AC 2009-928: ORGANIZATIONAL LEADERSHIP AND EFFECTIVE TEAM PROBLEM-SOLVING STRATEGIES IN ENGINEERING DESIGN PROJECTS: A CASE STUDY

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Organizational Leadership and Effective Team Problem Solving Strategies in Engineering Design Projects: A Case Study

Abstract

This project presents a case study examination of the problem solving strategies and discourse patterns used by members of an Engineering Capstone Design Team. In our study, a multi-disciplinary team of engineering educators from two institutions worked together to collect data and analyze results over the course of the Spring 2008 semester. The findings in this study represent the perceptions of team members documented through multiple measurement instruments including surveys, personal e-mail exchanges, written responses, and both personal and videotaped interviews throughout the design process. The perceptual data presents examples of effective and ineffective team problem solving communication strategies applied to an Engineering Capstone Design project. Collectively, we believe these findings document the opportunities found in integrating theories of Organizational Leadership into engineering education as potential problem solving benchmarks and assessment of communication in our engineering design student teams. Successful communication is facilitated by having clearly understood objectives, clearly identified individual roles, and a specified system of communication. Another critical aspect of all three of the aforementioned characteristics is the alignment of each team member's perception of the three characteristics; a concept found in Organizational Behavior theory. Another key point is that student perceptions and the requirements for the characteristics above change as the project matures. The study concludes with the finding that students' perceptions regarding the level of communication and work distribution in a group are integral to group alignment and agreement. Several recommendations are given that instructors can implement to facilitate accurate perceptions.

Introduction

As engineering educators, we understand the linkages between effective problem solving and communication strategies and overall group success. At the same time, we also acknowledge the inherent difficulties of attributing specific strategies between individual group members and the larger group's patterns of interaction. One method of identifying characteristics of effective and ineffective team communication strategies examines theoretical and instructional research findings from the field of Organizational Leadership.

Three basic foundations for effective problem solving interaction were determined and these were used to analyze the interactions between members of a six-person design team. Within these three foundations, one consistent characteristic is the role of individual perceptions related to shared team experiences. In other words, studies of Organizational Leadership assert that each student in a design team brings varying degrees of both content knowledge and communication strategies that affect how the individual perceives the project and other team members. An instructor's understanding of these characteristics is essential to modeling and promoting effective teams.

Our study integrates theories of Organizational Leadership, Engineering Education, and Educational Psychology to investigate our students' perceptions in relation to team experiences. With these objectives in mind, our study is guided by the following research questions:

> *How do team problem solving constructs of Organizational Leadership apply to team problem solving strategies in Engineering Design?*
>
> *How do team communication and problem solving strategies change at different points in an extended Capstone Design Project?*

Background

Group problem solving in any discipline is a complex process requiring individual knowledge, group knowledge, and successful communication of that shared knowledge to meet a stated goal. In the field of Engineering, solving problems effectively as a group participant is a critical component of both educational and professional success, yet little is known about the processes that take place among group members. In any problem solving activity, group members follow a continuous cycle of attempting to communicate ideas—through negotiation, discussion, argument, questions, and actions. At the same time, members must continually adapt and evolve with the introduction of new information and ideas. For example, just as individuals are navigating the anticipated social roles and expectations required for successful forms of communication as part of a group, they must also consider the strategies the group will use to transfer the content of the message. According to Hutchins, groups operate quite differently than individuals, and they tend to think, behave, and perform differently than individuals.[5]

As an example of this concept, Hutchins' likened groups to the crew of a large sailing vessel: it is impossible for any one crewmember to actually steer the vessel---there are crewmembers posted on the bridge of the ship, on the sides, and at the top to record visual information while other crewmembers monitor wind and weather conditions. Each crewmember contributes valuable navigational data from his/her point of reference that is then used to set and maintain the course of the ship. Hutchins describes the crewmembers, including the ship's captain, as a navigational team working together to pool resources and data for a common goal. Team success is a result of each crewmember's knowledge and his/her ability to communicate that knowledge to the collective knowledge of the group.[2, 5, and 6]

The parallels between Hutchins' example and group problem solving processes/communication strategies employed by members of a Capstone Design Team are significant.[5] First, this type of data is valuable because it provides insightful information of each group member's perceptions of group problem solving strategies as related to previous researchers' suggested characteristics, or "best practices," for effective team building. Additionally, this feedback conveys information across time, which then allows us to examine how individual perceptions change throughout the course of a lengthy design project. Combined, this information offers opportunities for engineering educators to examine, analyze, and understand students' perspectives and perceptions that may identify consistent areas of difficulty and/or gaps in students' use of effective communication patterns and problem solving strategies. As a result, it could be possible to obtain critical insight on problem solving processes at both individual and group levels. This study begins with a review of consistent findings from previous research in group problem solving that identify certain characteristics or "best practices", and is followed by a brief explanation of how individual perceptions influence the larger group. These findings are then applied in a case study format from the responses of a six-person group completing a Capstone Design Project over the course of two semesters in the Fall 2007 and Spring 2008 academic terms (data was only collected during the Spring 2008 semester). The study concludes with the finding that students' perceptions regarding the level of communication and work distribution in a group are integral to group alignment and agreement. Several recommendations are given that instructors can implement to facilitate accurate perceptions.

Characteristics of Group Problem Solving Processes

Examinations of recent research findings describe a progression that takes place as groups are formed and develop. Tajfel and Turner refer to this process as social identification where members see their team as more important than their individuality.[7] The primary vehicles for this socialization are communication and group problem solving strategies. Communication patterns found in engineering design groups suggest that effective groups adopt an intricately-connected web of both cognitive and social interactions.[1 and 6] Recalling the navigational example presented in the background, each group member brings a combination of technical knowledge and cognitive skills to the larger group.[5] Other researchers have made similar assertions that groups develop their own problem solving processes that are distinct from individual group members' problem solving processes.[3 and 9] Generally, these group processes are superior to those of the individual members.

> *When teams listen to divergent viewpoints, they tend to find more and better strategies for solving problems--and to arrive at better solutions—compared with teams in which members listen to the majority view.*[7]

The above quote could be extended by replacing majority view with an individual view. As teams progress in their development they begin to develop a syntality, which is essentially a team personality. However, "you can't add up the personalities of each member and come out with the team's syntality; the whole is much more than the sum of its parts."[7]

Critical Characteristics for Engineering Design Groups

For the purposes of this study, we have limited examination of problem solving strategies and communication skills to those most relevant to Engineering Design problems. More specifically, we have focused on three characteristics consistently identified as essential components for effective group problem solving: (1) shared, clearly understood group objectives, (2) clearly identified individual roles, and (3) clearly specified systems of communication.

Shared Clearly Understood Objectives:

One of the most critical characteristics of teams is the requirement for a common understanding of a team's purpose and overall objectives. All team members must have an understanding of the design problem and the desired outcome or product. However, this does not mean that all group members must envision the exact same solution to the problem. They just need a common understanding of the key design requirements. If it exists among team members, dissonance indicates a lack of communication and prevents work toward a common goal.

Clearly Identified Individual Roles:

Design teams take the common problem and break it into manageable portions. Team members are assigned tasks and are given responsibilities. Increasingly, engineering design teams are multi-disciplinary and, as a result, task distribution is facilitated. It is at this point that individual accountability becomes important as each member has a direct, individual input to the overall team success. If one member of the team fails to accomplish assigned tasks, then team alignment and motivation will decrease; other team members will have to work harder. This further reduces morale and cohesion in the team.

Clearly Specified System of Communication:

> *Effective communication is difficult in any setting…part of the challenge revolves around the communicative behaviors and misbehaviors of team members. <Team leaders> who led successful…teams related that they learned, from prior experience, to quickly establish some ground rules for how the team would communicate.*[4]

Teams must specify early in their formation what system they will use for communication. The system should include all aspects of team interaction. Frequency and location of meetings, data storage and transmission means, e-mail rules, and reporting responsibilities are just a few of the topics that must be addressed.

<u>Perceptual Characteristics in Engineering Design Groups</u>

All three of the aforementioned characteristics are susceptible to individual perceptions. Perception is defined as "the process of receiving information about and making sense of the world around us".[8] In problem solving, processes of perception are related to "mental models" that each member brings to the larger group. Perception involves both cognitive and social processes. Information from an individual's "mental model" represents a form of cognitive data, much like a folder within the individual's internal knowledge bank is representative of previous experiences and lessons learned from similar experiences. These lessons learned also represent the social component of perception through the individual's continual process of assessment and evaluation of situational results through a series of decisions. The cognitive portion of perception stores conceptual knowledge while the social portion makes sense of results through a more subjective process of attribution that establishes a cause and effect relationship.

Methodology

The methodological approach of this study was designed to elicit team members' perceptions of shared team experiences through a mixed-method research approach. External assessment data collected via (1) informal e-mail exchanges between the researcher and each team member; (2) direct observation of team members during the design phase followed by direct interviews with individual team members for additional clarification; (3) a brief questionnaire completed by each team member immediately following completion of a project milestone; (4) individual video-taped reflective narratives recorded 2-3 days following the project presentation. The research was conducted with a cohort of students from the United States Military Academy's Mechanical Engineering Department.

The data was collected at three specific time points. The Introduction point occurred in January 2008 as the class began. It happened in conjunction with an in-progress review during which students gave a status of their project to the mechanical engineering faculty in a formal setting. The second point is referred to as the High Stress point. This corresponded to the week before the project was to be demonstrated in support of the United States Military Academy's projects day. Students had to prepare a display poster, generate and deliver a technical briefing detailing their application of the engineering design process, and complete the physical construction of the project. The name of this data point was due to multiple requirements in a relatively short time period and observed student reactions. The final data point was the Retrospective point. This was a video taped interview where students were asked to reflect on their design experience and comment on learning in general and their project in detail. This occurred during the last week of the semester approximately one month after projects day.

Participants

Data for this study was obtained from undergraduate engineering students enrolled in ME496 at the United States Military Academy during the spring of 2008. ME496 is a required course for all mechanical engineering students, and must be completed successfully for graduation. Capstone design projects include problem solving and teamwork skills, and are designed to reflect the types of activities and situations students are likely to face as professional engineers.

Procedures for Data Collection

Data was collected through a mixed-method approach and each method had a slightly different procedure associated with it. The educational psychologist conducted the majority of the data collection to prevent a perceived bias on the part of the students. Had any of the engineering faculty members directly taken the data, students may have felt the need to adjust their feedback due to a desire to influence project grading. For the informal e-mail collection, the educational psychologist contacted the students directly and assembled the feedback. The direct observation was conducted by all three researchers and the follow-up interviews were conducted informally by the educational psychologist in a one-on-one question and answer format. Students were simply pulled aside and asked to clarify their thoughts and actions based on observed behavior. The questionnaire was developed by the educational psychologist and was distributed with an envelope to the students by one of the engineering faculty members. The students completed the questionnaire and sealed it in the envelope. The questionnaires were then delivered to the educational psychologist. Finally, the individual video-taped reflective narratives were taped using a personal camcorder by the students themselves. This was an assignment for the course and was performed by several other groups as well. The narratives were assembled and analyzed by the educational psychologist as described below.

Procedures for Data Analysis

Students responded to three prompts through different methods. The student feedback was evaluated using a dual-categorization rating. The short answers were examined to extract perceptual data in each of the critical characteristics for engineering design groups:

- Shared Clearly Understood Objectives
- Clearly Identified Individual Roles
- Clearly specified system of communication

Text was then coded as positive or negative to indicate individual group members' degrees of alignment and/or agreement in each characteristic. Compiled findings were examined for potential trends and consistent themes which could suggest potential areas of instructional intervention.

Findings

Table 1 shows a compilation of the data. The first value in each two-number set indicates the number of positive replies and the second number in each set indicates the total number of samples reported. For example, the high stress data point had two positive responses reported out of six total responses as indicated by a "2/6" for the second characteristic regarding individual roles. An ideal score showing that all group members were in alignment and agreement would be represented by a "6/6". Additionally, the prompt is the stem showing the common beginning of each statement. The table also shows how the responses changed over the course of the project as the three data points are arranged chronologically from left to right.

Table 1: Characteristics of Effective Team Problem Solving Communication

Characteristic	Data Points		
Prompt: I believe our group has a….	Intro-duction	High Stress	Retrospective
Shared, Clearly Understood Objective	6/6	6/6	6/6
Clearly Identified Individual Roles	5/6	2/6	2/6
Clearly Specified System of Communication	6/6	2/6	3/6

Characteristic 1: Shared Clearly Understood Objectives:

The results presented in Table 1 indicate that all team members shared and understood the project's objective at all three data collection points during the project. Excerpts supporting these findings from the team members are presented in Table 2.

Interpretation - Characteristic 1: Shared Clearly Understood Objectives

These data points were collected from team members at the introduction point of this study, and the responses indicated that all team members shared and clearly understood the project's objective. Similar responses were reported at the high stress point and the retrospective points of data collection. This indicates that students had a high degree of alignment in understanding their design problem and adjusted their individual perceptions and understanding as the design progressed and changed and were able to maintain this alignment over the course of the semester.

TABLE 2: Excerpts from Team Member Responses for Characteristic 1.

Prompt: Explain the objective of your capstone design project			DATA COLLECTION POINT		
GROUP MEMBER	GROUP MEMBER RESPONSE	RATING	INTRODUCTION	HIGH STRESS	RETROSPECTIVE
1	*To create a highly mobile, extremely realistic looking M1A1 Spirit Tank that will be able to drive into athletic events and fire T-shirts out of the main gun in an attempt to raise Corps morale and overall unit pride.*	+	X		
2	*Our mission is to design a realistic-looking Spirit Tank to replace USMA's existing Spirit Tank.*	+	X		
3	*To replace the existing, retired spirit tank with a more functional modern one with improved vehicle performance, rigidity, and realism.*	+	X		
4	*The mission of the Spirit Tank Team is to design and develop a motivational vehicle, resembling an M1 tank.*	+	X		
5	*The objective of our group has been to create scale model of an M1 Abrams that would look realistic and hold up to many years of use.*	+	X		
6	*The objective of our capstone is to produce a spirit vehicle that will motivate and inspire the Corps of Cadets for the next several years.*	+	X		

Characteristic 2: Clearly Defined Individual Roles

The data presented in Table 1 indicate that team members expressed differences in their perceptions of clearly identified individual roles for group members as the project developed. Excerpts of these differences are shown in Table 3 below.

TABLE 3: Excerpts from Team Member Responses for Characteristic 2.

Prompt: I believe our group has clearly identified roles			DATA COLLECTION POINT		
GROUP MEMBER	GROUP MEMBER RESPONSE	RATING	INTRODUCTION	HIGH STRESS	RETROSPECTIVE
1	*Only 2 of our team members worked directly on the poster and that is because of our effort to finish the final fabrication of our tank by the deadline. However, this was intentional, and our team works very well.*	+		X	
2	*The team was initially divided into three main categories, three pairs to make it shoot, move, and look real. Amit and Adam were in charge of the vehicle, John and Rob took over the Cannon, and Mike and I took realism and the body.*	+		X	
3	*Our work can be divided into two distinct phases: design and manufacture. Several members of the group knew what they were supposed to do, but had trouble maintaining focus during the design. However, those same members have had some of the greatest contributions since we started building our product.*	-		X	
4	*When we began the project, we broke down the work into three subsystems and assigned a team to work on each one. This worked pretty well for the design part, but it hasn't really continued through the build portion. We've all been working on whatever needs to be done to try to keep the project moving. Everyone does everything. Work was not truly equal, but it's okay.*	-		X	
5	*Initially each member had clear roles, but as the project has grown in complexity, each person pitches in as needed to complete the overall job, regardless of role*	-		X	
6	*During the project planning stage, we divided the project into separate parts so that everyone could work on something or some part that he was experienced with, but we had some problems getting everybody to work together yet separately. This is evident by the fact that work on the tank has not been equal.*	-		X	

Interpretation - Characteristic 2: Clearly Defined Individual Roles

For a more accurate interpretation of these findings, it should be noted that only five group members responded directly to this prompt at the introduction data collection point, therefore, the missing member's response was reported as a negative response. If this member's failure to address the prompt were to have been reported as N/A, all other group members (5/5) expressed positive responses. It should also be noted that all group members responded to this prompt at the other data points.

The team members' responses to the same prompt at the high-stress data point suggest some perceptual shifts. Only two of the six group members responded that distribution of roles was balanced. Of the four members who reported imbalance, two further noted that completion of equal amounts of work was secondary to completing the overall task (Group Members 4 and 5). Although the excerpted data in Table 3 was collected at the high-stress point of the project, it is interesting to note that these values were unchanged at the retrospective data collection point. Unlike the high-stress data point values, the negative responses from group members at the retrospective data point did not contain additional qualification or explanation. This disparity strengthens the suggestion that at the conclusion of the project, just two of the six group members reported clearly identified roles.

Characteristic 3: Clearly Specified System of Communication

The data presented in Table 1 indicate that team members also expressed differences in their perceptions of a clearly specified system of communication as the project developed. Excerpts of these differences are shown in Table 4 below.

Interpretation - Characteristic 3: Clearly Specified System of Communication

The group member responses related to the team's system of communication again indicated perceptual shifts. All group members indicated agreement at the introductory point of the project, but just two of the six group members indicated agreement at the high-stress data point. At completion of the project, the retrospective point responses suggested another slight perceptual shift, with three of the six members indicating agreement. However, the information for this last data point was collected via videotaped interviews in which students answered pre-established questions about the overall Capstone Design Project. In addition to the change in the method of data collection, there also may have been an element of peer pressure associated with these findings; other group members were seen working in the background of the videotapes. The interview for group member six, though, was filmed in a different location and he was fairly strong in his negative feedback. This would seem to discount the slight rise in positive comments from 2/6 to 3/6 between the high stress and retrospective data points. Regardless, similar to characteristic two, there was a significant drop from the introduction data point for characteristic three.

TABLE #4: Excerpts from Team Member Responses for Characteristic 3.

Prompt: I believe our group has a clearly identified system of communication			DATA COLLECTION POINT		
GROUP MEMBER	GROUP MEMBER RESPONSE	RATING	INTRODUCTION	HIGH STRESS	RETROSPECTIVE
1	*…the teamwork aspect of the project has been one of the most challenging. We communicated often, but not effectively about team goals and without a clear sense of how everything fits into the building process.*	-			X
2	*We coordinated to schedule our work around our other activities, but essentially, I pulled the night shift, and Amit pulled the day shift. There <was> some disconnect <when> no one seemed willing to work at the times I prompt them.*	-			X
3	*Group work is fun. We're all cadets, friends, <and> professional leaders. We communicate often and we are looking forward to graduation.*	+			X
4	*When you work in a team on a project as big as this one, you've got to work together and talk to each other or the project will never get finished. We finished.*	+			X
5	*Communicate? Well, we got things done, if that's what you mean.*	+			X
6	*We probably should've communicated more. Maybe once a week at least. With our group, this would be similar to pulling teeth because most of the time, we just can't sit still for more than 10 minutes. It would be hard to have everyone sit down for about an hour and not only discuss but also write down/illustrate a plan….*	-			X

<u>Summary</u>

Case study findings indicate higher degrees of group alignment and agreement in the strongly cognitive characteristic of a common project objective and lower degrees of group alignment and agreement in the more socially dependent characteristics of role distribution and communication. Additionally, the characteristics of role distribution and communication saw a significant decrease in alignment over the life of the project with the lowest alignment during the high stress data point. The group began the semester with a high degree of alignment in all three characteristics.

Ideas for Future Studies

If this same study is repeated, the researchers recommend that the second prompt, relating to role distribution, be divided into two related prompts. The responses indicated a need to ask the questions:

- Were clearly defined individual roles specified?
- Did the group adhere to these roles throughout the duration of the project?

As it is currently worded, the second prompt was unclear and may have increased the difficulty of classifying/categorizing responses as positive/negative. Changing the prompt as recommended would increase reliability.

Another topic for further research would be to expand the case study to investigate perceptions in multiple groups which would reduce the potential that the issues discussed were project related. In addition, numerous comments were recorded regarding the leadership of the group. The study could be expanded to include a leadership focus as this topic is already discussed in the data from the reflective essay with the question of, "How will this project make you a better leader as a lieutenant in the United States Army?" The concept of communication is central to leadership and the study could investigate the interaction between student leadership and student perceptions.

Recommendations

One key point underscored through this research is that student perceptions play a large role in determining group alignment and agreement. Of the three characteristics: shared clearly understood objectives, clearly identified individual roles, and clearly specified system of communication; the first one is strongly cognitive while the other two are more socially dependent. The last two are the primary indicators of group misalignment and instructors need to be aware of these factors. It is important to note that attribution plays a key factor in the social processes related to perception. How students assign responsibility for errors and difficulties is important.

To facilitate correct perceptions, design project advisors need to ensure that groups plan a detailed communication strategy as early as possible and then either adhere to it or adjust it, as necessary, as a group. One method to ensure this is to make it a graded requirement and force the group to redo incomplete or illogical communication plans. This avoids miscommunication and the erroneous perceptions that generally result. Faculty can address the second characteristic by assigning individual grades and monitoring students' level of participation. These actions are important to ensure that students perceive that work is fairly and equally rewarded. A final design experience is a common facet in most engineering programs and it is incumbent on instructors to prepare students to enter the engineering profession as confidently as possible. Additionally, since the design experience is the usually the final step in an engineering curriculum, it will be the one that is remembered.

Regarding the current case study, the design team experienced reduced alignment with regards to perceptions of work distribution and communication within the team. This reduction accompanied a pattern of reduced effectiveness and wasted time. Had the instructors forced the team to periodically reevaluate their communication and work assignments, and given the individual team members an outlet to express perceptions, this could have been prevented. One of the key points discovered from this investigation is that the perceptions of team members are as important as reality to effective problem solving, if not more so. Given this, instructors should have a plan to measure this aspect of team dynamics.

Faculty should ensure that periodic assessments are included as the project matures and develops, as what worked in the beginning may be completely misinterpreted as the semester develops. This is facilitated when students are required to break their project into distinct phases and each phase is evaluated to determine work distribution and communication requirements. The design portion of the project will have distinct differences as compared to the build portion or the testing and refinement phases. Perceptions should be measured at each phase to see how well group alignment is being facilitated.

Conclusions

The design team in the case study was ultimately able to complete their project on time and had an impressive performance at the projects day presentations. The vehicle functioned as designed and had the majority of the desired subsystems installed. However, the project lacked one primary subsystem and had numerous refinements that had been identified which were not able to be implemented due to time constraints. Greater team alignment could have prevented this.

As seen from Organizational Behavior theory, the problem solving process is facilitated when the design team has clearly understood objectives, clearly identified individual roles, and a specified system of communication. Additionally, the student's perceptions of how well these characteristics are being met will influence the success of the team.

Finally, instructors can and should monitor teams and determine ways to measure individual team member's perceptions in order to give feedback to the team and make necessary adjustments. Learning to apply the engineering problem solving process in a final design can and should be the most rewarding part of an undergraduate engineering student's education. The case study team had great things to say about the experience but it was tempered with some regret that might have been avoided with additional faculty intervention.

The engineering design processes used by engineering students in problem solving situations can be a source of professional development and an introduction to a career as a practicing engineer. At the same time it also can be an extremely frustrating experience that can leave a graduating student with a poor impression of problem solving. In this study, the framework's design of dual-categorization made it possible to examine problem solving processes at individual and group levels, and to identify areas of strengths and weaknesses that occurred consistently at specific points in the problem solving process. Such information also supplements the body of knowledge and increases understanding related to the types of problem solving processes and communication strategies present in all problem solving groups. With this information, it is possible for engineering educators to design appropriate instructional interventions to promote and support more effective types of group problem solving processes for individual group members and for groups themselves.

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