Manufacturing and Design Education Through National Competitions

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(1) Abstract

Entering national engineering competitions provides an opportunity for students and faculty to take part in well-planned educational activities. Competitions such as the ASCE Concrete Canoe, ASME Human Powered Vehicle, IEEE Robotics, SAE Aero, SAE Mini Baja, and SAE Formula SAE are well established regional and national engineering competitions designed to encourage good project-based engineering education and designed to demonstrate that engineering can be fun along with being challenging. They are designed to allow students to learn elements of design, organization, planning, teamwork, manufacturing, and competition. At the South Dakota School of Mines and Technology, multidisciplinary teams are established for all of these competitions as well as for solar car competitions and formally supported through the Center for Advanced Manufacturing and Production (CAMP). Team leaders are typically chosen from students who are members of CAMP. The teams are comprised of students at all class levels from freshmen through grad students.

Modern design methodology is used on all projects. Full engineering models are developed for all competition vehicles, and commercial industrial software packages are used for analysis and manufacturing. Solidworks is typically used to develop the models. Algor is used for finite element analysis of solids, and Fluent is used for fluid analysis. Mastercam is used to develop the CNC machine code. Working Model 3D is used for dynamic analysis.

Students work with professors and a manufacturing engineer to manufacture the weldments and machined pieces or they work with students from Western Dakota Technical Institute to do the actual manufacturing. This interaction between the engineering students and the technical students is a key to the success of this program.

The program is assessed by three methods. The FE exam is used to assess fundamentals, results in competitions are used to assess teaming and project knowledge, and job placement is used to assess how we are seen by our hiring constituencies. Placement of the students involved in projects is excellent. Results in the competitions are good. Most students pass the FE exam, but results will be closely monitored to assure quality in preparation of the fundamentals.
(2) Introduction

Many engineering societies and other organizations have developed regional, national, or even international competitions for students. At the South Dakota School of Mines and Technology (SDSM&T), and perhaps many schools that use them, these competitions serve to raise the visibility of the societies as well as to stimulate project-based education and to make engineering exciting. For example, SAE (http://www.sae.org/students/student.htm) supports the Mini Baja, Formula SAE, SAE Aero, Supermileage, Micro Truck Baja, and the Clean Snowmobile Challenge. ASME (http://www.asme.org/students/competitions/) offers the Human Powered Vehicle. ASCE offers the Concrete Canoe and the Steel Bridge (www.asce.org/students/). IEEE has the robotics contest at the Region 5 Student Conference. The work on projects for these competitions provides students with opportunities to solve real world problems of their own making and to actually have some fun in doing it. Much has been written on these competitions and how they are used in the curricula of other schools.\(^1,2,3\)

This paper presents the program used at SDSM&T to formally integrate a number of these competition projects into the educational program of the school and specifically addresses design and manufacturing issues. Included is a brief discussion of the Center for Advanced Manufacturing and Production (CAMP),\(^4\) educational philosophy of the program, facilities, teaming and team development, personnel issues, financial issues, and assessment.

This paper focuses on the SAE projects, but all function in a similar manner. A companion paper documents the solar car.\(^5\) There may be more or less senior design effort depending on the department that is primarily responsible for the project. The ASME and SAE projects tend to be focused in the Mechanical Engineering department, the solar car and the IEEE Robot are focused in the Electrical and Computer Engineering department, and the concrete canoe is focused in the Civil and Environmental Engineering department.

(3) Center for Advanced Manufacturing and Production

“To those who want to see real improvement in American education, I say: There will be no renaissance without revolution”\(^6\). These words were spoken by President Bush in 1991. The government of South Dakota and the Board of Regents were thinking in this way when in 1996 they asked the universities to change the way they do things – at least in a small way. During a time of downsizing state operations, the universities were given the chance to forgo the financial cuts seen in other state supported areas if they would reinvest the money to be cut in Centers of Excellence. These centers were to be somewhat revolutionary in their approaches to education.

SDSM&T had been involved with considerable development in the area of manufacturing and recognized that manufacturing is truly multidisciplinary in nature. Four manufacturing laboratories have been established on campus. These are: the Advanced Manufacturing Laboratory (AML) in Mechanical Engineering, The Injection Molding Laboratory in Chemical Engineering, The Advanced Composites Laboratory (ACL) in Civil and Environmental Engineering and the EE Prototyping Laboratory in Electrical and Computer Engineering. Each has industrial manufacturing equipment. The AML has a FADAL vertical machining center, a Bridgeport Romi CNC lathe and a Brown and Sharpe coordinate measuring machine. A
Cincinnati Millicron plastic injection molding machine is in the injection molding lab. A commercial composite winding machine is in the ACL and a commercial CNC prototyping machine is in the EE Prototyping lab.

It was recognized that maintenance, staffing and operation of these machines within the confines of the academic departments would be difficult. Encouraging or even allowing students and faculty from outside of a department to work in any of these labs was almost an impossibility because of the territorial nature (including funding) of the classical department structure.

It was recognized by many on campus that there was a need to change the way we approached design and manufacturing. There was a need to integrate design and manufacturing across campus. It was clear that industry and ABET were demanding that young engineers have significant design and manufacturing education in their engineering curricula and that they have multidisciplinary teaming experience in their programs of study. There was a need for industrial assistance to industry in South Dakota, but it was difficult to find enough good, well-balanced projects for senior design, especially if we were to impose a requirement that they be multidisciplinary.

SDSM&T chose to set up the Center of Excellence for Advanced Manufacturing and Production (CAMP) to integrate students, faculty and industry partners into a Center whose purpose is to develop a unique approach to manufacturing engineering education which simultaneously addresses explicit needs of industry. Specifically, CAMP: 1) is developing an innovative educational program based on the concept of multidisciplinary enterprise teams, 2) is creating an electronic community using advanced telecommunications technology to facilitate interaction between higher education and industry, and 3) is providing a focus for manufacturing technology assistance. This paper deals with item 1 only. CAMP was initiated in 1996 and officially activated in the fall semester of the 1997/98 academic year. It provides a program to create and maintain multidisciplinary projects. One of its main objectives is to foster multidisciplinary teaming.

(4) Educational Philosophy

Integration of projects into a formal center with students from all class levels and from all departments on campus is the goal of CAMP discussed in this paper. It has been an exciting although sometimes difficult goal to achieve, but now in its fourth year it is thriving and is respected on campus. The CAMP students are invited to join the center. They must have a 3.0 GPA and must have a desire to be leaders. They enter as juniors or seniors. They are especially valuable students for as they progress through their time at school they become teachers for the younger students. This teaching and mentoring by the CAMP students is what allows us to handle so many projects with no additional faculty. It is a tremendous benefit to the students who are being taught by other students, but it is also a tremendous benefit to the students doing the teaching. There appears to be considerably more interest, for instance, in the explanation of the free body diagram at a suspension mount point when done in this manner rather than when a professor does it for some hypothetical system. The older student must now have it correct and the younger students see a reason for the study. The SAE competitions have developed over about the past twenty years. They started as small regional competitions with less than ten teams.
competing to over a hundred teams today in both Mini Baja and Formula SAE. The SAE projects provide a well balanced format not only from the standpoint of design and manufacturing, but also from other engineering aspects. The students must conceive, design, build, test and compete with their vehicles. At the competition they must give a design presentation, cost or manufacturing presentation and a sales presentation. They must also compete in several dynamic events including a significant endurance event for the cars or flight event for the Aero competition. Students must focus on all aspects of the competition.

Taking part in the competitions provides an opportunity for structured design and manufacturing education while dealing with new problems each year. Students have a significant interest in learning the material. SDSM&T had been involved with some of the national engineering competitions in the past (the Sunrayce, SAE Mini Baja and Formula SAE, ASCE Concrete Canoe), and had seen some benefits from having students involved in such projects. It was not until we initiated CAMP that we realized that these competitions could provide a ready made set of good, well-balanced projects for our students and that CAMP could provide the necessary structure of management for these projects. The faculty would just have to learn and develop the pedagogy of engineering education using multidisciplinary team-based projects. A key focus of CAMP became very clear. CAMP students would lead projects for national competitions.

A key philosophy of manufacturing and design education at the School of Mines has been to put in place industrial equipment and software and to use it much as it would be used in industry. Modern design methodology is used on all projects. Full engineering models are developed for all competition vehicles and commercial industrial software packages are used for analysis and manufacturing. Solidworks is typically used to develop the models. Algor is used for finite element analysis of solids and Fluent is used for fluids. Mastercam is used to develop the CNC machine code. Working Model 3D is used for dynamic analysis. The Advanced Manufacturing Lab has a FADAL VMC 40 vertical machining center, a Bridgeport Romi CNC lathe and a Browne and Sharp CMM. A manufacturing engineer is supported full time to maintain the machines, computers and software as well as to work with students on actually running the machines.

Students are expected to complete engineering models in Solidworks, perform proper analysis (often including but not limited to analysis in Algor, Fluent, and Working Model 3D), and then submit proper engineering drawings meeting the ANSI/ASME Y14.5M 1994 dimensioning and tolerancing standard. Students go through a drawing approval process not unlike that in industry. The student, a design professor, and the staff manufacturing engineer must sign off on the drawings before they can be manufactured. It is the responsibility of the students to get the necessary signatures.

CAMP students must include in their programs of study courses that deal with the following: product development, business management, electronic communications and multidisciplinary senior design. Courses which support the projects but are not focused on the projects are:

GE 115 Professionalism in Engineering and Science
GE 117 Professionalism in Engineering and Science II
ME 262 Product Development
ME/EE 351 Mechatronics

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A new course, ME 499 Vehicle Dynamics (discussed below) has been created to support the projects.

Variability in parts is one of the critical issues dealt with in the design of the competition vehicles. The notation for tolerancing is introduced to freshmen in GE 117. It is used in ME 262. Statistics and process capability are dealt with in Product Development and Mechatronics. Determination of tolerance values is taught in some detail in CAD/CAM (ME 427). There is a very wide range of necessary tolerances, from fractions of an inch for some external dimensions to fractions of a thousandth of an inch for some bearing surfaces. Students must research their needs and apply proper values for tolerances and not just determine what the manufacturing machine is capable of and ask for that. Students have gained a great deal more respect for this seemingly small item (proper tolerancing) by working on competition projects. Freshmen and sophomores learn by interacting with the upperclassmen. For instance, the rear suspension uprights are relatively complex parts with two bearing race surfaces and several mounting holes. The seniors must actually determine the tolerances, but they must teach the younger students how to determine them. They must also determine the proper manufacturing processes and must mentor the younger students on the manufacturing as well.

Freshman

Developing design throughout the curriculum has been a major effort at this school. Students need some formal design theory in order to be prepared to deal with these complex projects. Since they are encouraged to join the teams and begin to learn about the projects as freshmen, some of the design theory must be presented in the freshman year. Two freshman general engineering courses are offered to begin this learning process. In GE 115 students learn to use engineering software and work on several small projects. In GE 117 they begin to learn engineering modeling using the commercial feature-based parametric modeling package, Solidworks.

Sophomore

In Product Development (ME 262) students form simulated companies and conceive, design, and manufacture a product using the CNC machine tools, the injection molding machine, and the EE prototyping shop. They must design the parts with Solidworks. They must generate the CNC code using Mastercam and must actually work with the manufacturing engineer to manufacture the parts. They must form departments of design, manufacturing, sales and marketing, and finance. In this course the students learn the fundamentals of teaming. The team theory presented below is presented in this course. Students actually break up into groups for teaming activities and evaluate themselves and their peers on teaming.
Also in Product Development the students learn the fundamentals of what we call “Design for All Reasons” or life cycle design. The students must evaluate designs based on design for manufacturability, function, cost, maintenance, serviceability, recycling, assembly, aesthetics, and disposal. Through brainstorming they must find at least twelve designs before beginning a formal decision-making process using decision matrices.

Junior

Mechatronics is a course that is team taught by two of the authors of this paper (Dolan and Batchelder) as a required course for all electrical engineering and mechanical engineering juniors. It represents a significant development on our campus because it is truly a multidisciplinary course with both professors in the classroom for all lectures. Labs integrate mechanical and electrical engineering. Students must complete a lab project in this course so they get an element of multidisciplinary teaming in this course.

Senior

CAD/CAM is used primarily to support senior design in mechanical engineering and thus heavily supports the vehicle projects. Students learn geometric dimensioning and tolerancing using Geometrics III. They must apply this knowledge to parts which they design in Solidworks and actually build themselves on the CNC machines. Tolerancing for mating parts as well as for mechanics issues is treated rather intensely in this.

Minimizing abstraction in design is a key topic in the CAD/CAM course. Students must work through detailed process plans for manufacturing and assembly of the project vehicle. They must assemble the complete vehicle in Solidworks as a part of the project, so in the course, considerable effort goes into mating of parts and assemblies. A Solidworks model is shown in figure at the right. In the past, students have been forced to spend a great deal of extra time adding details at assembly time that should have and could have been done correctly during the design process. The students are still surprised by some of the forgotten details, but the time lost on these is less each year. The inclusion of underclassmen in the projects is helping to solve this problem as well.

The frames for the vehicles are developed as projects in the finite elements course. The students evaluate at least twelve rather different frames. They must use decision matrices that involve design for all reasons using the functional reasons of suspension and drive train support, driver safety and egress, weight, stiffness (especially torsional stiffness), and body support. The torsional stiffness must actually be determined in the lab following fabrication of the selected design and compared with the calculated value.
Vehicle Dynamics is a new course initiated just to support the vehicle development projects. Fundamentals of Vehicle Dynamics by Gillespie \(^9\) is the text used. Spreadsheets using most of the equations of the book are created by the students. These are then used to understand fundamentals of acceleration, braking and steady state cornering. The students must each do a course project on a proposed suspension system for their vehicle. They must model it in Solidworks and then transfer the model to Working Model 3D for dynamic analysis. Students must be able to explain the primary setup of a vehicle in a final oral exam. That is, they must know how to predict understeer (or oversteer) at the steady state traction limits based on weight, center of gravity, tire load curves, spring rates, roll centers and anti-roll bar stiffnesses. They must be able to select springs and shocks based on sprung and unsprung weights and the details of their vehicles. Books by Smith \(^{10,11}\), Milliken and Milliken \(^{12}\), and Dixon \(^{13}\) are used for reference.

The philosophy of manufacturing is to design it well and have the part manufactured correctly on the first try. Through the approval procedure and the commitment of the students, this generally happens. Very seldom is a part manufactured incorrectly anymore. Prior to the initiation of the approval procedure (three years ago) there were too many incorrectly manufactured parts.

(5) Facilities

The Civil/Mechanical Engineering building was remodeled last year to match the educational philosophy presented in this paper. Part of the building is set up much like The Learning Factory \(^2\). Classrooms were converted into design labs. The photo at the right is one of the significant design labs. Although there are no students in the photo, this is one of the busiest labs in the building. The doors lead to the AML and the conventional manufacturing area. The windows look out into the newly constructed 3500 square foot Caterpillar Student Excellence Center. This is a project storage, fabrication and assembly area. The conventional manufacturing area and the Advanced Manufacturing Lab were expanded.

Students are allowed to work in the conventional manufacturing area during the daytime supervised hours after they have had significant training from the department engineering technician or a CAMP graduate assistant. Students work with the manufacturing engineer or the CAMP assistant to make parts in the AML. During the first few years of involvement in the projects there was considerable work in both of the manufacturing labs after hours, but today through the organization and planning that has come as a result of CAMP, there is very little after hours work in these labs. There is however considerable assembly and detail work done...
after the normal work hours in the new Caterpillar Student Excellence Center shown in the photo at the left.

(6) Teaming and Team development

This year a psychology professor at SDSM&T, Dr. James McReynolds, has been added to the CAMP leadership team. This has improved considerably the understanding of and the implementation of teams. We are beginning to use evaluation tools to set up and to adjust teams as discussed below.

There is a growing body of knowledge on teams and teaming. A very useful compilation of this information is coming out of work sponsored by the Gateway Engineering Education Coalition\textsuperscript{14}. Quoting from The Team Developer from that work:

“the following features characterize all teams:

A dynamic exchange of information and resources among team members occurs.

Task activities are coordinated among individuals in the group.

There is a high level of interdependence among team members.

Ongoing adjustments to both the team and individual task demands are made.

There is a shared authority and mutual accountability for performance.”

These statements certainly characterize activities with the competition project teams.

Again summarized in this booklet is information on successful teaming:

“successful teams have the following eight critical factors:

1. A clear, challenging goal; this goal gave the group members something to shoot for. The goal was understood and accepted by the entire group.

2. A results-driven structure (i.e. members had clear roles and accountabilities and there was an effective communication system within the team).

3. Competent, talented team members.

4. Unified commitment; in other words, members put the team goals ahead of individual needs.

5. A positive team culture. The factor consisted of four elements: (a) honesty, (b) openness, (c) respect, and (d) consistency of performance.

6. Standards of excellence (i.e., an expectation of high performance, to be successful as a team).

7. External support and recognition. Effective teams receive the necessary resources and encouragement from parties outside of the group.

8. Effective leadership. Simply put, successful teams have good leaders.”

This is perhaps the most important information that we use in developing the team leaders and the teams themselves. Four behaviors are necessary: communication, decision making, self-
management, and collaboration. A questionnaire developed by Dr. McReynolds extracts this information from team responses.

Management structure is built into the teams. Teams must have a team leader or co-leaders, a chief engineer, crew chief and project manager. Each subsystem of the vehicle becomes the responsibility of one senior design student who generally is assisted by several underclass students. Students must maintain a Gantt chart and must use it for project management. The senior design students are typically from the departments of Mechanical engineering, Electrical and Computer Engineering, Industrial Engineering and Materials Engineering.

The Formula SAE and Mini Baja teams each have about 50 student members. Three CAMP students lead each team. Several junior CAMP students are also on the team preparing for the following year. Each team has several students from each class year. Older students act as mentors to the younger ones. Younger students are given an older car to modify and learn with while the seniors build a new car in their senior design classes. The underclassmen on the Mini Baja team actually modify the car of the previous year and take it to competition. Each of the underclass years on the Formula SAE team is given a car from a previous competition to maintain, race and modify as necessary. This process helps to assure the transfer of knowledge from one year to the next, but written reports and other documentation are required of all teams. Engineering documents must follow the procedures discussed above.

CAMP students hold a weekly meeting to discuss project issues or for a seminar presentation on an issue of teaming or leadership. Once a month at this meeting the discussion is on interaction between teams. Suspension, for instance, is something that students from all of the vehicles need to discuss. They can learn from and help each other.

(7) Personnel Issues

CAMP is directed by two professors. They serve as advisors for many of these projects. The dean of the College of Systems Engineering is the executive director. There is a leadership team composed of professors from most of the departments involved in the projects. These include the director of the injection molding lab, the advisor for the concrete canoe, advisor for the ASME HPV, a materials professor and a professor of psychology.

It is important to have a dedicated manufacturing engineer on the staff and to have graduate students or undergraduate assistants who can operate the necessary manufacturing labs.

CAMP has a half time secretary who works with the students to purchase materials and who provides clerical support.

CAMP activity is multidisciplinary and thus there is interaction between personnel from different departments and even different colleges. It is necessary to have support from the upper administration. The President and Vice President are both solidly behind CAMP.
(8) Financial Issues

The teams are expected to secure most of the funding for the projects. Thus fundraising is a significant effort. The education of living within a budget is thus an important part of the experience. CAMP covers the expense of the trip for most of the teams. Major equipment used by all of the teams is also purchased by CAMP.

There is a significant cost involved in competition projects. As discussed throughout this paper, students are expected to use industrial tools and produce industrial-like results. Thus the tools must be in place. Latest releases of software are assured through maintenance contracts. Preventive maintenance is methodically carried out on the CNC machines. Modern MIG and TIG welders are maintained. The equipment at WDTI is maintained with the same care. Software costs are about $5,000 per year. Tooling and CNC maintenance is about another $5,000 per year. Material costs depend on the project.

The industrial machines have been obtained through NSF grants, industrial grants and State grants. The total investment is approximately $300,000.

(9) Assessment

There are several levels of assessment to discuss here: Assessment of team development and teaming education, assessment of department activities for ABET, and the assessment of the overall CAMP program.

Assessment of team development is an evolving process as all of our assessment is. The progress reports submitted by the teams on approximately a monthly basis give some indication of the level of proper teaming skills. A peer review of all team members at the end of the semester also gives some indication of the level of team development. Observations by the project advisor during weekly meetings or other meetings as needed give good qualitative evaluation of the teaming process. The best measure of team development used to date is the questionnaire developed by Dr. James McReynolds. The questionnaire has been applied in the past only when the advisors perceive problems within a particular team. The questionnaire is given to all teams to provide some level of control measurement. It has been used to identify a significant leadership problem in one team (leading to a change in leadership) and the lack of motivation within a significant number of members of another. That led to a significant involvement of the faculty advisor to help remedy the problem. In the future it will be given at several times during the year (life cycle of the team).

Although CAMP is a multidisciplinary program and not accredited by ABET as such, there is a significant assessment issue for this program. The engineering departments must show multidisciplinary teaming education for ABET accreditation. One simple assessment measure then is the fraction of design projects that are multidisciplinary in nature. In the Mechanical Engineering department there were no multidisciplinary projects in 1995/96. This year half of all senior design projects are multidisciplinary and the main manufacturing project in the product development course was multidisciplinary involving a significant ME component and a significant EE component.
Entry into the national competitions provides a type of built-in assessment of the program itself. The progress of CAMP is assessed by FE exam results, job placement following graduation, and by the benchmarking provided by the national competitions. Since the beginning of the program student teams have entered the Mini Baja, Formula SAE and Concrete Canoe each year. The Concrete Canoe team has made it to the national competition each year. The Mini Baja has been in the top ten in as many as 5 of the 7 events of the competition and won first place in the presentation event and been in the top ten overall once. The photo at the left is a picture of the 2000 Mini Baja team at the finish line. The Formula SAE team has completed all of the seven events twice and has been in the top twenty in sales presentation.

CAMP is monitored by an external advisory board composed of members from industry and other educational institutions in the region. The general consensus of the industrial members is that they are pleased with the activities that they see in the competition projects.

Companies that hire our graduates are very pleased with this educational program. Several of the CAMP students have started at salaries well above the national average and some have even received signing bonuses. Caterpillar donated the funding for the newly opened Caterpillar Student Excellence Center.

CAMP received the 2000 Boeing Outstanding Educator Award. Boeing felt that the preparation of the students in CAMP, primarily on the competition projects, best prepared students to meet the desired attribute Boeing seeks in young engineers.

(10) Summary and conclusion

Through a focus on national engineering competitions, a successful student-centered program has been developed at The South Dakota School of Mines and Technology to stimulate the understanding of manufacturing and design in the context of multidisciplinary teams. The projects pose significant manufacturing and design problems. Students in the Center of Excellence lead the teams. This year there are over 50 students in CAMP. Twelve of them are leading teams with total student involvement of about two hundred.

Two major companies have recognized CAMP for the education it is providing. Caterpillar donated the funding for the Caterpillar Student Excellence Center described above. CAMP was selected as the winner of the 2000 Boeing Outstanding Educator Award.
(11) Bibliography


Dan Dolan is a Professor of Mechanical Engineering at SDSM&T. He is a CO-Director of CAMP. He teaches manufacturing courses as well as IC Engines and Vehicle Dynamics. He is the SAE faculty advisor and serves as the advisor for all of the SAE competition projects.

Mike Batchelder is a Professor of Electrical Engineering. He is a Co-Director of CAMP. He is the faculty advisor for the SDSM&T Solar Motion Team.

Wayne Krause is the Dean of the College of Systems Engineering and the Executive Director of CAMP. He also teaches courses in thermal science in the Mechanical Engineering Department.

Casey Allen is an Integrated Manufacturing Specialist in CAMP. He serves as the staff manufacturing engineer for all of the competition projects. He holds a BS and an MS in Mechanical Engineering from SDSM&T.

Chenoa Jensen is an Instructor in the Mechanical Engineering Department. She is responsible for the team and leadership development in CAMP. She holds a BS and an MS in Mechanical Engineering from SDSM&T.