*Int. J. Engng Ed.* Vol. 26, No. 3, pp. 655–666, 2010
Printed in Great Britain.

0949-149X/91 \$3.00+0.00


# Using Project-Based Learning to Teach Six Sigma Principles*

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*An innovative approach of teaching Six Sigma, a tool widely used in industry, is discussed in this paper. The Six Sigma methodology was applied during a seven-week course project after the case-study of an actual Six Sigma project in a junior-level instrumentation course for a four-year engineering technology program at Texas A&M University. The students followed the Define, Measure, Analyze, Improve, Control (DMAIC) process to improve a given product design. Statistical analysis of final examination, course project, and survey results shows that the new approach is an effective way of teaching Six Sigma concepts.*

**Keywords:** Six Sigma; course project; project management; engineering education

## 1. INTRODUCTION

INCREASING INTEREST in research and application of the Six Sigma methodology [1, 2] has been shown recently. Six Sigma is a structured, disciplined, data-driven methodology and process where the focus is placed on improving business performance using tools with an emphasis on statistical analysis [3–6]. During the product development cycle, it is often desirable to reduce the variation of a particular performance measure such as a parameter value, as illustrated in Fig. 1. This strategy adds value to the product in many ways, including the reduction of failed components during the product test and after the product is deployed in the field, allowing more flexibility in choosing the nominal values for design parameters, and reduction of the cost associated with the defective product.

The Six Sigma process consists of five stages: Define, Measure, Analyze, Improve, and Control (DMAIC) [7]. The Project Charter including the purpose, scope and goals of the project is created in the Define stage. The process being studied is also identified in this stage. In the Measure stage, a data collection plan is created and the assessment of the measurement system is conducted. Process, data, and potential root causes are analyzed in the Analyze stage. Solutions for process improvement are then proposed, analyzed, tested and implemented in the Improve stage. After the validation of the results, the improved process is standardized and monitored in the Control stage. The DMAIC process provides a systematic approach for solving problems and improving the quality of products and is more effective than the trial-and-error method. There are several key aspects of this methodology that distinguish it from other process improvement methodologies: it is driven by data; statistical tools are extensively used; and the Voice of Customer (VOC) is emphasized throughout the entire process.

Six Sigma has evolved and grown over the years and today it is being used by companies such as GE, Honeywell, Motorola, DOW, DuPont, American Express, Ford, GM, TRW Automotive, and many others to improve business performance. According to [7], Motorola credited the Six Sigma initiative for saving \$940 million over three years and AlliedSignal reported a \$1.5 billion savings in 1997. Details on the history of Six Sigma and success stories of its implementation can be found in literature such as [1, 2, 8].

Six Sigma is often thought of simply as a tool for management or that it can only be applied to manufacturing processes. In fact, most of the research papers on this subject have been written by faculty members in Industrial Engineering (IE), Management, and Manufacturing Engineering departments, as evidenced by the references listed in this paper. As a result, it is typically taught in IE as a part of quality control courses, in business schools when management tools are discussed, or in quality control courses in Manufacturing Engineering programs. However, as pointed out in [9], if organizations want to obtain dramatic benefits from the implementation, Six Sigma cannot be only used as a method for project management, they must also use the more advanced statistical tools and other technical aspects of the methodology. In the real world, Six Sigma methodology can be effectively used in many areas other than management and quality control. It is used by engineers to solve technical problems and improve design processes in many different fields including electrical engineering, systems engineering, and chemical engineering.

* Accepted 12 December 2009.

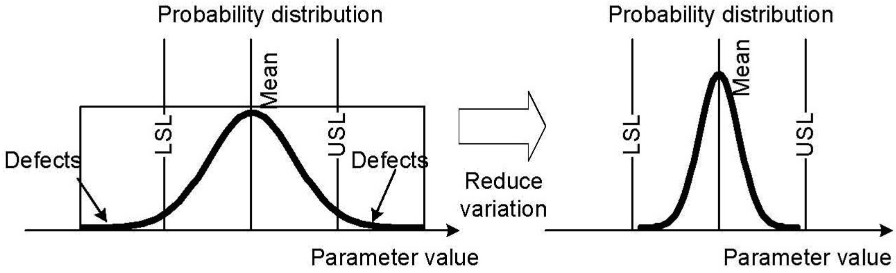



Fig. 1. Improvement of product quality by reducing the parameter variation.

The DMAIC process provides a systematic approach for improving any process, identifying the root cause for problem solving, robust design, statistical analysis of data, and assessment of measurement systems, all of which are relevant to the tasks of engineers in all engineering fields. One can find successful implementations of the Six Sigma methodology in the steel industry [10], financial services [11], the service sector [12], health care [13], engineering designs [14, 15], chemical processes [16], control algorithm development [17], software designs [18], and several other areas [1]. Originated in the United States, Six Sigma is now being accepted internationally in areas that include the Netherlands [13], India [10, 18], Taiwan [9], and the Middle East [14]. For many companies in the manufacturing and pharmaceutical industries, Six Sigma is even considered prerequisite knowledge for the successful engineers. As more businesses, government agencies, and organizations adopt this methodology to improve their products, processes, and services [8], many engineers have to take professional training seminars or in-house training in Six Sigma due to the lack of such education in engineering programs in institutions of higher education.

Many engineering undergraduate students without training in Six Sigma or similar processes have the misconception that the development of a new product only involves technical design. However, the reality is that in today's competitive marketplace, it is almost impossible to separate technical engineering design from the business aspect for any product. An electronics engineer may be able to come up with a new "gadget" based on a brilliant technical design, but if the product is of poor quality due to manufacturing problems, occasionally has a safety issue, or costs too much, it will not survive against the competition. To correct this problem, there is a need to teach students that in addition to functionality, the success of a product depends on many factors such as manufacturability, overall cost, needs of the customer, quality, safety, fault tolerance and detection capability, and cost of maintenance. In addition, in any technical design project, students must consider the effect of design parameter variation. They must learn that "Customers don't experience average, they experience variation." All these aspects of developing a successful product can be improved with the use of Six Sigma.

To better prepare the students for real-world tasks, it is beneficial for all engineering students to have some knowledge of Six Sigma. This can significantly reduce the gap between what students learn in school and what they face in the real world, helping students to have a better chance of making contributions immediately after graduation regardless of their chosen field of study. While it is clear that the Six Sigma methodology can benefit all engineering programs, students in many engineering disciplines including Electrical Engineering and Electronics Engineering Technology currently receive no formal education in this area.

Recently, many educators realized the importance and benefits of teaching the process of product quality improvement using Six Sigma methodology [19, 20]. Examples of such work include a "Total Quality Management Using Six Sigma Technique" course developed for students in the Masters of Engineering program at University of Nebraska-Lincoln by Jones [8]. Ho, Xie, and Goh [19] attempted to study the feasibility of applying the Six Sigma framework in higher education. They used an example of an operational amplifier circuit to illustrate how to embody Six Sigma in their electrical engineering curriculum. Furterer [21] realized the importance of Six Sigma for Engineering Technology (ET) students and offered a semester-long course in this subject to undergraduate ET students at the University of Central Florida based on her prior experience in teaching a similar course for Industrial Engineering students [22]. Some innovative instructional approaches, such as community-based projects, experienced Black Belt/Master Black Belt mentoring, team-based problem solving, learning from prior case studies and examples of tools, and web-based instructional materials, are used to teach these courses [21].

While these efforts are a good start, they point to some of the drawbacks associated with the current methods of teaching Six Sigma. For example, when given a choice while learning DMAIC concepts, students will often choose non-technical case studies. By choosing non-technical projects it is difficult for the students to relate Six Sigma to the technical coursework. Six Sigma then becomes simply a management tool for them as discussed earlier and its full potential is not realized. This may explain the observation by Furterer that in general, ET students did not do as well as IE students in her class [21]. For well-established engineering programs, another drawback includes the ability to add a Six Sigma course to an already crowded curriculum. The teaching method proposed by Furterer in [21] also seems to be somewhat excessive for undergraduate engineering students. The suggestion by Rao and Rao [20] that all the students should graduate as certified Six Sigma Black Belts may be appropriate for IE, but is not necessary for students across all engineering disciplines. Most engineering students simply need some relevant and practical exposure to the methodology instead of developing expertise in the area. Nonetheless, as pointed out by Rao and Rao [20], the world has grown much beyond the days of touching upon Six Sigma in just one or two paragraphs in a chapter on quality management.

The previously listed work cites important efforts but specific teaching methods and curriculum development are still sparse and difficult to find. However, it is clear that much more effort is needed to design the curricula for different engineering programs with different needs in Six Sigma education.

As a continuing effort to reduce the gap between the education and the real world, the Electronic Engineering Technology program at Texas A&M University has a focus in product development and entrepreneurship. As part of this program, students are encouraged to design commercially viable products and create their own "startup companies" [23]. Six Sigma has been identified as core knowledge in order to extend earlier efforts of integrating project management into senior design projects [24]. After a careful literature review, it becomes clear that a new approach for teaching Six Sigma concepts that can be applied to any discipline-specific, project-based technical course needs to be developed. This paper discusses the research question of how to integrate the Six Sigma methodology into existing engineering curricula and teach the methodology effectively to undergraduate engineering students. This research is a continuation of earlier efforts by Zhan and Porter based on their experience in teaching Six Sigma in a junior-level instrumentation course [25].

## 2. METHODLOGY

This paper proposes a new project-based learning-by-practicing approach for Six Sigma education. The new approach is based on the belief that students learn best by practicing the Six Sigma methodology over the course of a technical project. The intent is not for the students to become experts in Six Sigma or any related tool; instead, they just need to be exposed to the basic concepts so that they know when and how to apply the methodology. A program focusing on early exposure of any methodology and repetition in a few courses works well, as discussed in [26].

### *2.1 New approach for teaching Six Sigma*

It is well known that Project–Based Learning is an effective approach to improve learning for engineering students, in particular for engineering technology students. Engineering students are motivated to learn knowledge that can help them solve real-world problems. To overcome the shortcomings related to Six Sigma that were discussed in the previous section, the following approach was proposed:

- A detailed example based on a real-world Six Sigma research project [17] will be presented to students first so that they have a general understanding of the DMAIC process and some of the tools used in the research project;
- A technical course project will be designed so that students are challenged with a real-world problem that can be tackled using the Six Sigma methodology. The emphasis is on the application of the DMIAC process in solving engineering problems;
- The student learning will be accomplished mainly in the laboratory sessions, while they are working on their course project rather than the normal classroom lecturing;
- The objective is to familiarize the students with the overall process and tools, rather than the in-depth understanding of every aspect of the DMAIC process.

This approach has several unique aspects. First of all, the teaching and learning of Six Sigma theory can be incorporated into many technical courses. Instead of the four to eight weeks of intensive professional training seminar or a semester-long lecture course typically used in formal Six Sigma education programs, many aspects of the DMAIC process and related tools can be learned in course projects that typically last six to seven weeks. This allows for Six Sigma to be practiced in several technical courses. Each course can determine how and what aspects of Six Sigma will be practiced. This provides the flexibility that a standalone Six Sigma course cannot have. Second, there is no formal lecturing in Six Sigma theory. The process and tools are introduced in the context of solving real-world engineering problems. The problem is presented first, and the use of Six Sigma will be driven by the need to solve the problem.

The new approach allows easy integration of Six Sigma into any technical courses without major curriculum change; therefore it can be easily adopted by other junior and senior classes with course projects and the senior design class. As a trend in many engineering schools, laboratory classes have become a major part of the engineering programs due to the fact that most engineering students, particularly engineering technology

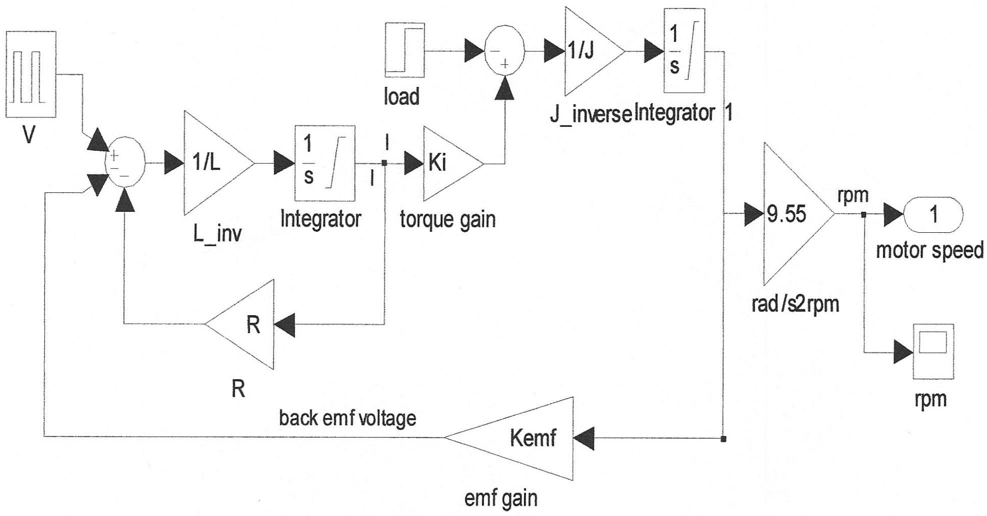



Fig. 2. MATLAB model for a DC motor.

students, learn better with lab-based course projects.

To test this proposed approach, it was deployed in a junior-level instrumentation course in the Electronics Engineering Technology program in the Department of Engineering Technology and Industrial Distribution at Texas A&M University. Electronics Engineering Technology is a four-year Bachelor's degree program within the College of Engineering. Before taking this course, students had completed several technical courses such as DC/AC Circuits Analysis, Digital Electronics, Advanced Digital Electronics, Microprocessors, and Electronic Devices and Circuits. They might be taking Mixed Signal Test and Measurement and Software Technology at the same time. After the presentation of the example Six Sigma project, the students were given an instrumentation-related product designed by students in previous semesters. Their task was to follow the DMAIC process to improve the quality of the product.

*2.2 Example of a Six Sigma project*

The example concerned the improvement of a Pulse Width Modulation (PWM) motor speed control algorithm using modeling and simulation. The following research problem was first presented to the students: "How to reduce the variation in average motor speed during PWM control?" This particular example was used because the students were familiar with the PWM control of motor in several earlier technical courses. Additionally, this particular example illustrated that an engineering design problem could be effectively tackled using Six Sigma methodology.

First, the business case was established in the Project Charter. The inconsistent PWM motor speed control was not meeting the requirement of the customer. Specifically, the customer complaints and returned products were costing the company money and hurting its reputation. The project goal was identified as reducing the average speed variation, measured through standard deviation, by 60% without any additional cost. The project scope was limited to simulation due to time and cost considerations. In the Define stage, a SIPOC (Supplier Inputs Process Output Customer) graph [7] was constructed to show the interrelationships that could be affected by the modification to the motor speed control process. Based on the SIPOC graph, the design engineer had to consider the impact of any design modification to the overall process. A Critical to Quality tree [7] was then constructed to help understand the customer needs.

To better understand the current process, the process map [7] was developed next. The SIPOC, CTQ, and process map developed in the Define stage are helpful in defining the project goals and scope, gaining better understanding of how the process works, and identifying the important variables to measure or modify in later stages.

In the Measure stage, a measurable performance metric needs to be established. In this example, a natural choice was the average speed error defined as the difference between the average speed and the speed target. A first principle model was developed and implemented in MATLAB$^R$ [27], as illustrated in Fig. 2. The advantage of using modeling and simulation over real testing was discussed briefly and the students were encouraged to try to use simulation to get rapid estimations at minimum cost for their course projects.

The parameters in the model included the applied voltage, the motor load torque, the PWM frequency and duty cycle, the armature coil resistance, the armature coil inductance, the rotor inertia, the back emf gain, and the torque gain. The PWM frequency and duty cycle were the control variables. The applied voltage and load torque were external variables that could not be controlled. The applied voltage was monitored,

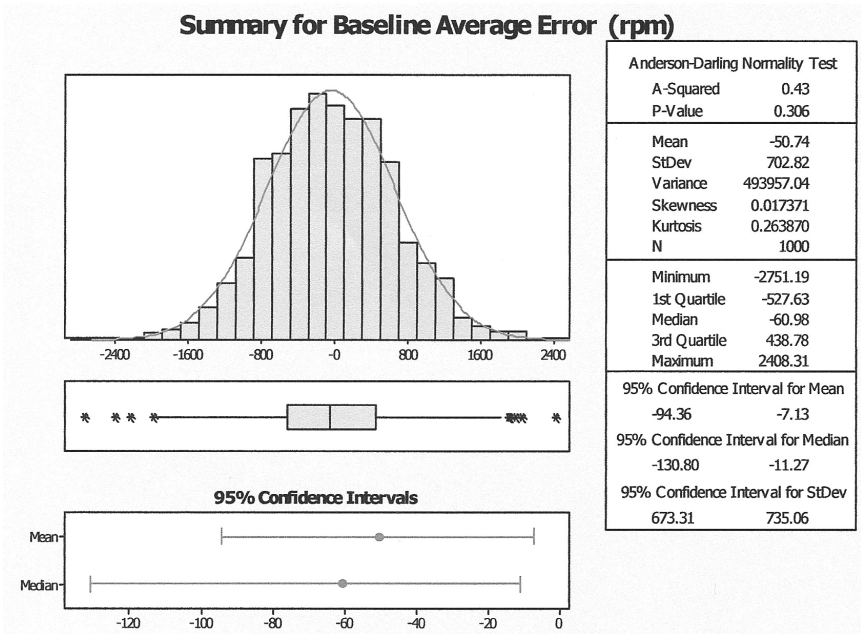



Fig. 3. Baseline performance established via Monte Carlo analysis.

but the motor load was not. All other variables were design parameters for the motor.

Using the MATLAB model, it could be easily shown that the PWM frequency had a negligible impact on the average speed. This allowed one to narrow down the scope of the project by assuming a constant PWM frequency, say 40 Hz.

To establish the performance of the baseline design, the Monte Carlo Statistical Method [28] was introduced to the students. The battery voltage, load torque and the motor parameters were assumed to have normal distributions. One thousand set of values were randomly generated using Minitab [29]. These values were then used as the parameters in the MATLAB model for simulation. The simulation result was used as test data to generate statistics using Minitab, as shown in Fig. 3. The histogram shows the probability distribution of the speed error (in rpm). For the definitions of the statistical terms shown in Fig. 3, the reader is referred to Minitab documentation [29].

In the analyze stage, a Cause-and-Effect diagram was used to find the potential causes for motor speed variation. A 2-level, full factorial Design of Experiments (DOE) [30] was used to identify the main contributing factors to the average motor speed variation. There were seven variables (factors), each assuming a minimum value and a maximum value. The total number of experiments in the DOE matrix was $2^7$, i.e. 128. The DOE results

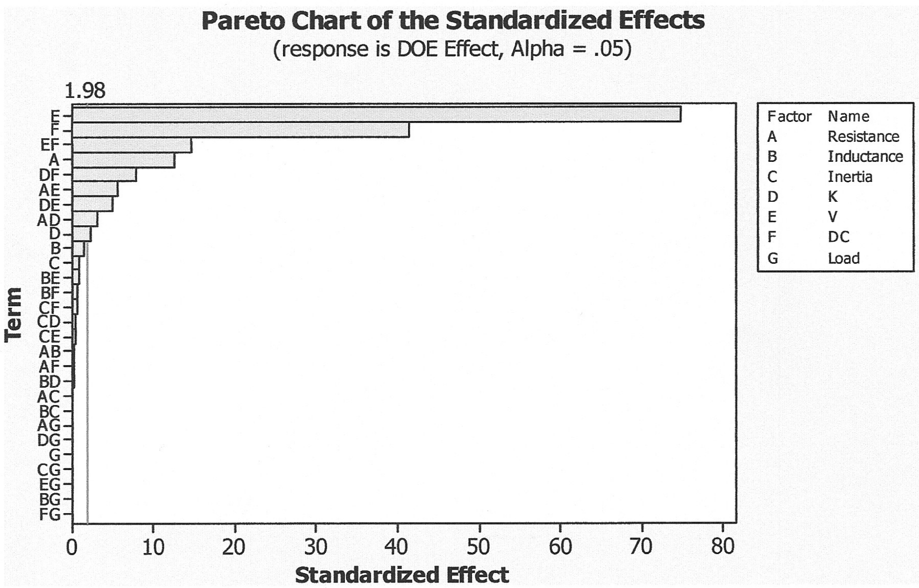



Fig. 4. Identification of main factors using Design of Experiments analysis.

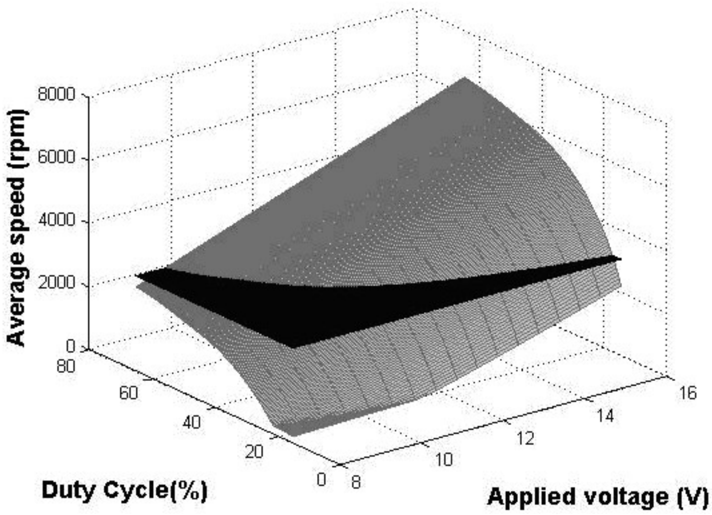



Fig. 5. Minimizing error using Response Surface Method.

were used to create the Pareto Chart in Minitab, as shown in Fig. 4. The vertical axis indicates the factors and the interactions between them. For example, the top three main effects are: E (applied voltage), F (PWM duty cycle), and EF (The interaction between applied voltage and PWM duty cycle). The threshold of 1.98 was calculated in Minitab$^{R}$ based on the research work of Lenth [31]. With a confidence level of 95% (1 –Alpha), any factor that has a standardized effect value (see [29] for details of calculation) higher than this threshold is a significant factor. Therefore, the applied voltage, the PWM duty cycle, and the interaction between them were three main contributing factors to the variation in the average motor speed during PWM control.

Based on the DOE result, the Response Surface Method (RSM) [7] was used to find a solution to reduce the speed variation. Since the applied voltage and PWM duty cycle were the main contributing factors to the variation in average speed, all other variables were assumed to be equal to the nominal values. The MATLAB model in Fig. 2 was used to find the average motor speed as a function of the applied voltage and the PWM duty cycle, as illustrated in Fig. 5. To achieve a constant average speed, a horizontal plane is also plotted in Fig. 5. The intersection between the two surfaces defined a relationship between the PWM duty cycle and the applied voltage. In other words, if the PWM duty cycle was adjusted as a function of the applied voltage according to this relationship, then the average speed would be maintained at the desired constant level.

For comparison, the same one thousand parameter sets used to establish the baseline performance was used to evaluate the performance of the new design. The simulation result showed that the standard deviation of the average speed error was reduced from 703 rpm for the baseline design to 190 rpm for the new design. The improvement of performance as measured by the reduction of standard deviation in the average speed error was 73%, exceeding the project goal of 60%. The improvement was achieved without tightening the tolerance bands for the motor parameters, i.e. there was no additional cost.

The new process was standardized in the Control stage to maintain the improvement. Through the presentation of this example, the students were exposed to many Six Sigma concepts and tools within one lecture. They saw how each tool was used in each stage of the DMAIC process for different purposes. The presentation of the example provided the students a high level understanding of the DMAIC process without going into much details of each tool used. The students could easily find the relevance of Six Sigma since they were familiar with motor PMW control. The example also brought the research of the faculty member to the classroom. The students learned that a potential solution to a practical engineering problem can be identified using modeling and simulation, before real tests are conducted.

### *2.3 Course project*

After introduced to Six Sigma concepts using the example taught in class, the students were assigned to work on a course project for seven weeks.

*Objectives*

The objectives of this project were:

- To expose students to the DMAIC process;
- To have students learn some of the commonly used engineering tools by using these tools in their projects;
- To let students manage their projects using project management tools so they are better prepared for their senior design projects;
- To have students apply the knowledge they learned in instrumentation to a practical product.

*2.4 Project content*

To achieve these objectives, a product designed by students from the previous semester was presented to the students. The product was a traffic control system that could adjust the time delay between the green traffic lights at intersections based on the weather/road conditions [26], as illustrated in Fig. 6. The main idea was to extend the yellow light duration when the road is icy/wet or when it is dark to give the drivers more time to react. For the baseline design, a temperature sensor, a humidity sensor, and a light sensor were used to detect temperature, humidity, and light intensity. The signals were amplified, filtered and converted to digital signals. The digital signals were transmitted wirelessly to a central controller, where digital signal processing was performed. The output from the controller was a delay time.

The original course project was designed such that the students could use what they learned in the instrumentation class to build a functional prototype. For example, the students learned to convert a resistance change in a temperature sensor into a voltage signal using a constant voltage potentiometer or a Wheatstone bridge; they learned to build an anti-aliasing filter before the signals were fed to the analog-to-digital converter; they learned to program a wireless communication system to transmit the data to a remote location; and they learned to design digital filters. To change this project into a Six Sigma project, the students were not just given the design specifications as is typical for a course project in engineering programs. Instead, they were asked to first analyze the baseline design.

*2.5 Project teams*

Teams consisting of three to four students were formed and were required to identify an area for further improvement. Students in each team took the responsibility of team leader, software engineer, hardware engineer, and test engineer. Depending on the number of students in the team, the team leader might also take another role such as software engineer. Each team met once a week. The team also had a review meeting with the faculty member every week. Team members gave a peer review for their teammate at the end of the project.

*2.6 Project scope and execution*

After the formation of the project teams, brainstorming sessions were held to define the project scope. Several teams identified cost reduction as their focus area; one team chose optimization of the signal conditioning circuit; other teams identified fault detection as the area for improvement.

Over a period of seven weeks, the students first defined their project charter and their metric for performance. One team actually visited Texas Transportation Institute to collect inputs from potential customers in order to better understand the design requirements. The performance metric was chosen to establish the baseline performance. A process mapping was developed using SIPOC, and a CTQ tree was created to better understand the customer need. QFD [32–34] was used to translate the VOC to a design requirement document before designing the system. They created a Work Breakdown Structure (WBS) and used the Critical Path Method [35] for the management of their project. The students then focused on the identified areas for improvement of the product. Test data was collected for statistical analysis. They tried to identify the root cause of the problem they were analyzing using the Cause-and-Effect diagram and FMEA [36–38]. Design improvement ideas were proposed and tested. Detailed documentation of the project was created to make sure that others could further analyze and improve the design and would not have to "reinvent the wheel". The students learned first hand how important documentation was: they struggled in the beginning to understand the baseline design due to poor documentation by the students from the previous semester. Note that the process they went through was almost identical to the one illustrated in the example presented before the start of their project.

There were many tools that could be used throughout the Six Sigma project. The students

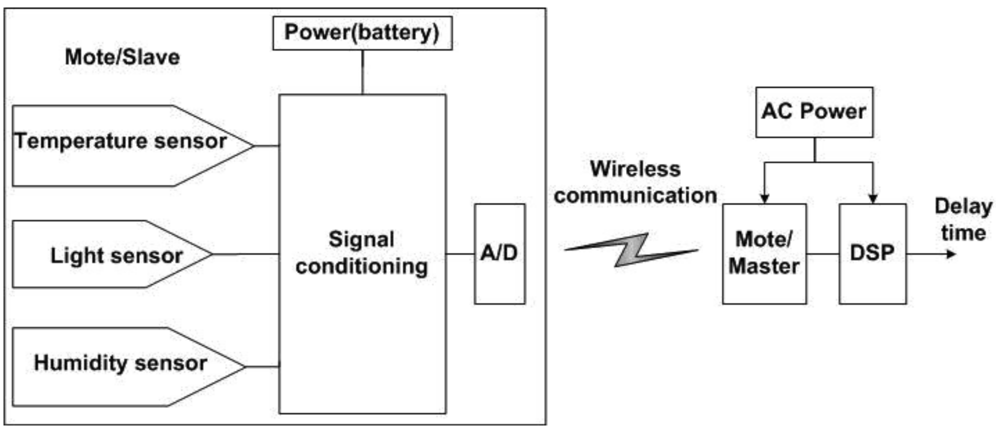



Fig. 6. Functional diagram for Weather Adaptive Traffic Light System.

learned simple tools such as SIPOC, CTQ, Cause-and-Effect diagram, WBS, CPM, and VOC from the example that was presented to them before they started the course project. Other tools such as FMEA, FTA [39, 40] and QFD were further illustrated by walking through some examples and working with the students to apply these tools to their projects. Because of the short duration and the large number of tools involved, the goal was breadth rather than depth. The goal was to have students exposed to these tools so that they would be able to make a decision on which to use for a particular problem. Once familiar with a given tool, it would be easier for them to learn the tool better in industry when needed.

Project management is an important part of a Six Sigma project. In previous semesters, students tended to do most of the project-related work near the end of the semester. The project management part of Six Sigma helped the students to conduct their project at a consistent pace. A Critical Path Method map was created by the teams, as illustrated in Fig. 7. The boldfaced lines indicated the critical path of the project. Instead of working in the "fire-fighting" mode near the end of the semester, they spent more time preventing fires from happening early on. The faculty member kept track of teams' progress by holding weekly review meetings. The students also learned other basic skills such as team voting, writing meeting minutes, brainstorming, and using affinity diagram. The students were required to do a demonstration for their prototype, give a presentation, and write a final report for their projects.

One team analyzed the cause for high cost and concluded that the expensive humidity sensor was not needed; instead, detection of rain was needed. They designed a simple circuit to detect a short-circuit condition caused by rain. As a result, significant cost reduction was achieved. Two teams conducted FMEA. One came up with the design change of eliminating the humidity sensor based on high risk for false detection. Another team used FMEA to identify the low battery condition as the highest risk fault. They included the low battery detection and prediction feature in their design. When the low battery voltage condition is predicted or detected, a message would be sent to the controller to go to the default of zero delay time while informing maintenance workers to check/replace the battery. This improved system reliability and reduced the maintenance cost. Another team conducted Monte Carlo analysis to investigate the tolerance requirements of the electronic parts in the circuit. The analysis allowed them to select less expensive parts without sacrificing the system performance. These design changes drastically improved the overall product quality or reduced the cost. Students learned first hand that the DMAIC process was a systematic approach which was much more effective than the trial-and-error method in design improvement.

Before the Six Sigma project, students used to collect one data point to show that the prototype

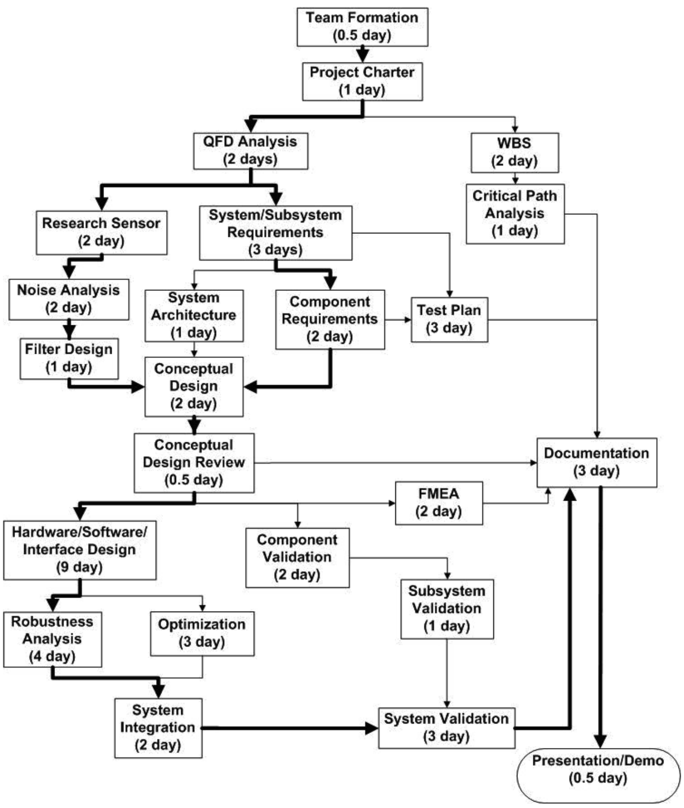



Fig. 7. Identification of the critical path for the project.

worked. Since Six Sigma is a data-driven process, it forced students to realize the importance of testing and statistical analysis of the test data. During the Six Sigma project, students conducted many tests to gather data for further analysis. This was reflected in the lengthy test data and analysis section in the final reports submitted by each team.

Another area of improvement was the emphasis of student teams on overall product quality including functionality, reliability, and cost, as opposed to simply building a prototype for a demonstration of the functionalities.

## 3. RESULTS AND ANALYSIS

The assessment consisted of two parts: one for the student projects and one for the effectiveness of the Six Sigma teaching. To measure the effectiveness of the new teaching method, surveys were conducted at the end of each semester and performance of the students on specific final examination problems related to Six Sigma was recorded.

For assessment of the projects, each team was evaluated based on the technical content of its project (15%), use of Six Sigma tools (15%), overall project management (10%), weekly review meetings (10%), prototype demonstration (10%), presentation (10%), documentation (10%), teamwork (10%), and individual contribution (10%). Students were also asked to evaluate their teammates. This peer evaluation result was used to determine individual scores for each student. The grading rubric is chosen in such a way that encourages students to focus on the overall product quality improvement process rather than technical contents only.

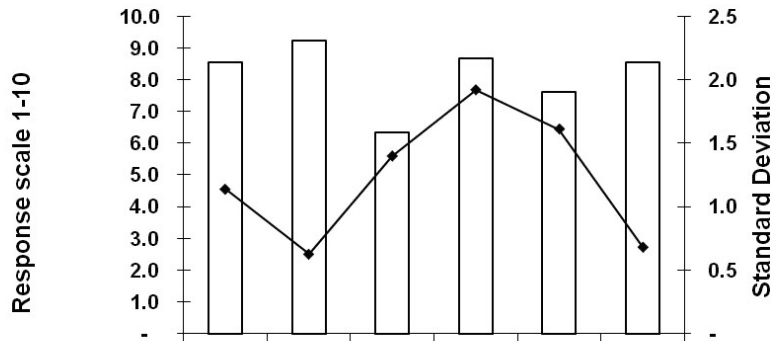
Assessment of the project-based Six Sigma teaching was accomplished by a carefully designed anonymous survey and a final examination. In the survey, students were asked to comment on what aspects of learning Six Sigma worked well and what could have been done differently. In addition, they gave numerical scores (on a scale from 1–10, 10 being the best or strongly agree) and comments to the following six questions:

1. How likely will you use Six Sigma tools in your future projects?____
2. Is the Six Sigma approach effective in improving the existing design?____
3. Did we spend enough time in class/lab to learn Six Sigma?____
4. Were the weekly meetings helpful and effective?____
5. Do you prefer to work on a Six Sigma project over a regular project?____
6. Overall evaluation for the usefulness of the Six Sigma project____

With a sample size of 30, the averages and standard deviations for these questions are summarized in Fig. 8.

Most of the students thought that Six Sigma was effective in improving the existing design (Question 2). This question had the highest average score and lowest standard deviation. The average score for the effectiveness of the weekly meeting (Question 4) is 8.7, however the standard deviation is the largest. The overall evaluation (Question 6) had an average of 8.5 and the second lowest standard deviation. Questions 3 and 5 received low scores with relatively large standard deviation. The students thought more time was needed in teaching Six Sigma. This is apparently due to the fact that the material was taught in one lecture and the students learned the details while trying to follow the DMAIC process during their projects. The students probably need time to get used to the new teaching method. The high averages for Questions 1, 2, and 6 show that the students felt they learned the material effectively.

In addition, most of the comments by the students were very positive: "I think this is an awesome project. It is good to learn the methodology to solve huge problems on a small scale like this." "Great for future projects!" "Project




| | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 |
|---|---|---|---|---|---|---|
| Response | 8.5 | 9.2 | 6.3 | 8.7 | 7.6 | 8.5 |
| Standard Dev | 1.1 | 0.6 | 1.4 | 1.9 | 1.6 | 0.7 |

Fig. 8. Average and standard deviation of the responses.

management is very helpful." "We got to see how business operations work in the real world." One student had an interesting observation about the Six Sigma project: "I learned it is easier to build than to fix." Through the Six Sigma project experience, the students realized that technical expertise is just one aspect of the successful product design effort. The emphasis on the Voice of the Customer is crucial when a commercial product is designed.

In addition to the student survey, the performance of a total of 30 students in the final examination was used to analyze the effectiveness of the new project-based learning-by-practicing method. The scores for the Six Sigma related problem are compared to the average scores of the other problems to see if there is significant difference in students' learning of materials taught with different teaching methods. Since the scores for Six Sigma-related problems and other problems are available for each student and the goal is to find out if the means for the scores are significantly different, the most appropriate analysis tool is the paired t-test with the following hypotheses:

**$H_0$**: $\mu_1 = \mu_2$ (The scores for Six Sigma related problem had the same average as those for other problems.)

**$H_1$**: $\mu_1 > \mu_2$ (The scores for Six Sigma related problem had higher average as those for other problems.)

The statistics from the final examination are summarized in Table 1.

$$t = \frac{\bar{d}}{s_d/\sqrt{n}} \qquad (1)$$

where $n$ is the sample size and equal to 30 in this analysis, $\bar{d}$ is the difference between the means of the two types of the problems, $s_d$ is the standard deviation of the difference, and $t_{0.05,\ 29}$ is the value in the t-distribution table [7]. A 95% confidence level is used. The $t$ value in equation (1) can be easily calculated using the statistics in Table 1 to be $t = 3.37$, which is greater than $t_{0.05,\ 29}$. Therefore, with a confidence level of 95%, the null hypothesis **$H_0$** is rejected and the alternative hypothesis **$H_1$** is accepted, i.e. the students' performance on the Six Sigma related problems was better than their performance on other problems.

Compared to the course projects completed in previous semesters, the following improvements were made by the student teams:

1. The projects were better managed.
2. The quality of the products was improved in terms of functionality, reliability, and cost.
3. The designs were supported by more test data and analysis of data.
4. There were significant improvements in documentation.
5. The average score of the course project was improved from 81% to 92%.

Table 1. Statistics of final examination scores

| | Mean | Standard deviation |
|---|---|---|
| Six Sigma problem | 85.33 | 12.79 |
| Other problems | 80.36 | 8.47 |
| Difference | 4.97 | 8.06 |

The paired t-test is to compare the following quantity to $t_{0.05,29} = 1.699$

## 4. CONCLUSIONS

A project-based learning-by-practicing method was applied to an instrumentation course project to teach the Six Sigma principles to junior level Electronic Engineering Technology students. The students learned to use many Six Sigma tools during the project. This better prepared them for the senior design projects and for their jobs after graduation. After this project, the students will have a general understanding of Six Sigma and will be able to make decisions on which tools to use for a particular problem in each of the DMAIC stages. The exposure to the tools and processes will better prepare them to study a particular topic or tool in more depth later if necessary for their career. The course was a success for the students and the instructor. The effectiveness of the new method for Six Sigma education was validated based on the statistical analysis of the student survey results, the comparison of the students' performance in the final examination between the Six Sigma-related problems and other problems, and comparison of the accomplishments of students teams on the course projects. The main objective of the course project, which was to reduce the gap between the education and the real world, was achieved.

The new teaching method provides an alternative way for Six Sigma education in engineering programs to those discussed in the literature. Future work includes getting feedback from former students several years after they graduated. This process can be repeated and reinforced in several technical course projects in junior/senior level courses and senior design projects. In different courses, some focused area can be identified to further learn Six Sigma knowledge. For example, in a Mixed Signal Testing course, Gauge R&R can be the focus. In a Control System course, modeling, simulation, and regression analysis can be the focus areas. In a Wireless Communication course, Design of Experiments can be used to optimize the communication throughput. In Senior Design projects, the entire DMAIC process and many related tools can be used to improve the product quality. Design For Six Sigma (DFSS) can also be taught for new product development.

Hopefully, the teaching experience presented in this paper can raise the awareness of Six Sigma, encourage more research and practice in this area, and provide some useful information for others who want to teach Six Sigma to engineering students.

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