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Structure as a Key to Successful Capstone Design Projects

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Structure in the form of design phases, phase exit checklists, learning modules, an example project, and a comprehensive handbook has transformed the mechanical engineering capstone design courses at Arizona State University. Prior to adding structure, over half of the projects failed to result in a complete and tested engineering prototype and a comprehensive final report. Based on industry product development processes and several iterations of course materials with student feedback, the authors have created a handbook and course structure that now results in all projects being completed on-time and within budget. These projects demonstrate that the teams meet all the ABET student outcomes as determined by an industry-led assessment fair. In addition, the students demonstrate their ability to use the entrepreneurial mindset as measured by the EM@FSE 2.0 Indicators developed at ASU as part of a Kern Foundation grant. This paper describes this structure, provides capstone project examples, presents objective evidence of course improvements and suggests ways of using this structure in other capstone courses.

Keywords: Capstone, Handbook, Projects, ABET.

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Introduction

Ten years ago, at Arizona State University (ASU), less than half of the mechanical engineering capstone project prototypes were working at the end of the two-semester senior capstone product development course. Today, all projects are delivered on-time and within budget. This dramatic turnaround is the result of using an innovative course structure as captured in a unique and affordable handbook.

The authors were assigned the task of improving this course due to their combined industry and academic experience. They were given the goals of each project team having (1) a validated, working prototype, (2) their project complete each design phase on-time and within the assigned labor and monetary budgets, and (3) a final presentation and report that convinces a team of faculty and industry assessors that the students have met all the ABET accreditation outcomes. Later, the outcome of demonstrating the ASU 17 Entrepreneurial Mindset (EM) indicators became an additional goal.

The authors started with a survey of existing design textbooks[1,2,3,4]. These textbooks were well-written and authoritative. But, none of them explicitly guided the project team on what to do, how to do it, when to do it, and what the specific outcomes should be. It was decided that a new textbook was needed. One that covered the product development topics in parallel with guiding the teams through the product design and development process. It needed to be useful not only during the capstone course, but also when the students graduated into industry. It needed to be a handbook.

Every year at ASU there are 30 to 35 mechanical engineering teams that present at the ABET Assessment Fair. Many of these projects are industry sponsored. All teams meet the ABET and EM outcomes. Many students initially object to the amount of documentation required by the course structure. However, end-of-course surveys indicate that these students along with the rest of the course participants now support this structured approach.

Several challenges still exist in quantifying the benefits of this structured approach. Next steps in this effort are covered at the end of this paper.

Capstone Handbook

The root cause of the unsatisfactory project outcomes was the assumption that the purpose of this course was for students to just demonstrate what they had already learned in their previous courses. The students knew how to do analysis and some testing, but they lacked skill in conducting a team-based product design and development capstone project. It was clear that the course needed more structure and that structure needed to address new learning as well as keeping the students on schedule.

The inspiration for this handbook was the renowned and successful integrated product delivery and support (IPDS) process developed at AlliedSignal Inc. The authors have modified and added more detail to this process. The result is the phased product development (PPD) process, which is the structural backbone of the course and handbook.

With feedback from every new class of capstone students and the Capstone ABET Assessment Fair, the handbook has evolved into a published book: *Product Design and Development Handbook: An Innovative, Entrepreneurial, and Structured Approach for Engineering Capstone and Industry Projects*[5].

This handbook leads the students through 44 learning modules. Each module starts with a lesson plan that includes an overview, learning objectives, pre-lecture individual assignment, post-lecture team assignment, and team deliverables. Both individual and team assignments for each module reinforce new learning as well as keep the team moving forward in preparing their project deliverables. Each project phase ends with a design review and the completion of a phase exit checklist. Individual and team reflection is a part of each assignment. The handbook integrates the engineering portion of product development into the larger process of product commercialization. Special emphasis is given to helping students gain an Entrepreneurial Mindset as developed by the Kern Entrepreneurial Engineering Network (KEEN)[6]. In addition to covering design, the book also addresses the important tasks of manufacturing, and developing and validating an engineering prototype. These activities are documented in an engineering prototype build book.

Capstone structure

This discussion of capstone structure starts with a description of the PPD process. This is followed by an explanation of how the course is divided into 44 learning modules. The paper also explains how the topics of the Goldsmith Commercialization Model, and the Entrepreneurial Mindset are key parts of the overall course structure.

Based on student feedback, an example product design and development example in the form of a travel iron was also added to the structure.

PPD process

As shown in Figure 1, the product development process is divided into six phases. Each phase has specific deliverables and culminates with the completion of a phase exit checklist and design review. During the first semester, each team forms, selects a project based on the National Academy of Engineering's Grand Challenges list, prepares a proposal and completes conceptual and preliminary design. There is not enough time during the second semester for design teams to take their projects all the way to production. Instead, the team selects key aspects of the production design to be featured in an engineering prototype that is part of the detailed design phase.

The engineering prototype is designed and manufactured during the first two-thirds of the second semester. This leaves adequate time for the unit to undergo development testing and the validation testing to ensure that the prototype meets all its engineering requirements.

At the end of each phase, the team prepares a draft of the applicable section of the final report. A detailed outline for the contents of the final report is included in the handbook. The team also presents a design review to the class and has their phase exit checklist reviewed and approved by the instructor. The course ends with the ABET Assessment Fair where each team presents their design to an industry panel of evaluators. Each team also submits a comprehensive final report and project notebook.

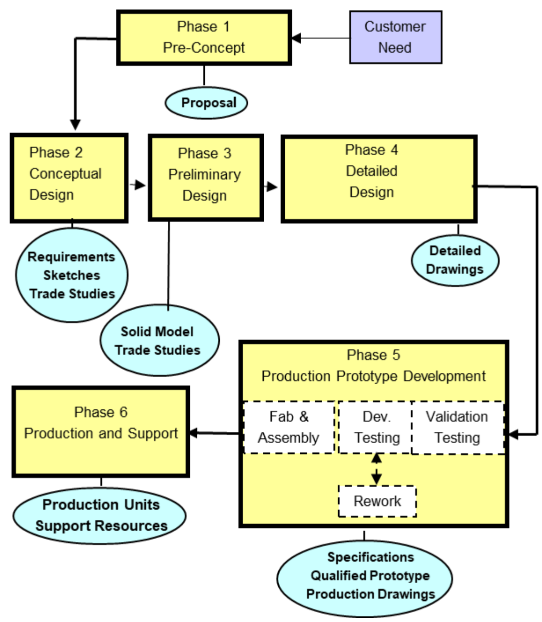

Figure 1. Phased Product Development Process

Learning modules

The learning modules provide an easy way for the capstone student or self-learner to study the material and conduct the project tasks. When this handbook is used in an academic setting, there is usually a lecture associated with each module. These lectures reinforce the concepts covered in the handbook; however, the reader can still receive the benefits of the lesson modules without the lectures. Table 1 lists the modules. Modules 1 through 28 are covered in the first semester.

Commercialization and the entrepreneurial mindset

An important part of the course structure is putting the engineering portion of product development into the broader context of commercializing the product. This is done by introducing the Goldsmith Model of Commercialization[7]. Figure 2 shows how this is accomplished. The idea of the engineer approaching product development with an Entrepreneurial Mindset has been embraced by Arizona State University

Table 1. List of Learning Modules

Module	
No	Title
1	Introduction to the Handbook and Course
2	Starting Work on the Proposal (Phase 1)
3	Project Selection
4	Selecting the Project Preconcept
5	Preparing the Project Proposal
6	Project Schedules and Budgets
7	Finalizing the Proposal
8	Completing Phase 1
9	Introduction to Phase 2: Conceptual Design
10	Capturing the Voice of the Customer
11	Updating Requirements with QFD
12	Exploring the Design Space
13	Selecting and Analyzing the Conceptual Design
14	Completing Phase 2: Conceptual Design
15	Introduction to Phase 3: Preliminary Design and Planning
16	Design Drivers and Commercial off the Shelf (COTS) Components: Part 1
17	Design Drivers and COTS Components Selection: Part 2
18	Product Baseline Preliminary Design: Part 1
19	Product Baseline Preliminary Design: Part 2
20	Updating the Requirements Matrix: Part 1
21	Updating the Requirements Matrix: Part 2
22	Systems Engineering and RMS Analyses
23	FMEA, DFMA, and DTC: Part 1
24	FMEA, DFMA, and DTC: Part 2
25	FMEA, DFMA, and DTC: Part 3
26	Final Preliminary Design and Commercialization
27	End-of-Phase 3 Deliverables
28	Preliminary Design Review and Exiting Phase 3
No.	Title
29	Phase 4 Plan, Prototype Scope and Requirements
30	Prototype Analyses, Long Lead Hardware, and Manufacturing Methods
31	Prototype/Test Rig Dwgs, Plans & DR4 Preparation
32	Starting Manufacturing, Prototype Testing Procedures and Conducting DR4
33	Engineering Prototype Build Book
34	Incoming Inspection and Manufacturing Troubleshooting
35	Deviations and Mid-Course Adjustments
36	Prototype Assembly, Inspection Forms and DR5 Preparations
37	Prototype First Article Inspection, DR5 Presentation and Final Report Work
38	Testing Issues and Repair/Rework
39	Test Analyses/Reporting and Updating Engineering Prototype Drawings
40	Validation Testing and DR6 Preparations
41	Conducting DR6 and Completing the Final Report
42	Preparation of Phase 4 Drawing Package and Project Final Presentation
43	End of Project Deliverables
44	End of Project Deliverables Due

through the Kern Engineering Entrepreneurial Network. The Entrepreneurial Mindset is a key part of the mechanical engineering capstone course structure. The Fulton Schools of Engineering (FSE) at ASU has identified 17 indicators of EM (EM@FSE 2.0)[8]. These indicators are described in the handbook, and they are included in each phase's exit checklist.

Travel iron as a design and development example

During the evolution of this course structure, students suggested that a specific example project in the handbook would be helpful in preparing the required course deliverables. To satisfy this need, the authors selected the design and development of a travel iron as an example.

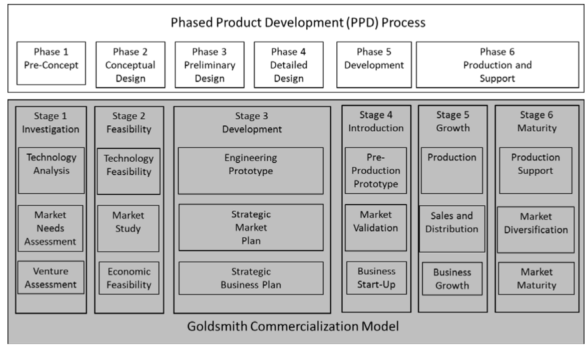

Figure 2. PPD Applied to the Goldsmith Commercialization Model

Students found this example project to be especially helpful in understanding how to identify candidate conceptual designs using a morphological chart as shown in Figure 3. This step is preceded by constructing function block diagrams of the product based on the list of product requirements, which are determined from the voice of the customer (VOC) using quality function deployment (QFD) and house of quality (HOQ) tools. The functions derived from the function block diagrams are used in the morphological chart to identify the candidate conceptual designs as shown in the referenced Figure 3.

Key Features of the Course

A major feature of the capstone design course is that the attributes of "thinking like an engineer" and meeting the sponsor's expectations are emphasized throughout the course and handbook and paired with industry examples.

Each phase starts with a plan including its tasks, time allocation, schedule, team member assignments of these tasks, and specific phase outcomes. The outcome of PPD Phase 1 is a project proposal to secure funding from the sponsor, or client. The conceptual design in Phase 2 includes developing the phase plan, capturing the voice of the customer, exploring the design space, selecting, and analyzing the conceptual design to ensure it meets all engineering design requirements. The preliminary design in Phase 3 takes the conceptual design and turns it into a specific product design with the goal of it being the best configuration to meet the engineering requirements and approach an optimum goal function as established during Phase 2. Figure 4 shows the flow of the preliminary design process, which covers many tasks of design for X.

On completing the preliminary design, the team starts Phase 4, where any final detailed analyses are completed, and a complete package of production drawings is prepared. It should be noted that, due to its limited budget and time resources, the capstone course goes only through Phase 4. A key task in Phase 4 is deciding what

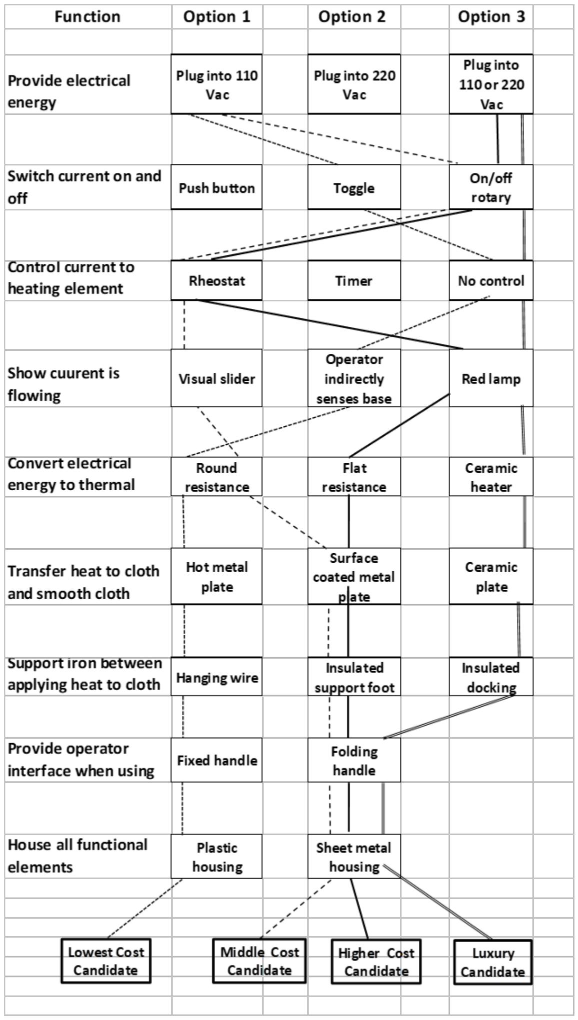

Figure 3. Candidate Concepts Travel Iron Morphological Chart

production unit requirements will be addressed in the engineering prototype subproject used in validating that the design meets all engineering requirements. The engineering prototype is then designed, manufactured, tested, and validated.

The course assessment is based on 50% for teamwork, 30% for individual work for the team, and 20% for individual competency demonstrated during the pre-lecture assignments.

Go-Forward Plans

The authors are planning the following:

- Perform quantitative research to support the findings of the current exploratory research
- Explore the use of this handbook for multi-disciplinary and transdisciplinary capstone projects
- Expand the use of this handbook into industry short courses on product development

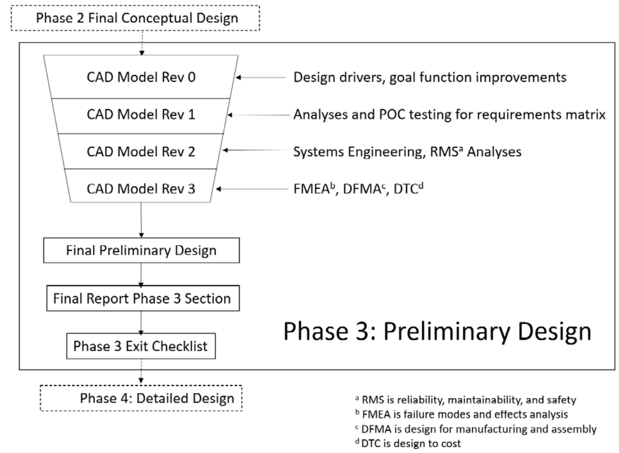

Figure 4. Phase 3 Preliminary Design Flowchart

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