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A Structured Approach to Capstone Design

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This paper reports on a structured approach to teaching and managing capstone design that we have developed at the University of Rhode Island in the Mechanical Engineering Program. The method applies to all types of design projects, including process or product design. The structured approach is based on a two-semester capstone design sequence. The first semester consists of defining the problem, conceptualizing solutions, analyzing, deciding among alternatives, and prototyping (DCP). The second semester consists of building a working model, testing, and redesign (BTR). We first developed capstone courses in 2007 and continuously made improvements each year to the present day.

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Background

A culminating major engineering design experience is a required curriculum element of engineering program accreditation by ABET.[1] ABET Criterion 5(d) requires that the major design experience incorporate appropriate engineering standards and multiple constraints and be based on the knowledge and skills acquired by students in earlier course work. The major design experience is more commonly named capstone design, senior engineering design, or senior capstone design in the engineering curricula.

ABET defines engineering design as "a process of devising a system, component, or process to meet desired needs and specifications within constraints. It is an iterative, creative, decision-making process in which the basic sciences, mathematics, and engineering sciences are applied to convert resources into solutions. Engineering design involves identifying opportunities, developing requirements, performing analysis and synthesis, generating multiple solutions, evaluating solutions against requirements, considering risks, and making trade-offs, for the purpose of obtaining a high-quality solution under the given circumstances. For illustrative purposes only, examples of possible constraints include accessibility, aesthetics, codes, constructability, cost, ergonomics, extensibility, functionality, interoperability, legal considerations, maintainability, manufacturability, marketability, policy, regulations, schedule, standards, sustainability, or usability."[1]

The structured approach described here is consistent with the ABET requirements. We structure the capstone experience as a two-semester experience where the first semester meets the ABET criteria. The second semester builds on the first-semester experience and accomplishments towards a more complete and mature design solution.

The structured approach is essential for industry-sponsored projects. A structured approach component is also to develop and implement an evaluation process. Well-written rubrics are crucial in teaching and communicating the complex process of design project evaluation to the student teams. Student teams are better equipped to respond to the demands of the capstone experience when they understand the evaluation metrics for their work.

The approach to structuring capstone design experience that we describe here has been implemented in the senior mechanical engineering capstone design sequence at the University of Rhode Island (URI) for the past ten years. More than 1000 mechanical engineering graduates have been educated with this approach successfully completing over 250 design projects (150+ industry-sponsored projects).

Structure by Project Management and Regular Reporting

Capstone design problems are complex and require teamwork, planning, regular activities, and management. The majority of engineering programs, including our engineering programs at URI, do not require a course in project management. Except industrial engineering and civil engineering programs typically have a project management course. So, we included two project management lectures in our capstone course to introduce our capstone design teams to project management and require that they use MS Project software to structure and plan their projects. The design teams are required to communicate their progress weekly in the form of a memorandum progress report, typically 2-4 pages. They are also required to maintain and update their project plans and submit them as an attachment to their progress reports. The progress reports, including the project plan Gantt chart, are forwarded to the project sponsors to communicate the project's status.

A critical component of structuring capstone design for success is regular project meetings and reporting.

Structure of the First Semester

The first-semester consists of: defining the design problem, conceiving multiple solutions, analyzing and deciding on the best solution among the alternatives, proving that the solution meets the design specifications, and documenting the design details in a preliminary design report.

Define the Problem

Figure 1 shows a diagram of our structured design workflow during the first-semester experience. Many considerations surround the design work and serve as guiding principles for the design work, e.g., safety, ethics, cost, sustainability, ergonomics, and operability.

The design work begins with defining the problem. Problem definition is crucial to the process. Design problem definitions that originate in the industry are open-ended and incomplete by their nature. The student design team must research the problem provided by gathering information from books, articles, conference papers, company-provided information, patents, and the internet. Gathering information may also include interviews with people who may be experts or even end-users of the designed process or product.

Problem definition also includes developing a set of comprehensive and quantitative design specifications. Design specifications are essential to conceiving design solutions and proving the validity of the design solutions.

Conceiving Design Solutions

Conceiving design solutions is the creative part of engineering design. We require that our students generate a minimum of 30 design concepts each, so a team of four students generates a minimum of 120 design solutions. This requirement seems daunting at first glance. However, our decade-long experience in the classroom with over 1000 students demonstrates that it is entirely reasonable for an average engineering student to generate the 30 design concept solutions. We employ several methods for teaching generating concepts, including brainstorming and the TRIZ[2] method.

Pugh Analysis[3], Quality Function Deployment[3], and charting (such as spider charts) are taught so students can decide among the alternatives.

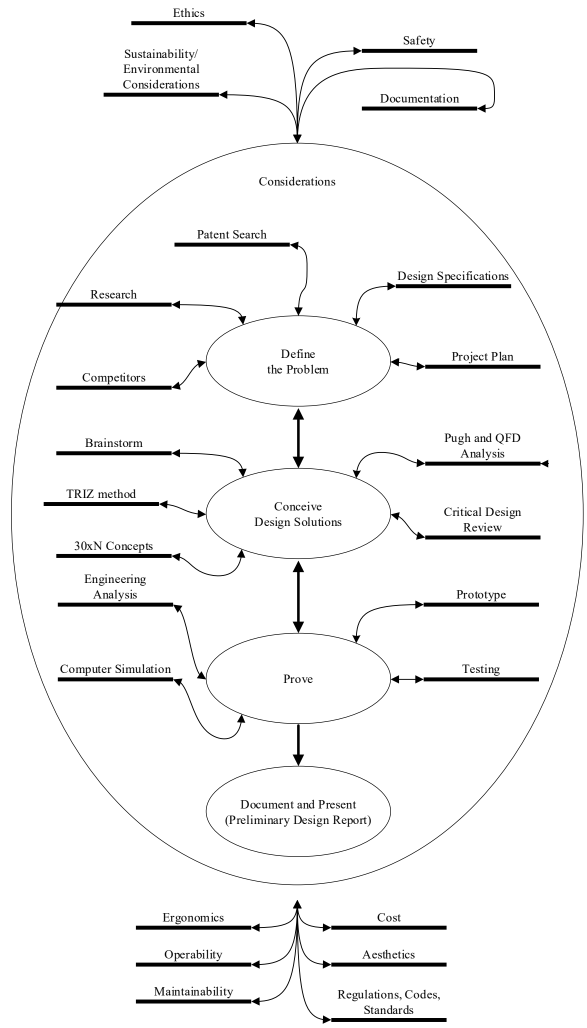

Figure 1. Semester 1 design workflow.

Proof of Concept

The design teams use Pugh analysis to reduce the number of alternative design solutions from the 120 design solutions down to 2 or 3 designs that are best among the alternatives. A critical design review(CDR) process is introduced so that the design team can receive feedback from their peers and mentors. After CDR, the team selects a single design solution and then proves that it meets the design specifications and satisfies the problem definition.

Proof of concept is achieved by a prototype of the design solution. The prototype may be a process or a product. The prototype may be a physical build or a simulation of the solution. It may be a part or the whole solution depending on the scope of the design problem.

Documentation

Documentation of the design process and solutions is a necessary requirement for semester 1 project closure and communication. Project sponsors demand and appreciate a design report that captures the entire process and design solution details. The design report is necessary to evaluate the team's work and their ability to communicate their work in a written and formal engineering document. Writing a design report is excellent preparation for entering the profession for engineering students.

Structure of the Second Semester

During the second semester (13 weeks), the design teams progress by building a working model of their design solution (process or product), testing the working model, and redesigning based on what was learned during the build and test steps.

Figure 2 shows the design flow during semester 2. The bubble around the workflow diagram shows the other considerations (safety, ethics, aesthetics, sustainability, operability, maintainability, etc.) surrounding the entire design activity in the form of design environmental conditions.

Build it

The build phase for the design solution involves manufacturing if it is a product. Manufacturing includes parts and then assembly. Manufacturing skills vary significantly among engineering students. Our program and engineering curricula typically do not include manufacturing methods such as machining and welding. Additive manufacturing techniques (3D printing) are included in our capstone design course because it is an effective way to create a physical working part or assembly to test many different design features. If the design-build scope is too large or complex, a simulation may be created instead.

For process design projects, the build is typically a simulation of the designed process to evaluate the process's timing, queuing, and sequencing.

Test it

The testing of the working model must be planned like a design project. The test engineering activities' scope and details must be managed so that testing can fit the project timeline and budget. Student teams learn about design project management and fit the test engineering phase into the overall project. For each test, the design team must record the test information and collect data for the test results. Each test is repeated multiple times (usually 3 or 5 times) for improved statistical results (average and standard deviation).

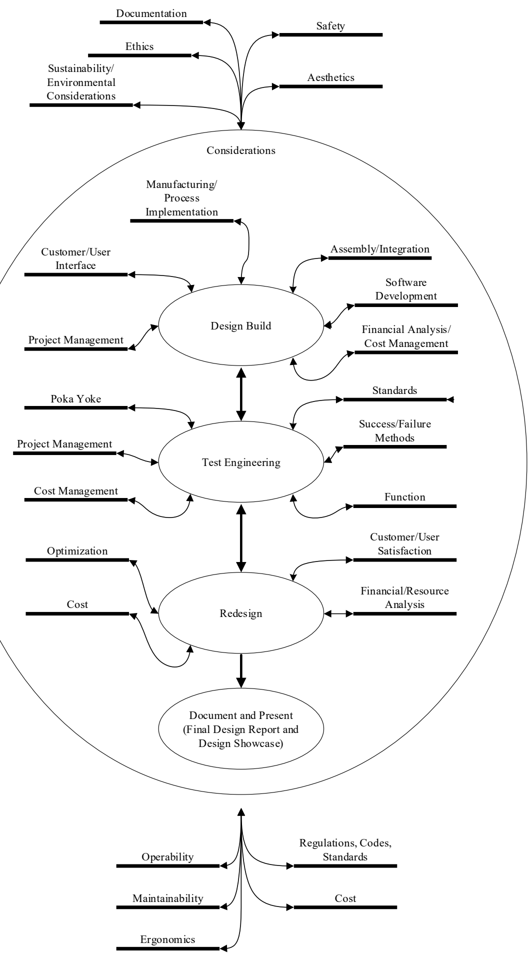

Figure 2. Semester 2 design workflow.

Redesign

Redesign is an inherent part of the entire design activity. Design is an iterative process where each iteration is a redesign. Information gathered from building and testing the design solution is essential to redesign improvements. Redesign iterations are expected to converge toward a better overall solution. However, the design team may run out of time before completing the redesign iterations. Most capstone design projects are first-time projects where there is no experience basis for proper scoping of the project for an exact match to the academic calendar time frame.

Redesign iterations are highly dependent on the scale and scope of the project. The larger the scale and scope, the fewer redesign cycles will be completed. For smaller projects, we have seen cases of 150+ redesign iterations. It is a good practice to expect a minimum of two redesign iterations for any project.

Final Design Documentation

After the two semesters of design activity, the project sponsor expects a comprehensive design report. The final design report is also required to evaluate the students' design work and assign a course grade. The final design report must capture all of the steps, the process, and details of the design steps and results. The entire two semesters of design activity, work, and analysis must be included in the report. Finally, design reports for our capstone classes at URI are an average of 150 pages (for 250+ projects over a decade).

Mapping Industry-Sponsored Design Projects to the Academic Calendar

The university's academic year timetable is relatively fixed and different from the industry timelines. Therefore capstone projects have a fixed timeframe and must conform to the academic calendar start and finish.

It is imperative to communicate the timelines with industrial partners and lay out the project plans so that students can accomplish their goals and meet their deliverables within the constraints of the academic semester (or quarter) boundaries. We have established the schedule for our projects that work very well with the industry projects.

Project Meetings and Interactions

The student project teams are taught and expected to behave like an engineering team. They regularly report and update their project progress. They produce agenda for their meetings. Take minutes of their meetings. Write progress reports and communicate with their sponsors by e-mail, phone, online and in-person meetings throughout their projects.

At the end of the design year, a comprehensive and concise presentation of the accomplishments of the project team and conclusions of the design project is a great way to wrap up the experience and communicate the results to the stakeholders.

A capstone design showcase is held at the end of the spring semester, which is open to all. Students showcase their designs and present their work in a poster format.

At the end of each year, a final wrap-up meeting is held with the student team, company management, focal, and professor in April-May time. The full design is reviewed, which usually includes a demonstration of the prototype design.

Capstone Design as an Assessment of Curriculum Effectiveness and Change

An essential role for capstone design in our curriculum has been in assessing our students' knowledge and abilities in working on open-ended design problems. The outcomes for our capstone design are assessed annually and reviewed by the entire faculty of the department. During the review meetings, the performance of our students on capstone design projects and the relationship to their knowledge and abilities are mapped back to our entire mechanical engineering curriculum. In this process, the weaknesses and strengths of our students are identified and discussed by the faculty. As a result of the regular capstone design assessment and review, we identified areas where our students could improve. For example, more design content during the earlier years was identified as an area for improvement. We updated three courses in our curriculum (machine design 1 and 2, and CAD) to contain more design content and included a major design project in those courses. Another area that we noticed an improvement was needed was in the programming skills of our students and abilities in the use of engineering software such as ABAQUS, MATLAB, COMSOL, FLUENT, etc. These observations resulted in the changes in the content of our courses in fluid mechanics, heat transfer, engineering analysis, machine design, and CAD. To further improve student computer and programming skills, we are in the process of creating a new course to be added to the curriculum at the sophomore level.

Capstone design has been an agent of change for our curriculum with detailed and measured assessment and identification of strategic changes to the content and structure of our curriculum.

Conclusions

The structured capstone design approach described here has proven to work well for our program engaging over 1000 mechanical engineering seniors for a decade. The method has successfully gone through two ABET reviews and has been instrumental in curriculum changes to better prepare our students for the capstone design experience and professional preparation.

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