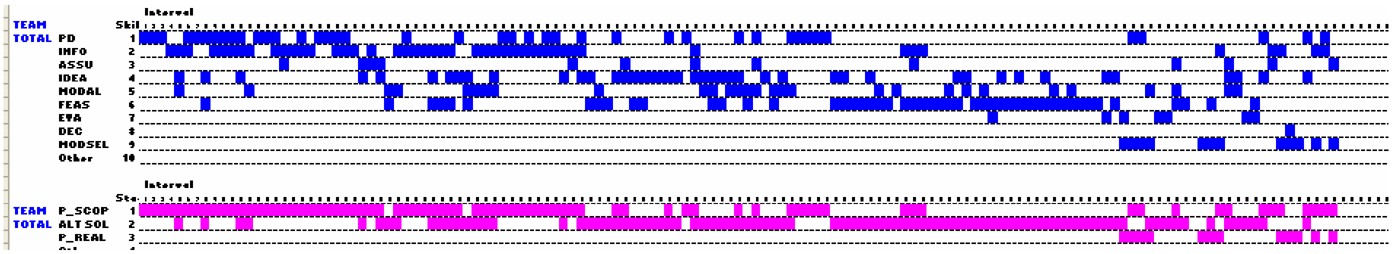

Figure 9. Freshman Mixed Team (Iterations=44)

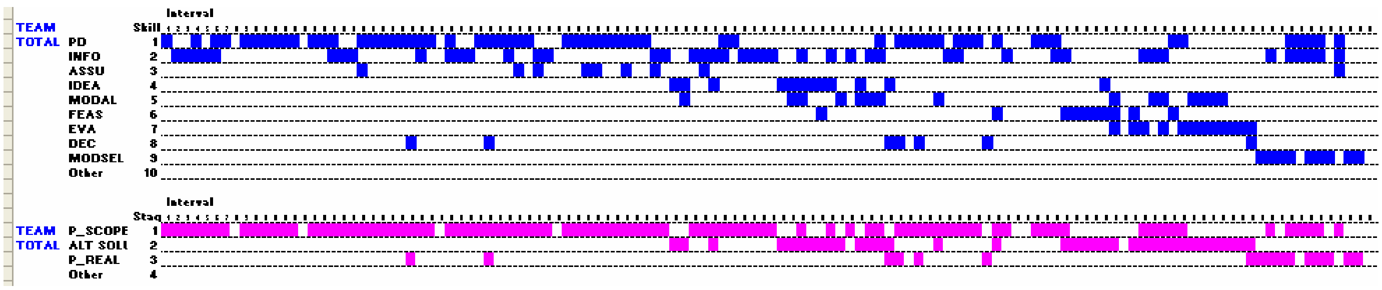

Figure 10. Freshman Male Team (Iterations=35)

Table 4. Freshman Engineering Teams

Team Name	Number of Iterations Between Design Stages	Percent Time Spent Before Idea Generation
Freshman Mixed Team	44	4%
Freshman Male Team	35	44%

Both freshman teams documented their design selection processes; however, they used different tools. Mixed-gender team used a problems/benefits analysis and discussed all of their alternative ideas in detail (See Figure 11).

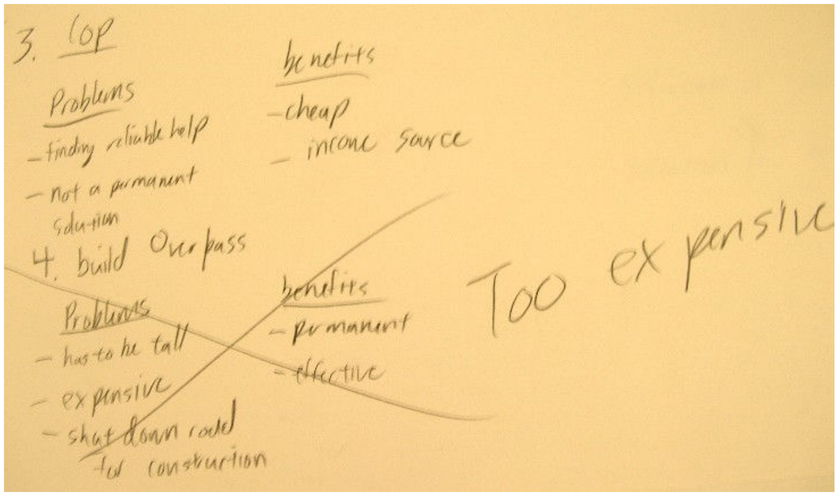

Figure 11. Problems-Benefits Analysis by Freshman Mixed Team

All-male team used a decision matrix to compare and evaluate their design alternatives. They listed the design criteria and weighted them for importance. Then, they individually rated each alternative and consolidated their ratings (See Figure 12).

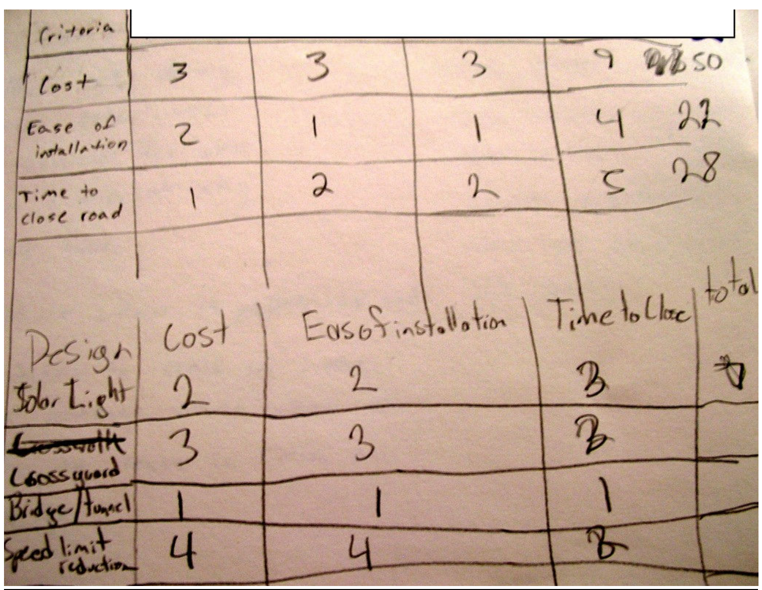

Figure 12. Design Selection Matrix by Freshman Male Team

Comparison of Senior Product Design and Freshman Engineering Teams

Our analysis revealed a number of similarities among the senior product and freshman engineering teams. Firstly, all of the four teams used an iterative process to solve their design problem by transitioning among problem scoping, alternative solutions, and project realization stages. In addition, all of the solutions produced by these four teams were simple and feasible and included combination of different alternatives they developed such as using an island and mirror or using fences and moving the location of the bus stop (See Table 5).

Table 5. *Comparison of the Design Processes of Senior Product Design and Freshman Engineering Teams*

	Problem Definition Method	Brainstormed Ideas	Evaluation Method	Selected Solutions
Mixed–Gender Seniors	❑ Defined problem with sketches ❑ Relied on internal information	❑ Road level ❑ Bridge ❑ Under ground	Team Discussion	❑ Café rejuvenation ❑ Signage ❑ Relocating bus stop ❑ Fence
All-Male Seniors	❑ Defined problem with sketches ❑ Relied on internal information	❑ Tunnel ❑ Bridge ❑ Zebra crossing ❑ Road rearrange (erasing bus lane, ❑ Road rearrange island- using mirror) ❑ Traffic light synchronization	Pros/Cons Evaluation	❑ Ramp ❑ Railing ❑ Mirror at the median
Mixed–Gender Freshmen	❑ Defined design constraints and criteria ❑ Gathered external information	❑ Fence ❑ Hedges ❑ Cop ❑ Overpass ❑ Push button crosswalk ❑ Changing class time ❑ Attack dogs	Problems/ Benefits Evaluation	❑ Change class times, temporarily post a cop to ticket, build a fence ❑ Change class times, temporarily post a cop to ticket, build cross walk in the jay walking area.
All-Male Freshmen	❑ Defined design constraints and criteria ❑ Gathered external information	❑ Traffic light ❑ Solar powered traffic light ❑ Cross walk/guard ❑ Bridge/tunnel ❑ Speed limits	Decision Matrix	❑ Two 15 mph speed limit signs with time constraints and 2 speed reduction signs

Another commonality among all teams was related to the allocation of member roles. These roles were sometimes explicitly discussed (e.g. record keeper) but other times tacitly taken (e.g. team leader). While the teams worked well together and were able to complete the assignment in the given time, none of the teams allocated time to establish a timeline or create a project management plan.

The differences between campuses were most apparent in the ways the teams approached the problem and communicated their design solutions. Figure 13 shows the amount of time each team spent at different steps of the design process and provides a comparison of all teams. Team information gathering and modeling alternative design ideas steps differed significantly between the senior product design and freshman engineering students.

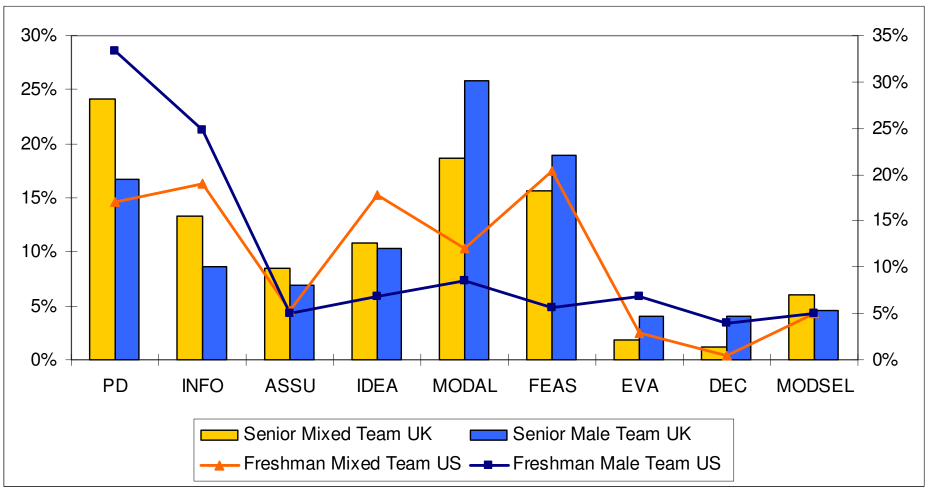

Figure 13. Comparison of Percent Time Spent by Senior Product Design and Freshman Engineering Teams

On one hand, the freshman teams gathered more information and spent more time discussing the information they gathered. On the other hand, senior students used sketches to define the problem. Moreover, these drawings also lead to the modeling of alternative design ideas with an indistinct transition. They used drawings to not only model their solutions but also to model the problem as they drew the street and buildings based on the information they had. Consequently, they spent more time on modeling than did the freshman engineering students.

The freshman teams also used drawings; however, they used drawings after the problem definition stage. In addition, their drawings were solitary activities. For example, Figure 13 presents the sketch one of the students drew while his team members brainstormed these ideas. On the other hand, senior teams used the drawings as a space to share and discuss their ideas. Their sketches grew as they moved through the design process.

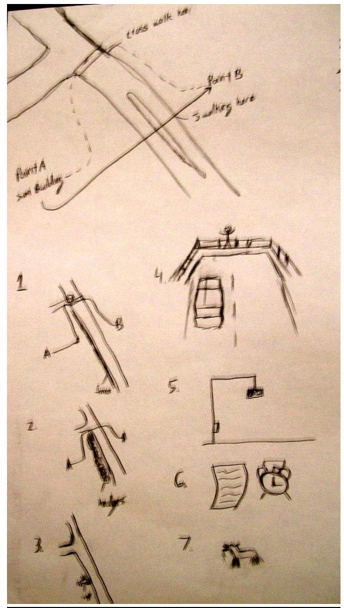

Figure 14. Drawings of Alternatives by Freshman Mixed Team

<u>Comparison of Mixed-Gender and All-Male Teams</u>

We also explored the differences between the teams based on their gender distributions. We should state that this analysis is based on a very small sample but we think these findings would help support future research. We did not observe any differences between the all-male and mixed-gender teams based on the quality and the characteristics of solutions they produced. Their solutions were feasible and met the design constraints and criteria. There were also no patterns in terms of the design evaluation methods used by these groups of teams. Teams used various methods, oral discussions, pros/cons evaluation charts, or decision matrices to evaluate their alternative design ideas. The design solutions of all teams included simple designs that essentially require people to change their activity patterns (e.g. relocating bus stop, offering classes at a different location) rather than involving elaborate construction (e.g. building a bridge). While there was some evidence that the mixed-gender teams had explicit discussions on whether they can change people's behaviors, our sample is too small to make a robust claim.

Conclusions and Recommendations

Design problem solving is a global concept but can be executed in many different ways. Our goal with this study was to characterize the design problem-solving strategies and processes used by four student teams. We explored methods and tools students used to solve a design problem and identified the differences between product design and engineering student teams in the US and UK as a first step before exploring global teams.

The differences between senior product and freshman engineering teams reflected the emphasis areas in their curriculum; however, despite the variances in their backgrounds teams showed similarities in areas such as iterations and project planning. In summary, our analyses present five key findings and offers recommendations for future research.

1. Design sketches are used for various means when solving design solutions. In our study, senior product design teams used drawings at every stage of their design processes. Their use of drawings for problem definition enabled them to reach a common understanding of the problem they were given. Establishing a common understanding was a challenging but a critical element when working in teams. The freshman engineering students relied mostly on verbal communication and spent most of their time on problem scoping. Visual tools could be one method in supporting effective team communication. Future studies might explore whether the use of drawings support team communication and improve the quality of team design solutions. The senior product design teams spent more time modeling the alternative solutions than did the freshman engineering students.

2. In our sample, the freshman engineering teams collected external information for problem definition while the senior product teams tended to rely more on the backgrounds of their team members. The behavior of the freshman teams was more aligned with the behavior of expert designers; however, information from team members would also be valuable as long as they provide accurate and reliable information. Further research should investigate how student teams acquire, select, and use information (internal and external) in making design decisions. The type of questions students ask (i.e., divergent and open-ended vs. convergent) could also be explored in relation to educational experience and team composition of teams.

3. All teams overlooked project and time management. Neither the freshman engineering nor the senior product design teams discussed a plan that they would use when solving their design problem or established a timeline. We predict that a plan would support the design processes; however, in this study none of the teams allocated time for planning. It is possible that for a short problem solving activity used in this study, project planning might not have much affect on the quality of solutions and the processes. Expert problem solvers do plan and monitor their progress[2]; however, they draw on their significant prior experiences to evaluate their progress. Planning and monitoring is a more challenging task for novices who rely on limited knowledge and experiences. Nevertheless, the role of project planning in supporting student design processes would be another focus area for future research.

4. Iteration among design stages was a common behavior observed in all teams. Students did not follow the design process in a linear fashion. Future research can explore the processes used by non-engineering students or professionals when solving design problems. Investigating the differences and similarities in the problem solving processes of engineers and non-engineers can inform us regarding the essentials of engineering problem solving skills.

5. There were no significant differences between the solutions produced by mixed-gender and all-male teams. However, only the mixed-gender teams had explicit discussions on people's behaviors. Further research is needed to increase the number of team studies and explore how team diversity support innovative design solutions.

We understand that our sample entails several variables in terms of geographical location, grade level, and educational background; however, we believe that this diversity provided us with opportunities to explore multiple ways in approaching a design problem. Despite these variables, student teams were able to develop compatible solutions.

Acknowledgements

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