Framework for Organization and Control of Capstone Design/Build Projects

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Abstract

Senior design capstone projects frequently require team members to self-organize for a project and then execute the design/build portion with limited resources. This is challenging for inexperienced students who struggle with technical as well as program management and team building issues. This paper outlines a general framework that can be used by students and faculty advisors to outline goals and objectives and to facilitate communication among team members. It outlines how students set the team goal and organize the project to ensure team members fully understand their contributions and major performance objectives. Once performance objectives and individual responsibilities are fixed, team members can use the framework as a guide to design and build the project. Since each team member has a vested interest in the overall project, program management is aided. Faculty advisors can also use the framework to mentor students and evaluate student performance for grade assignment. A case study for a large multi-discipline project that spanned a two-year design/build period is provided.

I. Introduction

Senior design capstone projects frequently require team members to self organize and then execute the design/build portion within a resource-constrained environment. This is usually challenging for inexperienced students who are struggling with technical as well as program management and team building issues. This, coupled with the adoption of Engineering Criteria 2000[1] and the requirement to work on interdisciplinary teams, makes projects even more challenging.

There also appears to be a general lack of ability by students to function on teams.[2,3] We agree with Lewis et al.[4], that engineering faculty cannot afford to take a chance to leave team building processes to students without some guidance. It is also not enough to give students a conceptual model of teaming skills, such as presented by Carley.[5] Students are unable to translate these skills into practice. They are simply overwhelmed and often do not have the proper background for building effective teams. In general, it has also been our observation that students do not learn a great deal from a project that has failed miserably. This is not to say that students should not be allowed to fail, only that a dismal failure (especially if due to lack of organization) is usually accompanied by less learning. The goal then, is to focus students so that they learn from their projects, without specifying the tasks that must be accomplished or structuring their project as in a traditional classroom environment. Teams are more successful if they develop their own goals.[6]

Teaming skills can be improved through the use of a structured framework using a Team Process Document (TPD), which is a general document that can be used by students and faculty advisors to outline goals and objectives and to facilitate communication among team members. When used properly it provides a method that facilitates good teamwork and organization. It is not a stand-alone method for developing good teamwork, but assists in developing the well-established and essential components of a successful team.[7-10] This paper will present an example of how this process contributed to the design, build and competition of a solar powered car; a large multi-discipline project that spanned a two-year period.

II. Teamwork on Student Projects: What Makes An Effective Team?

Many books and articles have been written on teamwork in industry, business, and education.[11,12,13] It is however, useful to briefly review some of the key elements of teamwork and the qualities that make an effective team. Katzenbach and Smith define a team as "a small number of people with complementary skills who are committed to a common purpose, performance goals, and approach for which they hold themselves mutually accountable."[14] Effective teams must have a clear and measurable goal, be able to communicate both within and outside the team, structure themselves to utilize individual strengths, and be committed to each other and the team.

A. The Goal

In order for a team to succeed, they must have a clear goal that is attainable, specific, and measurable. Without concisely describing the goal and listing performance objectives in such a way that it can be clearly shown if they have been achieved,[15] the success of the team is unlikely. In fact, research conducted by Larson and LaFasto found that in every case of an effective team, members felt the team had a clear understanding of the team goal. Additionally, they found that in every ineffective team, without exception, the reason for failure was in some way related to the goal.[16] Specific goals help a team assess their performance and track their progress. A team should write a clear statement of their goal and purpose[17] and then continue a refinement of the goal and objectives through the life of the project.[18]

However, having a clear goal in and of itself is not enough to ensure the success of the team. The goal must be specific, challenging, reasonable, and measurable so that one can tell when it has been achieved. If, for instance, one wants to lose some weight, they are far more likely to be successful if they set a reasonable goal. Someone who sets the goal of losing ten pounds in the next three months is far more likely to be successful than the poor soul who merely says they want to be thinner. Katzenbach and Smith tell us that desire for performance is essential to the success of a team and that without this desire, the team is likely not to form.[19] For this reason, a goal that can be broken into small, measurable successes is essential to the team. It allows them to quantify their achievements and gives them the motivation to continue their efforts. Additionally the more involved team members are in the planning strategy for goal achievement, the more motivated, involved, and committed team members become.[20]

B. Communication

Team members must be able to communicate effectively, not only to each other, but to the outside world as well. The whole premise of a team is that their work is interdependent and without communication, efforts are misplaced, work is duplicated or wasted, and eventually team members are discouraged. Thompson[21] gives numerous examples where hundreds of lives and millions of dollars were lost because teams failed to communicate clearly. Part of the communication process among team members is the iteration of the goal and the steps for achieving it.[22] Team members must communicate to each other on a continuing basis their individual efforts and progress. They also must keep their faculty advisor apprised of the status of their project for evaluation and redirection. Without constant and clear communication the team is unlikely to succeed.

C. Structure and Organization

In assigning people to fill positions, groups are often faced with determining the best role to place individuals. In the workplace, one can pick team members based on their technical expertise or skills. However on student teams, this isn't an option and it is important to place team members where they not only utilize their strengths but also improve their weaknesses by learning from their fellow teammates. The selection of team members is a crucial part of team building, and how students are assigned to capstone teams is a problem that nearly every program struggles with. Brickell et al.[23] investigated five team-organizing techniques and concluded that assigned groups perform better than self-selected groups. They also found that groups with a wide range of GPAs, but with similar interests, performed most consistently, achieving the best results. The type of team you are building largely determines the role of individuals. According to Larson and LaFasto,[24] the "tactical" team model best describes the design team. In tactical teams, the goal and the steps to achieve it must be unmistakably clear. Each individual must be aware of their role and the tasks for which they are responsible. Tasks should be clearly defined utilizing operational standards. The structure of the team should emphasize execution and achievement of the goal.

When selecting leaders for the tactical team, it is best to select individuals who not only possess the technical skills to understand the goal and the required steps to get there, but those who are best suited for dealing with others. The team leader will need to be able to see the big picture, organize the project into discrete steps, and follow-up with subordinate team leaders and team members. This person should be the one with the best interpersonal communication skills.

Subordinate team leaders should be individuals that are task oriented. They need to be technically competent and detail oriented. They should be able to communicate task requirements to other team members, monitor achievements, and reassess the steps to achieve their intermediate goals. They also need to be able to determine when to ask for assistance.

III. Team Project Document – Purpose and Process

A. Background

The Team Project Document (TPD) is a simple written document that promotes two-way communication and helps to focus a team on meeting the project goal and objectives. It is useful not only to students, but also to their faculty advisor. It provides a framework in which students can self-organize, communicate and best utilize individual talent of team members. Providing the framework to students is the equivalent of showing them an example problem. Faculty advisors can teach the theory, but it is the example problem that students can grab onto. It facilitates all of the previously listed elements required for a successful team. Additionally, it can be used as an evaluation tool by faculty to help in advising and grading team performance.

The TPD is modeled from the US Army's Officer Evaluation Report Support Form (OERSF);[25] which was designed to foster the communication process between senior and junior officers. It aligns the goals and objectives of the unit with those of the individual. The OERSF is a form that gives the junior officer the opportunity to list their own goals and objectives, with input from their senior officer. It was derived[26] from the management principles described in Odiorne.[27] The outcome of the OERSF is twofold. First, it gives the junior officer a clear understanding as to his or her individual duties and organizational mission as well as promotes performance and career counseling by the senior officer. Secondly, the senior officer uses it to rate the performance of the subordinate officer. The officer performance rating is the primary tool used by the Army to determine promotions and advancement.

Implementation of the OERSF is a three-step process. The initial step is for the junior officer to initiate an OERSF by listing the significant duties and responsibilities of their job (the goal). Usually, the senior officer aids them in this process by providing them with his or her own support form. The junior officer also lists their performance objectives, the process by which they plan to accomplish their duties and responsibilities. Once the junior officer has completed the OERSF, they meet with their senior officer to discuss and amend the form until they agree on its content. Once the OERSF is completed, the junior officer uses it throughout the year to guide him or her as to what they must accomplish. Finally, at the end of a performance evaluation period, the subordinate officer completes the OERSF by listing their major accomplishments and passes the form to the senior officer. The senior officer can then use the form as input for evaluating performance.

B. Student Use of the Team Project Document

The TPD process parallels that of the OERSF but starts with the team leader providing a top-down copy of a TPD to fellow team members. In this document, the team leader provides vision for what is to be accomplished and sets intermediate goals that should be met. The team leader's job description and major performance objectives should be included. If we use the Sunrayce project as an example, the team leader's duty description may include responsibility for coordinating the design, build, test, and logistical phases for building a solar car. For a race that is to be conducted in June, the team leader may envision major milestones such as having an operational car by February to allow for four full months of testing and re-design. The TPD may also include the team leader's plan for organization of sub-teams to complete major tasks, such as a suspension team or power team. This is shown as process step 1 in Figure 1.

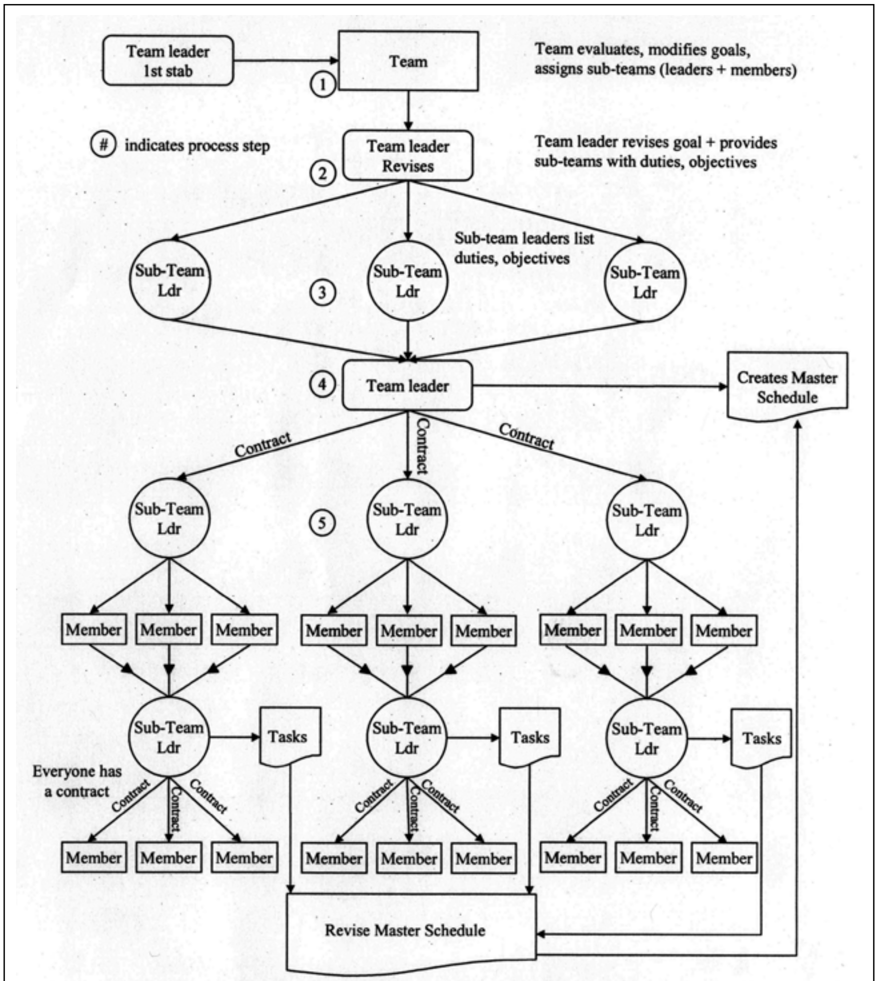

Figure 1. Team Process Document flow chart

Subordinate team members review the leader's TPD and assess their vision and milestone schedule. Using this as a starting point, the team can discuss and modify the vision and team composition to facilitate the greatest opportunity for project success. This step would not be required in most professional organizations because the CEO or in the case of the military, the senior leader, has the experience to set a vision. Students, in general, lack this ability. However, this additional step brings the team together early, gives them ownership in the team purpose, and allows them to set the level at which they expect to perform. This is usually a good point for the team to assign members to sub-teams and to determine who will be the sub-team leaders.

Once this feedback process is completed, the team leader revises the goal and provides subordinate team leaders an updated duty description and performance objective for completion of major tasks. This time the TPD provides a top-down emphasis on leadership communication to enhance planning and subordinate team performance. This is shown as process step 2 in Figure 1.

Armed with the TPD, subordinate teams can start planning their work for overall project success by writing their own duty description and major performance objectives (shown as process step number 3 in Figure 1). The sub-team leader, in charge of the front suspension team in the Sunrayce example for instance, lists his or her duty responsibility, the major tasks that must be accomplished and the time frame in which they must be done. It is at this time that the sub-team leader ascertains the details, to include deadlines, of what must be accomplished by that team. This is essentially a plan that will guide the sub-team effort. Team member responsibilities may also include items such as safety, contracting and acquisition, budget development and execution, information management, property accountability, and logistics. As with all plans, the more thoroughly they are crafted, the more useful they are as a guide.

Sub-team leaders return their duty descriptions and major performance objectives to the team leader (process step number 4 in Figure 1). This is not just a passing of a piece of paper, but must include a discussion that results in agreement of goals and tasks. Once completed, the sub-team leader's TPD becomes a contractual agreement for work effort. It is the responsibility of the team leader to use subordinate TPDs to develop a detailed master schedule, complete with resources required for project success. This method enables detailed planning without bogging down team leaders, allowing them to focus on the big picture, and not the details of sub-components.

Subordinate team leaders now repeat the process with team members at the next level in the team structure (process step number 5 in Figure 1). The sub-team leader provides his or her TPD to members who initiate their own TPDs, again listing their duty descriptions and major performance objectives. The process of goal setting and discussion and agreement is repeated. At the end of the process, every team member has a TPD, which becomes a contractual agreement for work effort. Figure 2, an example document taken from a Sunrayce '99 subordinate team leader,[28] shows the TPD between the team leader and the solar array leader.

As with the OERSF, the TPD can be used throughout the project's life to keep the project on schedule and for team members at all levels to assess project status. Both the team leader and sub-team leader use the TPD to assess progress and to insure adjustments so that ultimately the project is successful. The TPD may also be amended as students find better ways to accomplish the project, but caution should be taken so that they do not amend the document to lower standards or slip deadlines.

B. Faculty Use of the Team Project Document

By providing students with the TPD, faculty advisors can help them organize and give them a starting point. The TPD provides students the opportunity to break a huge goal into discrete manageable steps. Once the process

TEAM PROCESS DOCUMENT

Project Name: Sunrayce Solar Car	Date: June 11, 2000
Team Member: Joe Sunshine	Principle Duty Title: Solar Array Team Leader
Supervisor: Sally Solarcar	Position: Sunrayce Project Team Leader

a. State Your Significant Duties and Responsibilities

I am responsible for overseeing the activities of the solar array team and ensuring that all assigned tasks are met in a timely fashion. I am also to work within the budget provided to me and ensure that my work is coordinated with other teams to facilitate the operations of the solar car project as a whole. I will coordinate with the body and power team to ensure proper placement of cells on the car. My team's duties are to: Complete required technical analysis, manufacture and encapsulate solar cell strings, mount strings on body, assist in wiring strings into electrical system and test and troubleshoot the array.

b. Indicate Your Major Performance Objectives for Fulfilling Your Duties

- 15 Jan Design, match to other components and optimize the solar array for maximize power output.
- 31 Jan Finish encapsulation of 10-cell practice string, complete construction or selection of assembly site and techniques, complete gathering of necessary equipment and design test bed for cells
- 5 Feb Encapsulate first 20 strings, complete test bed, test first 20 strings.
- 12 Feb Encapsulate and test next 20 strings. Attach first 20 strings to body
- 20 Feb Encapsulate and test next 20 strings. Attach first 20 strings to body
- 26 Feb Encapsulate and test next 20 strings. Attach first 20 strings to body
- 6 Mar Attach another 25 strings to body, test modules
- 12 Mar Catch up week. Test all the cells if possible in sunny and cloudy conditions
- Spring Break 99 Super catch up week, if needed. Help other teams if necessary
- 31 Mar Make spare strings and encapsulate them all. Attempt to salvage damaged cells into strings.
- AprilTake data on array, attempt to optimize operating conditions, recharge position angle and determine best cooling method and affect of water spray. Assist power team (or any other team) as needed. Run the vehicle on the array's power. Charge the batteries with the array.

** Note, by mid-semester briefing, we will develop a timeline to meet the second semester tasks, but since most of them are dependent on the progress of other teams, we are unable to make a schedule at this point

c. List Your Significant Contributions

- Designed solar array to maximize power output for conditions expected during the race.
- Developed a device and a system to encapsulate all cells within the specified timeline.
- Developed a test procedure to test power output of solar array.
- Mounted cell strings to body and installed all wiring to power system.
- Troubleshot the electrical system from solar cells to power trackers. Assisted power team in troubleshooting motor controller problems.
- Met all deadlines for all aspects of the project.
- Adjusted battery voltages so that available energy storage was maximized.

Figure 2. Example Team Process Document

is underway, faculty advisors can use the TPD to monitor team structure, methodologies, and decisions. Although not formally a part of the TPD process, periodic review of the document can provide valuable insight of the thought process of students. It will assist faculty advisors in determining the questions that should be asked of students. It may also reveal design flaws that require early and immediate intervention for the sake of safety.

At the end of the project or academic period, the faculty must assign grades to students. The TPD provides objective input that might otherwise be missed. There are two reasons that the TPD is useful. First, faculty advisors do not rigidly structure capstone design courses and thus might not have a course syllabus to measure student performance. Secondly, when the TPD is completed at the end of the academic term, the students will list detailed accomplishments that may otherwise be forgotten by the advisor. This helps to insure credit is given where credit is due.

IV. The Sunrayce Competition

Sunrayce is a biennial intercollegiate competition to design, build, test, and race a car that is powered entirely by solar energy. The 1999 race covered 1,425 miles over a 10-day period (20-29 June), and ran from Washington, DC to Orlando, Florida. By design, it is meant to be technically challenging and to foster creativity in students. Cadets at West Point participate in this competition because the skills acquired as they learn to design, fabricate, test and race a vehicle are valuable to them when they enter a technologically advanced Army as lieutenants. The 1999 USMA Sunrayce Project utilized the Team Project Document as described.

V. Team Organization Using Framework

The TPD was used to organize the USMA Sunrayce team. The process started when the team leader developed and then distributed a TPD for subordinate members. This was provided to the entire team as a vision for goal setting. The team evaluated and further developed team goals for the project as described in step 1 of the process.

At this point sub-teams were formed and sub-team leaders were assigned. Even though Brickell suggests assigning teams, the USMA Sunrayce students were allowed to self-organize so as to further develop team bonding. As is common in team selection, students used a method that balanced the interests of individuals, perceived competencies in specific areas, and thought as to how the project would be completed.

Ideally, strong team members should be placed with weaker ones, but this does not always happen with student projects. In the case of the USMA Sunrayce team, students did assign strong and weak team members to work together. Faculty advisors were somewhat surprised to find that in some instances students placed weaker team members in the role of team leaders. When asked why they organized as they did, students were candid in pointing out that weaker members would be forced to work and be involved if placed in a leadership role. They felt that had they placed strong team members in charge, weaker members would have let them provide leadership as well as most of the work. The students instinctively knew what research has determined: when workload is distributed among team members, both teamwork and productivity increases.[29]

Once team members were selected and modified goals were established, the team leader revised the team goal and provided the team an updated TPD complete with objectives. With an updated TPD, subordinate team leaders set their goals and map the goal to specific tasks (step 2 of the TPD). The team leader then used those tasks to develop a master schedule for all to use. The process was iterative. On the first try, they included every step, but provided insufficient detail to make a working plan. The lack of detail in part stemmed from a lack of knowledge of how they would complete each step of the project. As they soon realized a plan without detail results in no plan, they formalized their TPD twice more to get a working product. Although they still lacked detail, they had enough to start. A master schedule was posted on the team room wall to keep everyone abreast of where they were in the process. Each student was responsible for keeping his or her portion of the project updated. Updating the master schedule not only provided an efficient way for members to keep the team apprised, but for team members to receive updates on overall project status. The master schedule updating is merely another format for filling out block c of the TPD. It helps students and faculty advisors to assess project status and insure that objectives are obtained.

VI. Team Dynamics As The Project

Progressed

Assessments made by the team and faculty members repeatedly concluded that the team was functioning as well as possible. The 1999 USMA Sunrayce Team motto "If it does not matter who gets the credit, we can accomplish anything" exemplified their team focus and commitment to each other. However, the best-laid plans can fall aside and earnest attempts to stay on schedule can still fail when team leadership is inexperienced. This was the case with the USMA Sunrayce project. With the detailed timeline and plan provided by the TPD, students realized early on that they were falling behind schedule and tried to commit more of their time to working on the car. However, the West Point system is very structured and cadet activities are minutely planned. Cadets are told when to awake, when they will eat, and are required to attend all classes. Neglecting another class to work on the car was not an option. Since they couldn't 'rob Peter to pay Paul' they realized they would have to commit their highly valued free time to get back on schedule. This would require a much greater commitment than any student project had formerly demanded. The greatest evidence of team cohesion was when over 50% of the team forfeited their spring break to work on the car. While classmates were basking on beaches, team members were sleeping in the garage on army cots to work on "Christine." No team at USMA had previously done this and their selfless acts certainly demonstrated their commitment to each other and the team.

The TPD certainly did not eliminate all problems. For example, one team member had a small but critical portion of the overall project and insisted on completing it alone. His inability to stay on schedule nearly caused the entire project to slip even further behind and the rest of the team questioned his competence. According to Larson and LaFasto[30] teams who lose trust in one another are diverted from the team goal. This indeed led to uneasiness among team members. The team struggled to determine if and when it was appropriate to take over the task of the headstrong student for the overall good of the team. As it turned out, the lone cadet was able to complete his section of the project in time and the team was not tested on this issue.

VII. The Actual Race

The race was held two weeks after the end of spring semester and after the team senior leadership had graduated. At most universities, senior team leaders would be expected to guide the team through the remainder of the race. However, at USMA, seniors are commissioned upon graduation and are given only a short break prior to entering military service. For that reason, the team leadership was changed prior to attempting qualifications and the race itself.
Changing leadership at such a critical point in the cycle caused considerable problems for the team. Although exceptions exist, studies show that success of team performance covaries with the time a team has trained together (i.e. a stable team lineup has a positive covariance with team success and personnel turnover has a positive covariance with team failure).[31,32] Team members and faculty advisors felt that the team had worked together long enough to accept new personalities. However, the new team leadership did not have the experience required to lead a project already running at 110%. There were early indications that the new leadership was struggling but with many pressing deadlines, it was felt that the team could adjust and continue to function. In retrospect, this was a mistake and the newly formed team should have gone through the process of developing a new TPD complete with goals and objectives.

The failure of the team to develop a new TPD resulted in a team that was confused and unorganized. More than just a transformation of team members had occurred. Not only had team members taken on new roles, but the team also lost technical expertise to graduation. Additionally the focus of the project had changed from building a car in a fixed facility to racing and logistically supporting a car over long distances. The team was unable to make the large adjustment and resorted to making decisions by committee. Accountability was not distributed equitably among team members and individual tasks and responsibilities were not assigned. As a result, details were often omitted and productivity suffered by not having individual persons responsible for specific tasks.

Additionally, the TPD had focused on building the car, not on racing the car. It should have been modified as progress was made so that team members could start thinking about the race itself and organize and commit to how they were going to compete. By incorporating the race into the TPD, critical items such as maintenance could have been integrated into the design. Additionally, responsibilities during the race would have been given the same priority as during the building of the car.

Poor standings by the team early on in the race contributed to team ineffectiveness.

The USMA vehicle was not well designed or constructed (attributable to inexperienced students and limited resources) and was very inefficient by Sunrayce standards. This led to a vehicle that broke down frequently, was a struggle to maintain, and was not competitive. As it became apparent that placing near the top of the field was impossible, there was a lack of urgency to address every detail. The cadets, used to being leaders amongst their peers, were hard pressed to maintain enthusiasm. Although the team did not quit, continuing to work hard to the finish, they lacked the focus observed in the top racing teams. In retrospect, because the TPD failed to address the race itself, there was no clear goal for the team. The fuzzy 'win the race' goal was insufficient to keep the team motivated when it became apparent that it was unachievable.

The strain of trying to maintain a poorly constructed vehicle, and struggling through terrible racing conditions (little or no sun) took its toll on the students. Late in the race, after overcoming multiple hurdles, the team transport vehicle, trailer, spare parts and critical equipment were stolen. This seemed to be the final blow and it was questionable as to whether the team could finish. After all, without the transport vehicle and trailer, it would be impossible to move the car when there was no sun for power. Other schools, who were in direct competition, offered support vehicles and tools to continue. The team questioned whether they were willing to continue when they had no hope of even being close to the top at the finish of the race. After a team meeting, 80 percent of the team voted to continue. The team completed the race and there was no evidence that the 20 percent who voted to quit ever caused a problem for the rest of the team.

Given the large number of personnel changes, difficulties encountered during the race and the number of variables that can affect a team's performance, it is difficult to quantify the TPDs affect on team performance. However, the perception by students (and faculty alike) indicate that it was of great assistance to the team during those phases of the project in which it was used. It provided an organized structure where team members understood their contribution and role in the project. From post project interviews, the team leader for the race portion of the project (who was a team member for the build portion) was quoted as saying "We are living proof that if you don't use the TPD, you are going to set yourself up for failure." Another team member stated, "Any team would improve if they followed the TPD." Another member even went so far as to say that its use should be mandatory. In short, the Sunrayce project was a single project that did and did not use the TPD and had considerably different outcomes as a result of its implementation, or lack thereof.

Although the team was able to qualify for the race, at the race's conclusion the team placed 29th of the 29 racing teams. It rained nine days of the 10-day span and not a single team completed the race without towing their car. It was the slowest race in Sunrayce history. It should be noted that the team received the Sunrayce Endurance Award and at the awards ceremony they were given a standing ovation for their efforts to continue the race in the face of substantial adversity.

VIII. Conclusion

This paper outlines a method that can be used to organize student teams for group projects. It provides a method that allows students to self organize and then execute a design/build project within a resource-constrained environment. This is usually challenging for inexperienced students who are struggling with technical design issues as well as program management and team building issues.

Included in this methodology is a general framework that:

- Is a simple form for use by the team to set goals and performance objectives. When properly used, goals and objectives can be mapped to specific tasks that must be completed for the project to be successful.
- Provides a starting point for building a cohesive team. Facilitates communication among team members and insures team members fully understand their contributions and major performance objectives.
- Provides an assessment method for students to monitor progress.
- Provides faculty advisors an assessment and evaluation tool for the project.

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