AC 2007-2462: A PILOT STUDY OF ENGINEERING DESIGN TEAMS USING PROTOCOL ANALYSIS

Chell Roberts, Arizona State University

Senay Yasar, Arizona State University

Darryl Morrell, Arizona State University

Mark Henderson, Arizona State University

Scott Danielson, Arizona State University

Nancy Cooke, Arizona State University

A Pilot Study of Engineering Design Teams Using Protocol Analysis

Abstract

The development of design, problem solving, and communications skills within a team setting is a crucial component of the education of a globally competitive engineer. The importance of these attributes has been repeatedly recognized, by both the National Academy of Engineering and Accreditation Board for Engineering and Technology (ABET), the accrediting body for engineering programs in the United States. Unfortunately, very little is known about the dynamics of engineering team-based engineering design and problem solving processes. How do the team processes of experts differ from those of novices? How do students develop the necessary skills over time? In this paper we present background on the problem and a Verbal Protocol Analysis (VPA) pilot study of freshman engineering team design and team processes as a step in the development of an empirically based understanding to address these questions. The research method used was based on the methods and the design categories used by Atman, Cardella, and Robin[1]. An important distinction is that Atman's work was exclusive to individuals while our pilot used student teams. The pilot study was conducted in an introduction to engineering class. Data was collected and analyzed for four teams (three teams consisting of four team members and one team consisting of three team members). The pilot study resulted in the development of a modified verbal coding schema for team design processes. Broader findings of the pilot study included a difference between team and individual design activities, a need to add process to the content categories analyzed, a need to improve our instrumentation, and a need to acquire better software for the coding and analysis of the design activities.

Introduction

ABET requires that all accredited engineering and engineering technology programs demonstrate student attainment of outcomes related to design and problem solving. For instance, the engineering accreditation Criterion 3 published in 2005[2] specifically addresses design, problem solving, communication, and teams: "an ability *to design a system, component, or process* to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability (criterion 3b);" "an ability to *function on multi-disciplinary teams* (criterion 3d);" "an ability to identify, formulate, and ***solve*** *engineering problems* criterion 3e;" and "an ability to communicate effectively (criterion 3g)".

Two of the recent National Academy of Engineering reports, *The Engineer of 2020: Visions of Engineering in the New Century*[3] and *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*[4], recognize the growing need for teaming skills to solve increasingly complex problems in a global context (p.10) and criticize the lack of a research-based assessment of these skills. Educational research in engineering is still in its infancy in terms of the development of effective assessments for measuring a variety of professional engineering skills, such as the ability to function in multidisciplinary teams[5]. What is known about what happens in engineering work groups often relies on self-reports[6] rather than evidence-based measures of group dynamics. In short, little is known about good team performance and how team performance affects the team task completion. Clearly, it is difficult to develop effective assessments until more is understood about the characteristics of engineering learners and experienced engineers as they acquire these professional skills.

This lack of understanding makes reform of engineering curricula difficult and impacts the entire field of undergraduate reform in STEM (science, technology, engineering, and math) education. As stated by Seymour in 2001[7], "...in reform efforts, the theory or theories that underwrite the chosen forms of actions often remain unstated. Reformers may jump from identification of a problem to a selection of strategies intended to ameliorate it without reference to what is (or is not) known about the relative importance of the factors contributing to the problem, or about their chances of success" (p. 90). In order to address this need and to develop innovative curricula that will effectively educate the engineer of 2020[4], it will be necessary to develop foundational knowledge that uniquely characterizes engineering learning and engineering expertise.

The growing cognitive and technological complexity of many tasks has made it increasingly necessary to enlist teams of experts to work together to plan, think, decide, solve problems, design, and take action as integrated units. Some examples of these team-level cognitive tasks include military command-and-control, emergency management, surgery, and air traffic control. Engineering is no exception, with teaming arrangements for design and problem solving serving as the rule rather than the exception.

From years of research, we are beginning to understand that the nature of team expertise is not simply an aggregate of the characteristics of individual expertise. Teamwork expertise is more than the simple collection of individual expert team members[8]. Team-level expertise emerges from interactions among a collection of experts. The 2004 US Olympic basketball team is an interesting case in which a team of expert players was assembled; yet the result was far from an expert team. How does a team acquire and maintain team-level expertise? Team-level skills such as coordination, collaboration, conflict management, and communication are essential to team-level expertise and can be monitored, assessed, and trained like individual skills. Metrics for assessing these team-level skills are central to an understanding of team expertise, with more work needed[9,10]. Likewise, cognitive research on team performance and cognition needs to be integrated into engineering research.

Recently, there has been some progress in the development of curriculum and assessment tools for engineering teaming including BESTEAMS[11] and the Team Developer[12]. BESTEAMS provides a series of nine learning modules that are designed to be delivered in 50 – 90 minutes each. The Team developer is an 80-page text on team development. However, the effectiveness of teaming curriculum and pedagogy in terms of helping students progress toward expert levels will remain difficult to assess until baseline data on teaming experience (novices to experts) is available.

Protocol Analysis

Verbal protocol analysis (VPA) is a tool that has been used to characterize behaviors associated with situational expertise and developmental learning using observed and "think-aloud" protocols to evaluate cognitive processes. There has been a large increase in the use of verbal data to study cognitive processes in many areas of psychology, education, and cognitive science. Studies have used verbal reports for research on topics such as decision-making[13], second-language learning[14], text comprehension[15], human factors research[16], and engineering design[17, 1]. The method typically begins by encouraging the participants to pursue a given exercise while thinking out loud and recording the utterances. The investigators typically hypothesize a specific series of content and process activities that the participants will follow (an expected protocol) and then look for these steps by coding the transcription of the recordings.

VPA has been used in the analysis of engineering tasks, executed both individually[18] and in teams[19] to determine the cognitive processes present in engineering design activities. Atman developed a process to manually transcribe the verbal expressions of a single designer during a 20-minute to 3-hour range of design problem solving. Several observations were noted: the time spent in transition among various design process steps was somewhat dependent on the experience of the designer. Less experienced designers stayed longer in a brainstorming and prototyping stages than experienced designers, who transitioned more frequently and spent more time in analysis and problem definition. The resulting designs were evaluated by engineering faculty members for quality and innovation. The more experienced designers, spending more time defining the problem and modeling, were rated higher by the evaluators than the freshmen engineering students.

Stempfle and Badke-Schaub studied how teams of engineers used Design for the Environment tools during engineering design[17]. They concluded that team verbalizations indicated significant time spent in process-related tasks such as planning next steps. On the other hand, individual designers verbalized mostly technical content rather than process content. This observation led them to design categories for both "process" and "content" related tasks.

A Pilot Study

A pilot study was conducted with first year engineering students to investigate the processes teams of students used when solving an open-ended design problem. The research method was based on the methods and the design categories used by Atman, Cardella, and Robin[1] and used verbal protocol analysis to describe students' approaches to solving the design problem. Besides studying student design and problem solving processes, we were interested in studying the differences in applying VPA to teams as compared to individuals. An important distinction is that Atman's work was exclusive to individuals while our pilot used student teams.

While we used Atman, Chimka, Bursic, and Nachmann study[1] as a foundation for our study of teams, our study was different than theirs in five main aspects. First, we studied teams while Atman et al examined individual students. They also compared the design processes used by freshmen and seniors; however, our study included freshman only. Second, in our study each team were given 20 minutes to complete their design solution. On the other hand, Atman et al. did not limit the time to solve the problem. In their study, freshmen spent an average of 6.3 minutes and seniors spent an average of 11.8 minutes to solve the problem. Third, we adopted the context of the street crossing problem and modified the statement to address a location that is familiar to our students on our campus. Next, when coding the video recordings of student teams' design activity; we included two additional categories that Atman et al. did not have. Finally, we used real-time protocol coding while Atman transcribed the audio and then coded from the transcription.

Dwarakanath and Blessing[22] have also used engineering design protocols. Our study was different than theirs in three ways. First, their study included verbal protocols of an expert individual designer and a team of expert designers rather than novice freshman engineering students or seniors. They compared the differences in the design process used by an individual designer to a team of designers. Second, their design problem involved the design of a device to fasten and carry a backpack on a mountain bike. Third, participant designers in their study were given 2 hours to solve the problem.

Various problems, with a range of constraints and criteria, have been used in the literature for protocol analysis of engineering design sessions[20, 18, 17]. We selected the street-crossing problem presented by Atman and her colleagues[1]. The street-crossing problem asks the students to design a cost effective and safe street crossing method at a very busy intersection on a college campus. We modified the problem statement in the published problems by describing a location on our campus that was familiar to our students.

The pilot study was conducted in an introduction to engineering class consisting of 28 freshman students. Students in the class had been working in teams throughout the semester. The study was conducted toward the end of the semester. Teams of four to five students were assigned to teaming tables. Each team had the use of a connected computer and a faculty team mentor that could be asked clarification questions. Each faculty team mentor also had data that could be given to the teams upon a request for the information from the team. Each team table was equipped with an audio recording device in the center of the table. A video camera was also focused on each team.

The data from four teams (three teams consisting of four team members and one team consisting of three team members) were analyzed. The freshman student teams were allowed to work on the street-crossing problem for 20 minutes. We collected the video and audio recording of the teams while they were solving the design problem as well as any written artifacts they produced. We coded each student's comments individually and then combined their scores to determine the team performance.

Due to the complexity of team interactions and communication we developed a macro program using Microsoft Excel™ for real-time coding. This macro program, which we call I-PACE (instant protocol analysis coder encoder) is an instant protocol analysis tool. This prototype tool enables the coding of the video and audio data without transcription. I-PACE is programmed so that each possible combination of student team member and design category is mapped to a key on a computer keyboard. Thus an entire team and their possible design activities can be assigned to the keyboard and a team session can be coded while watching the video. When a coder observes a student addressing a design step the coder captures the person, the design step, and the time of the activity with the press of a single key. In the pilot study, a graduate student first coded the data. The entire research team then observed parts of the video to validate the coding.

The data in Figure 1 shows a detail of all of the team-coded design activities for one of the teams. The horizontal axis of the chart separates the 20-minute design activity into 30-second intervals. The vertical axis indicates the design steps, i.e., the design scheme investigated. A square indicates that at least one team member is addressing a design step. The coding shows a significant amount of movement between design activities with little time spent on problem definition. The definitions of the skills are a combination of codes received from Dr. Atman at University of Washington along with the customizations we added for this study. The descriptions of the abbreviated codes (e.g. PD) are described in Table 2.

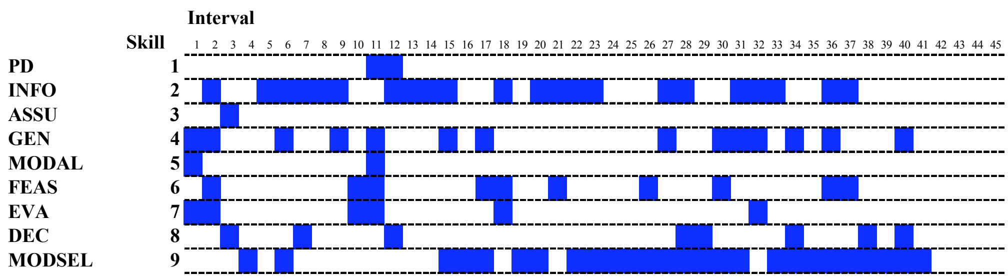
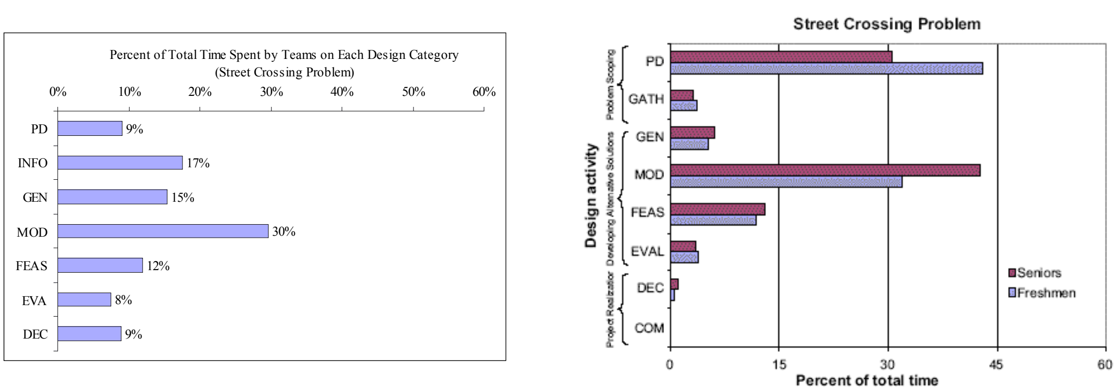


Figure 1. The Timeline of a Novice Team's Transitions between all Coded Activities

The data in Figure 2a presents the aggregate protocol times for the 15 students. The resulting coding of student design activity showed that there was a difference between teams and individuals. The data show that students spent most of their time on *modeling* (30%), followed by *information gathering* (17%) and *idea generation* (15%). A comparison of our findings with the findings of Atman et al.[1] showed that the student team's approaches to the design problem were different than the Atman data (see Figure 2b). Our data indicate that students working in teams spend more time gathering information than students working individually. Although these are preliminary findings, it appears, in fact, that novices act more like experts in terms of information gathering[20] when they work in teams. This finding is supported by research on collaborative learning situations where group interactions and peer argumentation result in better solutions compared to individual problem solving[21]. It is also an observation comparing our student team profiles to those from the Atman data representing freshmen, upper classmen and professional expert designers, respectively.



(a) (b)

Figure 2. Comparison of the Mean Percent of Total Time Spent by (a) All Student Teams, and (b), Individuals in Atman et al. (2005)[1].

Another difference between novice teams and novice individuals was related to the time they spent on problem definition. Individuals spent more time in defining the problem compared to teams. A similar pattern also exists when expert teams and expert individuals are compared[22]. There were also similarities between the teams of students and the individual students. Both groups of students spent the majority of their time on the modeling activities.

Another outcome of the pilot study is a modified coding classification schema based on an original schema by Atman et al[1]. Additional categories for identification of assumptions and for modeling selected solutions were added. These two categories were added because teams exhibited activities in these areas and they did not seem to fit well in the previously defined coding categories. We also added a new category, assumptions, which captures the assumptions students used. We decided not to include communication step in coding because this category was evident at all times within the team interactions. The revised coding classification is shown in Table 2.

Table 2. Revised Coding Schemes

Design Stages	Coding Label	Atman's Categories	Coding Label	Revised Categories
Problem Scoping	PD GATH	❑ Problem Definition ❑ Information Gathering	PD INFO ASSU	❑ Problem Definition ❑ Information Gathering ❑ Identification of Assumptions
Developing Alternative Solutions	GEN MOD FEAS EVAL	❑ Generating Ideas ❑ Modeling Alternative Solutions ❑ Feasibility ❑ Evaluation of Alternative Solutions	GEN MODALT FEAS EVA	❑ Generating Ideas ❑ Modeling Alternative Solutions ❑ Feasibility Analysis ❑ Evaluation of Alternative Solutions
Project Realization	DEC COM	❑ Decisions ❑ Communication	DEC MODSEL	❑ Decisions ❑ Modeling Selected Solution

Comparison of Freshman Teams and Expert Teams

Figure 3 presents a VPA analysis of a novice team as an example of the study. This team was composed of four freshman engineering students. The team initially began producing alternative solutions and decided on a design concept very early in their session. Consequently, they spent most of their time on Project Realization and the least amount of time on Alternative Solutions. The team made 16 iterations between Problem Scoping and Alternative Solution stages to clarify the problem. Figure 3 shows these iterations in a timeline. The behavior of this team is similar to the expert designers' behavior reported by Dwarakanath, S. and Blessing[22] who found that expert designers entered the searching for concepts (alternative solutions) phase earlier but had more step backs to the clarification of the task in their proceedings. Experts started by brainstorming alternative solutions and then systematically identified the sub-problems. On the other hand, the individual designer spent more time gathering information about the task before he actually started to search for solutions and started exploring solutions after understanding the problem. The freshman design team also spent a significant amount of time (24%) on problem scoping which appears to be an individual expert behavior. Figure 3 shows the data presented in Figure 1 from the modified coding perspective. Figure 4 shows the separation of the design activities. The students in our sample spent most of their time on modeling their selected design (21%) and only 8% of their time to model alternative solutions. The phrase "two heads are better than one", when applied to these results, shows that multiple "heads" applied to a design problem result in more expert-type behavior. However, it is not clear if the resulting designs are better than designs produced by individuals and how one might evaluate "better designs".

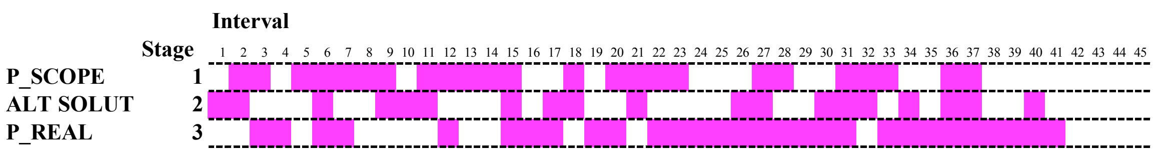


Figure 3. The Timeline of a Novice Team Transitions between Coding Stages using the Modified Coding Schema (Team #2 – four male students)

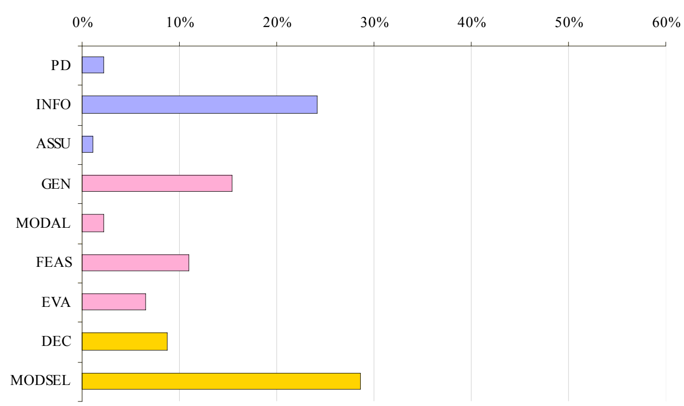


Figure 4. Percent of Total Time Spent by a Novice Team on Each Design Category (Team #2 – four male students)

Discussion and Conclusions

Through this preliminary study, we found that there are differences between team and individual design activities. In particular, teams tended to spend more time on information gathering than individuals. One possible reason for this is that with more people involved in the design process, there may be more questions and a need for more time to address these questions. Another explanation is that the social environment in a team context supports discourse and enables the students to address and understand the problem from different perspectives.

Also, it appeared to the investigators that a 20-minute period was insufficient for a team to go through the entire design process. The Atman results were based on 8-11 minutes for an individual and it appears that teams may need more time than individuals. We believe that there is likely a greater clarification and communication need when working on a team. We also found that there were team activities that were difficult to code using the Atman schema. Most of these difficulties centered on the team discussing their own process. This is why we included process categories in the modified schema.

For future studies, we plan to enhance our instrumentation methods. We had difficulties at times hearing all of the team members from the single recording device. Likewise, the video camera was fixed at a particular angle for each team and there were interactions that were missed. For these reasons we plan to use individual recording devices and two or three cameras per team in the future. Minimally we would like to use two cameras that are positioned at different angles. As teams often sketch and write notes, we also think it might be good to position a camera above the team. This additional instrumentation will result in more data streams. While our in-house developed software could be modified, we will look for better software that can handle all of the tracks simultaneously and permit tagging within the streams.

Finally, we believe that several of the ABET criteria can be studied from the same data set, including: an ability *to design a system, component, or process* to meet desired needs within realistic constraints such as economic, environment (criterion 3b);" "an ability to *function on multi-disciplinary teams* (criterion 3d);" "an ability to identify, formulate, and *solve engineering problems* criterion 3e;" and *an ability to communicate effectively* (criterion 3g)".

In the future we intend to study several of these issues using a cross sectional study of engineering and engineering technology students. We are also considering examining the optimal time for teamwork, studying the improvement over time so team-based performance, and comparing engineering student performance to expert teams.

Bibliography

[1] Atman, C. A., Cardella, M., Turns, J., and Adams, R. (2005). Comparing freshman and senior engineering design processes: An in-depth follow-up study. *Design Studies, 26* (4), 325-357.

[2] ABET Engineering Accreditation Commission (2005, October 29). 2006-2007 Criteria for accrediting engineering programs. Retrieved May 15, 2006, from http://www.abet.org

[3] National Academy of Engineering (2004). *The engineer of 2020: Visions of engineering in the new century.* Washington, DC: National Academies Press.

[4] National Academy of Engineering (2005). *Educating the engineer of 2020: Adapting engineering education to the new century*. Washington, DC: National Academies Press.

[5] Shuman, L., Besterfield, M., and McGourty, J. (2005). The ABET "Professional Skills" – Can They Be Taught? Can They Be Assessed? *Journal of Engineering Education, 94*(1), 41-55.

[6] Leenders, R. Th. A. J., van Engelen, J. M. L., and Kratzer, J. (2003). Virtuality, communication, and new product team creativity: A social network perspective. *Journal of Engineering and Technology Management*, *20*, 69-92.

[7] Seymour, E. (2001). Tracking the processes of change in US undergraduate education in science, mathematics, engineering, and technology. *Science Education, 86*, 79-105.

[8] Cooke, N. J., Salas, E., Cannon-Bowers, J. A., & Stout, R. (2000). Measuring team knowledge. *Human Factors, 42*, 151-173.

[9] Brannick, M. T., Prince, A., Prince, C., & Salas, E. (1995). The measurement of team process. *Human Factors, 37*, 641-651.

[10] Entin, E. E. and Serfaty, D. (1999). Adaptive team coordination. *Human Factors, 41*, 312-325.

[11] Schmidt, L. C., Schmidt, J. A., Smith, P. E., Bigio, D. I., and Contardo, J. B., (2005). *BESTEAMS (Building Engineering Student Teams Effectiveness and Management Systems): A Curriculum Guide for Faculty.* Knoxville, TN: College House Enterprises.

[12] McGourty, J. & De Meuse, J. (2000). *The team developer: An assessment and skill building program: Student guidebook.* New York, NY: John Wiley & Sons.

[13] Montgomery, H., & Svenson, O. (1989). *Process and structure in human decision making*. Chichester, Great Britain: John Wiley & Sons.

[14] Faerch, C., & Kasper, G. (Eds.) (1987). *Introspection in second language research*. Clevedon, Great Britain: Multilingual Matters.

[15] Laszlo, Jr., Meutsch, D., & Viehoff, R. (1988). Verbal reports as data in text comprehension research: An introduction. *Text, 8*, 283–294.

[16] Deffner, G. (1990). Verbal protocols as a research tool in human factors. *Proceedings of the Human Factors Society, Santa Monica, CA, 2*, 1263-1264.

[17] Stempfle, J. and Badke-Schaub, P. (2002). Thinking in design teams - an analysis of team communication. *Design Studies, 23*, 473-496.

[18] Atman, C. J., Chimka, J. R., Bursic, K. M., and Nachtmann, H. N. (1999). A Comparison of freshman and senior engineering design processes. *Design Studies, 20*(2), 131-152.

[19] Chira, C., Chira, O, & Roche, T. (2005). Multi-agent support for distributed engineering design. *Lecture Notes in Artificial Intelligence (Subseries of Lecture Notes in Computer Science), 3533*, 155-164.

[20] Cross, N., Christiaans, H., Dorst, K. (eds.) (1996). *Analysing Design Activity*. Chichester, UK: John Wiley & Sons.

[21] Bransford, J., Brown, A. & Cocking, R. (2000). *How people learn: Brain, mind, and experience and school*. Washington, DC: National Academy Press.

[22] Dwarakanath, S. and Blessing, L. 'Ingredients of the Design Process: A comparison between Group and Individual Work', in N. Cross, H. Christiaans and K. Dorst (eds.), *Analysing Design Activity*, John Wiley & Sons Ltd., Chichester, 1996, pp. 93-115.