AC 2007-3119: A DESIGN METHODOLOGY FOR EMPOWERING PROJECT-BASED LEARNING

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A Design Methodology for Empowering Project-based Learning

Abstract

One of our primary objectives is to equip undergraduate engineering students to be successful global engineers, ready to face the challenges of the 21st century. Students need to develop self-directed learning skills, systems level thinking, the ability to integrate principles of sustainability into design solutions and recognize that they serve a global community. Project-based learning (PBL) has been identified as an effective process for developing these skills; however, to be effective, project-based learning activities require a clearly articulated design methodology. Engineering students must learn to recognize the similarities and differences between the scientific and design methods. Both can be looked at as systems for solving problems; however, the input for the scientific method is a theory with the output being increased knowledge while the input for the design method is an application with the output being a device or process. Design is a method that involves both creativity and innovation but it is also constrained by such practical factors as time-to-market and cost-effectiveness. Throughout their undergraduate education students are immersed in the scientific method but often they are not exposed to design methods until their capstone senior project. We have developed a seven-step method that guides students through projects and enables them to achieve the skills we have identified as essential to their success as global engineers. The steps include 1) identifying user's needs, 2) developing product concepts, 3) translating performance requirements from the language of the customer into technical functional requirements, 4) brainstorming several conceptual designs and choosing the optimum solution, 5) developing a detailed design solution, 6) fabricating a prototype and testing to ensure that it meets the performance requirements and 7) determining the commercial feasibility of the design solution. An example of how we implemented this design method in our junior level electrical and optical properties of materials course is presented along with an assessment of our student's confidence in being able to apply the design method to the types of unstructured problems they faced in their PBL activities.

Equipping the Global Engineer

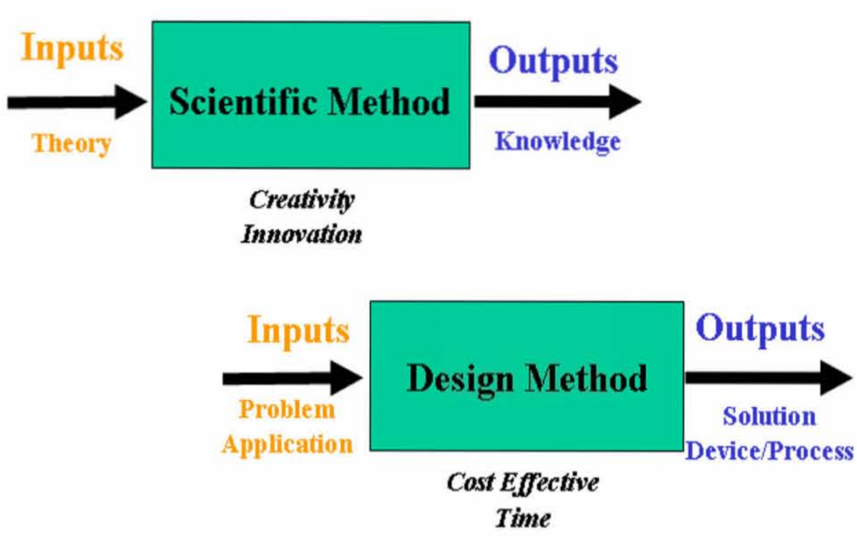
One of the primary objectives as an educator is to equip engineering students with the tools necessary to become successful global engineers, ready to face the challenges of the 21st century. Students need to develop self-directed learning skills, systems-level thinking, the ability to integrate principles of sustainability into design solutions and recognize that they serve a global community. Project-based learning (PBL) has been identified as an effective process for developing these skills[1]. However, to be effective, project-based design activities require a clearly articulated design methodology. Engineering students must recognize the similarities and differences between the scientific and design methods. Both can be looked at as systems for solving problems, but the input for the scientific method is a theory with the output being increased knowledge while the input for the design method is an application with the output being a device or process. Design is a method that involves both creativity and innovation but it is also constrained by such practical factors as time-to-market and cost-effectiveness. Throughout their undergraduate education students are immersed in the scientific method but often they are not exposed to the design method until their capstone senior project. At Cal Poly, we have developed a seven-step design method that guides students through their project-based learning activities and enables them to achieve the skills that are essential to their success as global engineers.

Design is a Key Element in the PBL Tool Kit

The dictionary defines *design* as "a process to create, fashion, execute, or construct according to a plan." The Accreditation Board for Engineering and Technology (ABET) defines it as "a process of devising a system, component, or process to meet desired needs." Practically, design is an iterative decision making process that applies the basic principles of the sciences, mathematics and engineering to solve a problem. A good design solution requires engineers to approach the problem with a systems perspective. It requires them to recognize how the design will operate in relationship to the world around it. Moreover, being proficient at design requires creativity and judgment as well as a mastery of technical fundamentals[2-5].

Design is a methodology that blends science with engineering[6]. It involves inquiry and innovation but it is also constrained by practical factors such as time-to-market and cost-effectiveness. Engineering students must learn to recognize the similarities and differences between the scientific and design methods. The goal of the scientific method focuses on the establishment of fundamental truths from theories that have been proven by extensive observation, testing and analysis. The goal of the design method is to produce a product that satisfies the functional requirements derived from a customer or market application. Looking at the design method as a system, a customer's application would provide the inputs with the output being a product that meets the requirements of that application, as illustrated in Figure 1. Within the system, there is a loop that begins with establishing the performance and functional requirements of the application, then establishing a design solution that must be verified against the original requirements. This is an iterative process that continues until all of the performance requirements for the application have been achieved. Minimizing the number of iterations is the key to minimizing time-to-market and costs which also increase the likelihood of the product's success in the marketplace.

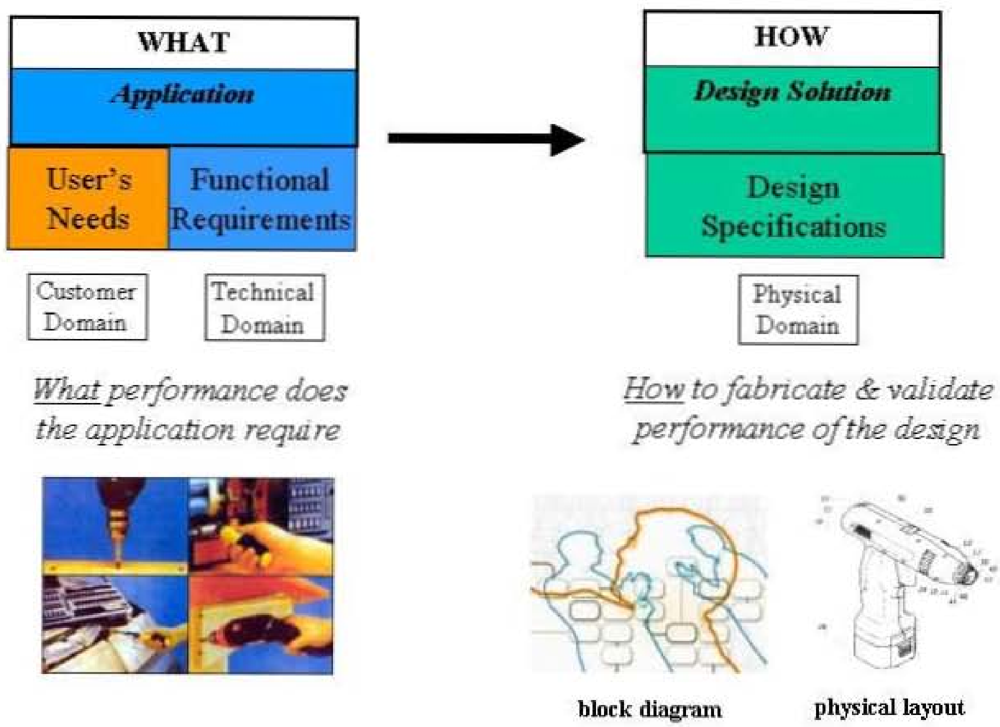
Figure 1 – Looking at the design method as a system



What are the Goals of the Design Method?

The *design method* begins with a careful evaluation of the needs of a customer or marketplace and a specific application or problem that must be solved. A product concept that meets these needs along with a complete set of performance goals for the product or device must be established. The user's performance goals must then be translated from the customer's domain into the technical domain. Functional requirements and boundary conditions or constraints must be identified that completely define what performance the application requires, as illustrated in Figure 2. Next, through brainstorming sessions, several conceptual design solutions that satisfy these functional requirements should be outlined. The optimum solution should be carefully selected utilizing a decision matrix. A detailed design solution must then be documented including a block diagram of the product's sub-systems and components along with a detailed list of its physical specifications. From these specifications a prototype should then be fabricated and the design must be thoroughly tested to verify that it meets all of the functional requirements. The results of these tests must be clearly and effectively reported so that the commercial feasability of the design can be determined.

Figure 2 – The language of the design method



A 7-Step Design Method

A 7-step design method has been developed for our project-based learning activities and it has been incorporated throughout our undergraduate curriculum in the materials engineering department at Cal Poly. A summary of the activites associated with each step follows:

Objective: devise a system, component, or process that meets a user's need and brings value to society

Steps:

1 - Evaluate the Application
2 - Develop a Product Concept
3 - Define Functional Requirements
4 - Brainstorm Conceptual Designs
5 - Create a Detailed Design Solution
6 - Fabricate & Test Prototype
7 - Commercialization

Step 1 - Evaluate the Application

At the beginning of each project students should profile their user's needs. An engineer should have a broad systems-level perspective of all of the technologies that define the user's performance requirements. Students should be guided to develop a holistic perspective or understanding of the application. This will allow them to balance and optimize their design solutions to achieve the targeted performance goals in a timely and cost effective manner. It is important to develop a user profile that prioritizes performance requirements and articulates the hierarchy of the user's requirements.

Step 2 - Develop a Product Concept

The product concept should solve a problem that has value to the customer. Product concepts can be evolutionary, based on making small changes to existing designs or revolutionary and based on taking an entirely new approach. Here is the opportunity to practice creative and innovative thinking and instructors should ncourage students to consider ideas that embrace new paradigms, such as selecting materials that would enhance sustainability by reducing a product's overall energy footprint. The product concept should include a detailed description of *what* the device should do and *why* it needs to do it. Performance requirements should be clearly articulated in the language of the customer and the operating conditions or environment of the product must be characterized.

Step 3 - Define Functional Requirements

Functional requirements are the minimum set of technical requirements that completely characterize *what* the design must do in order to satisfy the user's needs. They should be expressed in technical terms or in the language of an engineer. Make sure all of the functional requirements are clear, mandatory and prioritized. They should cover areas like operating environment (temperature & humidity), physical dimensions, weight, ergonomics, serviceability, reliability, safety and life-cycle goals. Functional requirements should be non-ambiguous, achievable and verifiable. Develop a prioritized hierarchy for the functional requirements along with any design constraints or relevant boundary conditions. Make sure you identify any functional requirements that are dependent on each other. Dependent functional requirements are often described as being coupled. For example, if your product concept is a faucet and a user's goal is to deliver water at a constant temperature regardless of flow rate, then the functional requirements for water temperature and water flow rate are coupled. A faucet designed with two separate knobs to control the hot and cold water would not easily achieve this user requirement. It would be difficult to turn both knobs equally to maintain constant temperature while increasing flow rate. A better but more complicated and costly design would employ a single lever with a mixing control mechanism that would balance the proportional amount of hot and cold water while increasing flow rate. Typically, large numbers of coupled functional requirements lead to more complex design solutions.

Step 4 - Brainstorm Conceptual Designs

The next step involves identifying *how* to physically achieve the functional requirements. It is the step where the engineer must translate the functional requirements from the customer's technical performance domain into the physical reality domain. Creativity and innovation should be applied during this step and more than one conceptual design solution should always be evaluated. At this point, any and all ideas, no matter how radical, should be considered. Brainstorming sessions are an effective process for a team of students to create and evaluate different design concepts. Conceptual designs require students to identify and acquire the knowledge or skills necessary to translate functional requirements into physical specifications. This gives students the opportunity to practice their self-directed learning skills.

Conceptual design solutions can be developed by utilizing concept mapping techniques to sketch out the physical structure of a design solution[7]. Concept maps provide a visual framework for guiding creative out-of-the-box thinking or blue-skying ideas. Students should sketch out a block diagram and a physical layout of the design concept, then make sure everyone on a team agrees on the major sub-systems and components before going any further. Teams should focus on the top-level requirements and not get bogged down in the minutia and wind up arguing about the details of any one idea. Challenge everyone on the team to participate and embrace the design concepts that everyone agrees upon. This gives the teams an opportunity to practice their conflict resolution techniques. It also provides an opportunity for teams to build trust and respect along with laying a foundation for good communication skills.

Dry erase boards or large sheets of drawing paper are the best media for documenting this process. Teams should begin by drawing a block diagram of the major sub-systems (e.g. hardware, software & electronics) of a prospective design solution. Next, visualize and sketch the actual layout of each sub-system and identify the major components associated with each. Circle the components on your diagram and use arrows to show where they fit into the sub-systems of the block diagram. The concept map should identify any linkages or "coupling" between dependent functional requirements. Use dashed lines to indicate which components are linked in their design requirements. Continue working on a concept map until all of the sub-systems have been broken down into either components that will be purchased or parts that will be fabricated. List all of the primary specifications for each component by using a fishbone type diagram that is attached to each component with a solid line. Make sure to include measurable tolerances and put limits on each of the specifications. Instructors should review each concept map and make sure that all of the functional requirements are achievable and that the design does not violate any of the design constraints.

Decision Matrix: Now the engineering team must analyze the strengths and weaknesses of each of the conceptual design solutions. Consider the following criteria:

1) technical performance
2) manufacturability
3) reliability
4) safety
5) ergonomics/aesthetics
6) life-cycle analysis
7) costs
8) schedule

Evaluate each conceptual design in light of these criteria. Construct a decision matrix (e.g. numerical evaluation matrix) that quantifies how well each design concept performs in each of these key areas. Every member of the engineering team should assign a score from 1 to 10 for each criterion. A ten means that the design concept fully meets all expectations associated with the critera. The criteria can also be weighted to balance out their importance in the overall scope of the design project. The design concept with the highest score should be selected to move onto the next step of detailed design. It is important to make sure that the entire engineering team embraces and accepts this decision. Any doubts or disagreements should be fully discussed until a consensus of agreement is reached by everyone. Here is where “the rubber meets the road” for teamwork.

Project Plan: Once the optimum conceptual design has been selected, it is time to lay out a project plan for developing the product. Begin by clearly articulating a statement of work which defines the tasks required to completely implement and document the design, fabricate a prototype, test its performance and validate that it meets all of the functional requirements. Identify the timeframe for starting and ending the project based on the number and duration of all the tasks required. Develop a work breakdown structure based on the tasks and identify duration, manpower and resource requirements. The tasks should be integrated into a Gantt Chart which will be utilized to create the overall project schedule. A roadmap should be constructed that gives the overall timeline for the project and highlights major milestones that can be used to track progress. A preliminary cost analysis should be included that estimates: 1) the material costs to fabricate a prototype and 2) the man-hours required to complete the project. It is helpful if students update the project plan each week and comment during their final project report on why they did or did not hit their target schedule and costs for the project.

Conceptual Design Review: After the project plan has been completed, a conceptual design review should be held. A summary of the design concepts that were considered along with the results of the decision matrix that support the team’s final design choice should be clearly communicated. Each team holds an informal oral design review with the instructor and must submit a decision matrix including the rationale for selecting the final design concept, block diagram, sketch of physical layout, project plan and cost analysis.

Step 5 - Create a Detailed Design Solution

The conceptual design step should have generated a block diagram for the product, sketches of the major sub-systems and specifications for key components and parts. Now the engineering team must begin the detailed embodiment of the design and produce a full documentation package including: 1) a systems level diagram and layout drawings, 2) detailed part & assembly drawings, 3) assembly/test procedures and 4) a bill of materials. The engineering team begins by expanding the basic block diagram from the conceptual design into a more detailed system level diagram. Layout drawings should then be generated showing the exact physical relationship of multiple components followed by detailed drawings of individual components. All component dimensions must be properly toleranced, fabrication materials selected and detailed manufacturing processes specified. Drawings are usually generated using computer-aided design (CAD) software routines and must follow ANSI (American National Standards Institute) and/or ISO (International Standards Organization) standards. ANSI/ASME Y14.5 (1994) standards for geometric dimensioning and tolerancing are widely accepted today and guidelines for implementation can be found in many textbooks. All of the parts contained in the final design solution must be listed in the bill of materials (BOM) along with part/drawing numbers, quantity, suppliers and estimated costs.

Final Design Review: Each team presents the details of their design solution to the entire class and there should be an opportunity for peer review and feedback on the merits of their design. Once approved, the teams continue onto the final step which involves fabricating a prototype and testing its performance.

Step 6 - Fabricate & Test Prototype

Finally, it's time to cut metal and build a prototype. Remember that designs typically undergo several cycles of design-build-test-redesign-build-test before they are completed. Usually it is easy to reach the 90% completion level on the design but it's that last 10% that can make the biggest difference to the project schedule. It is important that the most critical part of the design be tested early in the process. Frequently, engineers test the easy things first and leave the really difficult parts to the end. This is a sure way to encounter project delays. First, test components, then sub-assemblies and finally the entire system. It is important that your tests are capable of leading to conclusive answers. The quantity of data that is collected does not count; it is the quality of the data and its ability to verify that the design meets the functional requirements.

Final Project Report: Oral presentations are given by each team along and written reports are submitted by each individual; both are evaluated according to a published grading rubric. Self-assessment, peer-assessment and instructor-assessment tools are utilized to reach a final grade for each member of the project team.

Step 7 - Commercialization

In industry, after the product is designed, built and tested and hopefully meets all of the functional requirements and user performance goals then the design team must convince management that it makes good business sense to commercialize the product. It is important to remember that every design must make business sense (e.g. achieve revenue targets, be differentiated from competition and meet return-on-investment expectations) for the company to continue to invest and bring the product (device) to the market.

Implementing the Design Method – A Light Measurement System

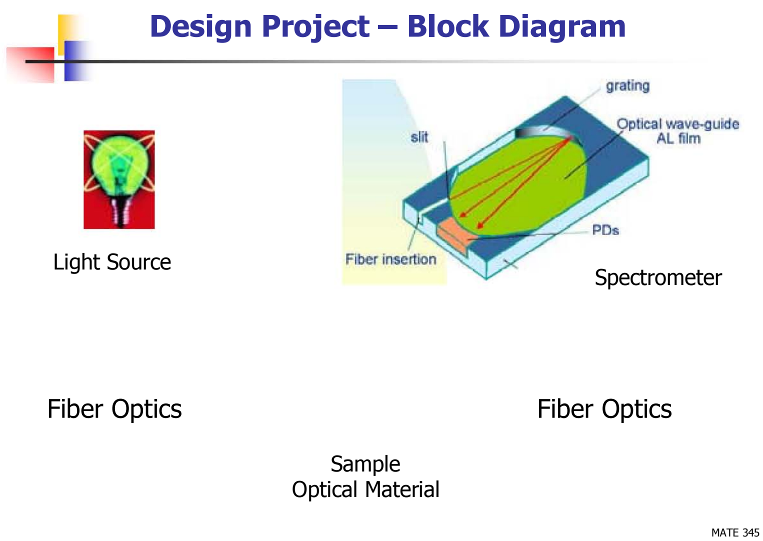
The following project was completed as part of the junior year curriculum in the materials engineering department at Cal Poly State University in San Luis Obispo, CA. The project provided a frame of reference for learning the principles behind the optical and electronic properties of materials. The project challenged students to design, fabricate and test a light measurement system. The system must generate photons, launch them down a fiber optic cable to a sample holder that directs the light through a transparent sample, then separates the light by wavelength (energy) and converts the photons into electrons for counting. The objective of the project is to measure the optical behavior of three different types of transparent samples (color, bandpass & interference filters). The learning objectives centered on equipping students to be able to perform the following tasks:

- Develop design solutions from a systems or holistic perspective
- Collect and interpret spectral data to determine the optical behavior of materials, such as, color, bandpass and thin-film interference effects
- Design and fabricate a fiber optic cable as a light conduit cable
- Develop part drawings with proper geometric dimensioning and tolerancing for cost effective fabrication
- Develop a breakdown structure for a design project and summarize it in a Gantt Chart
- Contribute effectively as a member of a design project team and resolve conflicts by consensus building
- Use written and oral communications skills to effectively convey the results of their design project to their peers and customer
- Demonstrate a capacity to solve problems through self-directed learning and extract key technical information from the literature and relevant technical resources

Evaluate the Application: To properly design such a system the students needed to understand how each component of the system works together to produce the desired performance result. The sample materials were a series of optical filters which could be utilized in a wide range of industries including LCD displays, medical instruments, astronomy, defense systems, photography and industrial process control. Some types of filters selectively block portions of the visible spectrum (color filters), others transmit a range of wavelengths across the optical spectrum (broadband) and some only transmit a very narrow range (interference) of wavelengths. Their light measurement system must be able to determine the following properties for the optical filters: 1) spectral bandpass or transmission efficiency (0-100%) over the 300 to 900 nm region of the optical spectrum, 2) the range of wavelengths with a %T greater than 1% (passband), 3) the cutoff wavelength where the %T value is one-half of the maximum %T, 4) the central wavelength which yields the maximum %T (interference) and 5) the full width half maximum (FWHM, nominally 10nm) bandpass around the central wavelength. For the color filters (red/green/blue) the CIELAB color values should be determined from the spectral transmission profiles.

Develop a Product Concept: A block diagram for a basic light measurement system is illustrated in Figure 3. The system utilizes a commercial quartz halogen light source that is capable of providing spectral energy over the 210 to 1500nm wavelength range. The source delivers light to the 1st fiber optic cable through an SMA connector. The 1st fiber optic cable must be terminated with an ST style fiber optic connector and interface to a sample holder designed to hold all the optical filters. The light will exit the sample holder and be transferred into a 2nd fiber optic cable through a ST connector. It will exit the 2nd optical fiber through an SMA connector attached to the input of a wavelength sorting device (spectrometer). The spectrometer separates the wavelengths of light using a diffraction grating and images the light onto a CCD detector. The detector will convert the photons into electrons and software must be written to plot the number of electrons detected (counts) versus wavelength of light and calculate the optical properties that have been specified for the filters. The students were asked to perform a light throughput analysis on the system and beginning with the sensitivity and signal-to-noise specifications for the detector work back through the system and determine the light losses associated with each component. From this analysis they could determine what illumination intensity would be required to achieve their precision required by the measurement goals defined by the application.

Figure 3 – Block diagram of light measurement system



Like most engineering projects, their systems will include commercially available parts along with components that each team of students must design and fabricate. For this project, the light source and spectrometer were provided and the teams focused on the fabrication of the fiber optic cables along with the design and fabrication of the sample holder. In addition, all of the materials used in the design must comply with RoHS/WEEE regulations, which restrict the use of certain hazardous substances in electrical and electronic equipment.

Define Functional Requirements: The next step in the design method is to translate all of the performance goals into functional requirements. It is important to captures all of the design constraints and a few of the key requirements for the light measurement system are listed below:

- Send/Receive Optical fibers: 100mm core, NA=0.22, θ_a= 12.5^o
- Lateral misalignment of fiber cores < 10% (loss <0.5dB)
- Angular misalignment of fibers < 3^o (loss <0.5dB)
- Separation of send/receive fiber tips 20mm (loss 40 dB)

- Polished & clean ends of optical fibers (loss < 0.5dB)
- Accepts Fiber terminated in ST-type connector: 0.100" dia.tip
- RoHS compliant materials: no Cd, Hg, Cr^{+6}, Pb, polybrominated biphenyls or polybrominated diphenyl ethers
- Hold 3-filters with 1.0, 1.1, 1.2 inch diameters & 0.125, 0.25, 0.375 thickness
- Concentricity of filters to send/receive fibers ± 1mm
- Transmits wavelengths from 300 to 900 nm with a resolution of 1 nm

Brainstorm Conceptual Designs: Each student team held several brainstorming sessions. The teams were required to develop three different concepts for a sample holder design and interface to the fiber optic cables. Some of the designs required students to investigate the use of optical elements such as lenses for collimating and transferring the illumination light through the optical filters. Each team generated three sketches and identified key components for each design. A decision matrix was developed which evaluated each design based on 1) technical feasibility, 2) alignment and calibration, 3) manufacturability, 4) reliability, 5) light throughput efficiency, 6) RoHS compliance, 7) cost and 8) schedule. The design with the highest score was selected and the results from each team were presented at a Conceptual Design Review. A project plan was developed next based on a work breakdown structure. All of the tasks required to complete the project (detailed design, fabrication, test and data analysis) were identified along with their duration, dependence factors and resource requirements. Gantt chart was constructed including major milestones (such as design reviews) and the critical path for the project was identified. A parts list and cost model for the purchased and fabricated parts was included in each team's project plan.

Create a Detailed Design Solution: Each team then proceeded to create a documentation package that included a system level diagram with detailed specifications along with layout and detailed part drawings created in SolidWorks . All the drawings were checked to insure that they were properly dimensioned and toleranced for fabrication. Details for each design were presented to the entire class at a Final Design Review, before the teams were given the approval to continue with fabrication and purchasing of required materials and components.

Fabricate & Test Prototype: Each team fabricated their own sample holder through CNC milling and lathe operations or with a Z Corp rapid prototyping machine. Fiber optic cables were assembled by attaching 3M Hot Melt ST connectors to multi-mode fibers and polishing the tips for maximum transmission. The parts were integrated with the other purchased parts such as lenses, a grating based spectrometer, a CCD linear array detector and a light source. The entire light measurement system was then calibrated to detect 0 to 100% transmission through the sample cell. Specific filters were assigned to each team and their optical properties were analyzed and reported in a final summary project report. Each team presented an oral final project presentation to the entire class and was assessed as a team by an external advisory board composed of people from industry, member of the materials engineering department and faculty from outside of our department. Each individual student prepared a final written project report which gave them an opportunity to demonstrate their individual capabilities.

Assessing Student's Ability to Apply the Design Method

Design is a cognitive activity that encourages students to develop skills in analysis, synthesis and application which are part of Bloom's taxonomy of educational objectives that we have adopted for our PBL curriculum[8-10]. In order to assess our student's understanding and abilities to apply the design method we have adopted the Design Attribute Framework Survey developed by Safoutin[11.] This survey asks students to consider their level of confidence when solving unstructured design problems and includes the questions outlined in Table 1. The questions consider the following design attributes: need recognition, problem definition, planning, information gathering, idea generation, modeling, evaluation, feasibility analysis, selection, implementation, documentation, communicating and iteration. Safoutin describes the characteristics of each of these attributes in detail and they can be summarizes as follows:

- **Need recognition** – identifying the needs to be served by the design
- **Problem definition** – transforming statement of need to statement of design objectives (functional requirements)
- **Planning** – develop a design strategy (work breakdown structure)
- **Management** - make changes to the initial plan as necessary
- **Information gathering** – gather data to verify the performance requirements
- **Idea generation** – transform functional requirements into physical possibilities
- **Modeling** – employ models to inform design decisions
- **Feasibility analysis** - evaluate multiple alternatives in terms of constraints
- **Evaluation** – use criteria to objectively judge acceptability of outcomes
- **Selection** – discern feasible solutions
- **Implementation** – build prototype of system and test the design performance
- **Communication** – exchange design information with others utilizing appropriate formats
- **Documentation** – produce usable documents of record regarding the design process
- **Iteration** – incorporate new knowledge into design decisions

While we recognize that no single set of survey questions can serve to verify that students are competent in these attributes of the design method, the results can indicate if our student's perceptions and levels of confidence in their abilities are changing. Our hypothesis is that students (juniors, in materials engineering at Cal Poly) exposed to the design method through PBL activities would indicate a higher degree of confidence in practicing the design attributes than the quasi control group (students from across the college of engineering at Cal Poly including civil, mechanical, electrical, manufacturing and aerospace engineering) who have not been exposed to our PBL based curriculum. We should note that students at Cal Poly are immersed in a "hands-on" learning environment and so the control group has been exposed to some elements of the design method through courses outside of the department of materials engineering.

Table 1 also tabulates the means for the responses from the junior and control groups along with p-values (one-tail) calculated by a t-Test assuming unequal variances. Questions in bold and italic indicate items for which the junior cohort scored higher than the quasi-control group at a significance level of less than 0.05 (i.e., using a 95% confidence interval).

Table 1 – Safoutin's design attribute framework survey
For the following statements about solving unstructured design problems, indicate your level of confidence.

Disagree - 1	Disagree Somewhat - 2	Unsure- 3	Agree Somewhat - 4	Agree - 5	X juniors	X Control	P value
1. Recognize the needs to be addressed by the problem.					3.56	3.43	0.244
2. State the needs of the problem in clear and explicit terms.					3.66	3.38	0.106
3. List the performance requirements that a solution must satisfy.					3.91	3.48	0.008
4. Establish criteria for evaluating the quality of a solution.					3,47	3,28	0.193
5. Develop a solution strategy given a model of the design process.					3.68	3.26	0.025
6. Divide a problem into manageable components or tasks.					3.84	3.64	0.179
7. Identify the knowledge and resources needed to develop a solution.					3.78	3.29	0.011
8. Describe procedures or techniques to search for and generate solutions.					3.50	3.05	0.023
9. Generate possible alternative solutions.					3.56	3.33	0.148
10. Select a mathematical model that can be used to characterize a solution.					2.97	2.71	0.156
11. Identify the pros and cons of possible solutions.					4.00	3.74	0.101
12. Compare a set of solution alternatives using a specified set of criteria.					3.50	3.45	0.412
13. Analyze the feasibility of a solution.					3.81	3.31	0.022
14. Select a solution that best satisfies the problem objectives.					3.91	3.72	0.186
15. Build a prototype or final solution.					4.09	3.14	0.000

16. Document your solution process.	3.25	3.33	0.365
17. Understand the different roles and responsibilities of being an effective member of a team.	3.75	4.00	0.127
18. Resolve conflict and reach agreement in a group.	3.66	3.83	0.238
19. Identify the characteristics of effective communication.	3.66	3.86	0.228
20. Recognize when changes to the original understanding of he problem may be necessary.	3.84	3.52	0.057
21. Suggest modifications or improvements to a final solution.	3.91	3.71	0.216
22. Develop strategies for monitoring and evaluating progress.	3.41	3.05	0.070

The results indicate that the junior cohort have a higher level of confidence in their ability to define the design problem and identify design requirements as well as implementing a plan for developing a design solution. They also seem more confident in their ability to practice self-directed learning and identify the resources needed to develop design solutions. Both of these are key elements that we have identified as critical characteristics of successful global engineers. In addition, the juniors were heavily immersed in the fabrication side of materials engineering, which has not traditionally been a strong part of our curriculum, and therefore their confidence in analyzing the feasibility of a design and the actual building of a prototype was significantly strengthened.

The survey was given to three cohorts of students 1) our materials engineering freshman class (45 students) immediately following the completion of a 10-week long PBL design activity, 2) our junior level materials engineering class (32 students) immediately after completing the light measurement project outlined earlier and 3) a control group of students (42 students) taking an introduction to materials engineering class composed of non-materials engineering students from other departments of engineering. All of these surveys were completed at the end of the Fall quarter of 2006 at Cal Poly State University in San Luis Obispo, CA. The average scores for each of the cohorts are summarized in Table 2.

Table 2 – Survey results for confidence of students at applying the Design Method

Design attributes	Freshman (PBL)	Sophomores	Juniors (PBL)
Need recognition	3.5	3.4	3.7
Problem definition	3.3	3.6	3.6
Planning	3.6	3.4	3.8
Information gathering	3.5	3.4	3.7
Idea generation	3.4	3.1	3.6
Modeling	3.2	2.7	3.0
Evaluation	3.8	3.5	3.8

Feasibility analysis	3.5	3.3	3.8
Selection	3.4	3.8	3.9
Implementation	3.2	3.1	4.1
Documentation	2.6	3.2	3.3
Communication	3.6	3.8	3.8
Iteration	3.5	3.4	3.7

Scores: 1-Poor, 2-Fair, 3-Good, 4-Very Good, 5-Excellent

The scores reflect the mean values for the entire class and indicate their level of confidence with 1 being Poor and 5 Excellent at their ability to apply the design attributes to unstructured problems. In the areas of planning, idea generation, feasibility analysis and iteration it appears that both the freshman and juniors, who have experience with PBL design activities, feel more confident in their abilities. Overall the juniors, who have had the most experience with applying the design method, demonstrate the highest levels of confidence across all of the attributes.

The survey data for the freshman cohort is still being analyzed to see if there are any statistical differences between their performances against the sophomore control group. However, the freshman class only meets once a week and their exposure to PBL and the design method has been somewhat limited. It would seem unlikely that they have had enough experience with design to expect that their levels of confidence at solving unstructured design problems has had enough time to become well developed.

Next Steps

Our goal is to continue to integrate the design method outlined in this report throughout all of our junior year PBL design activities. We are also developing an assessment strategy that can demonstrate evidence of competency in our student's abilities to demonstrate the learning objectives that we have identified as being critical for becoming a successful global engineer[12]. We intend to utilize the results from these assessments to guide our strategy for implementing continuous improvements in the design methodology.

Acknowledgements

This work was supported in part by a grant from the National Science Foundation (Grant#EEC-0530760). The views expressed in this paper are solely those of the author and do not necessarily reflect the views of the National Science Foundation. Valuable contributions were made to some of the project-based learning activities by Katherine Chen, Blair London, Trevor Harding and William Hughes.

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