Introduction

All engineering activity can be classified into one of two categories: synthesis and analysis. Synthesis concerns the creation of new solutions. Analysis concerns making determinations about an existing solution. Today's engineering curricula overwhelmingly emphasize analysis tools, knowledge, and skills. In comparison, they expend little effort developing synthesis capabilities in undergraduate engineering students. As a consequence, most baccalaureate engineering students leave the university with little ability to design, and with little ability to even recognize "good" design from "bad" design. They are thus ill prepared for the engineering profession.

I hypothesize that this weakness in design in engineering education stems from a knowledge gap regarding the synthesis process. We do not adequately understand the cognitive skills required to effectively reason about open-ended problems, conceptualize ideas, and realize design solutions. To optimize the training of design engineers, we first need a basic understanding of the processes designers use to conceptualize ideas, synthesize them into representations, and transform abstract, imprecise design ideas into concrete, detailed end products.

This CAREER proposal requests funding to systematically study the synthesis process of student design teams, measure project outcomes, and quantitatively model the design process using outcome measures as the dependent variables. The research design is theory-driven, and triangulates both qualitative and quantitative approaches. The findings will provide a strong empirical basis for theory on the synthesis process leading to improved pedagogy and training materials, course strategies, and curricula design.

Objectives

The objectives of the proposed career development plan are three-fold:

1. **To better understand the synthesis process—what makes a good designer.**

   The ability to synthesize new and creative solutions to problems is important in many fields, but is absolutely central to the engineering profession. In fact, designing physical artifacts and systems defines the engineer. And yet, the synthesis process is not well understood. Insight into this area would have pervasive implications for engineering education across disciplines, professional development of engineers, and development of computer-aided design and engineering tools.

2. **To further develop a theory of design representation—how it affects the synthesis process, cognitive development, and ability to solve open-ended design problems.**

   Design representation is the process of organizing and representing information, and often refers to the product of this process (e.g., a sketch, a mathematical formulation, a computer rendering, a prototype, etc.). It functions as a mediator between designer and product, between design and designer, and between design and user (Bodker, 1998). The use of representations is therefore central to the synthesis process. It is the mechanism through which designers reason about design problems and potential solutions.

Some work on design representation has been done in the area of cognitive science, particularly with respect to human-computer interface (Bodker, 1998; Stary and Peschl, 1998; Johnson, 1998). This project would extend this work through a large-scale study of student design processes, investigating the impact of design representation on students' cognitive processes and ability to synthesize design solutions. The proposed work will result in well-grounded theory on the effective use of design representation to maximize design output.

3. **To identify the knowledge and skills needed to become a "good designer," and determine how these skills can be developed.**

   Student design teams achieve varying levels of success in their design projects. The research design compares the processes of teams that create "good" designs versus those with "bad" designs, in order to gain some insight into the skills and processes needed to create successful design solutions. By sampling a wide cross-section of students and disciplines, the insights should be widely applicable in engineering education and practice.

The proposed activities are part of a research program to supply the engineering education and professional communities with fundamental knowledge of the synthesis process. The implications even extend to the development of design tools such as computer-aided engineering software. If tools are developed without the knowledge of how humans generate and synthesize design solutions, they will likely impose an unnatural synthesis process upon their human users resulting in sub-optimal design processes. This project will also provide developers of computer-aided design tools and information systems with strong empirical evidence regarding efficient design processes.

Background

Design has traditionally been an important part of an engineer's training. The Accreditation Board for Engineering and Technology (ABET), for example, emphasizes the importance of design in both the current criteria (see ABET Criteria Section IV.C.3.d.(3)) and in the new criteria to be adopted in the year 2000 (see EC2000 Criteria 3c). This section will review the current literature on engineering design education and design theory and methodology.

Engineering Design Education

The literature on engineering design education can be grouped into three broad categories: curriculum construction, course structures, and learning to design. A number of authors focus on how to most effectively build design into the curriculum through a sequence of semester courses (Bailie, et al., 1994; Wilczynski and Douglas, 1995; and Rockstraw, et al., 1997). The design sequence ranges from 4 to 8 semesters in which material and projects build on previous course work. These authors view design as a developmental process that should be taught at all levels of education. Some authors advocate exposing students to design even during the first year to provide students with a realistic introduction to engineering (Ercolano, 1996; McConica, 1996, Courter, et al., 1998). There is even a desire by some to introduce design to elementary students, K-6, to increase interest in engineering and design (Crawford, et al., 1994).

Several authors recognize the impact resource limitations can have on the quality and effectiveness of design courses (Hsu, 1998; Ozturk, et al., 1995). Lamancusa, et al. (1997) describe the “Learning Factory” as one solution to the limited resources problem. The Learning Factory provides students with opportunities to apply theory covered in the new courses through hands-on laboratories.

The second component of engineering design education focuses on individual course structure and teamwork. Several authors recognize the benefit of team projects whether teams are within one discipline or multi-disciplinary (Mertz 1997; Amon, et al., 1996; Gorman, et al., 1995; Miller and Olds, 1994; Catalano, 1994). The primary benefit of team-based projects is an increase in communication skills resulting from interaction between different backgrounds of education. These skills prepare students to make the transition from academics to industry.

The transition to industry is primarily fostered through the culmination of the capstone course. Capstone courses can be one or two semesters long, and center around industry-sponsored, group projects, with open-ended problem statements. Deliverables consist of oral presentations, written reports, and working prototypes (Dunn-Rankin, et al., 1998; Miller and Olds, 1994; Seider and Kivnick, 1994; Mertz, 1997; and Shaelwitz, et al.,1996; Morris and LaBoube, 1995). The structure of capstone courses usually follows the engineering problem solving process with initial effort focused on idea generation and detail design following.

Many freshmen design courses also follow group oriented, open-ended, hands-on projects (Dym, 1994; Richard, et al., 1997; Ercolano, 1996; Willey, et al., 1998; McConica, 1996). Courter, et al. (1998), for example, developed a study to capture the freshmen design experience from a student’s perspective. Benefits include: teamwork, hands-on experience, motivation to pursue engineering, confidence, introduction to faculty and students, and friendship.

Lastly, a number of authors address teaching of the engineering design process itself. The traditional approach of teaching problem solving through sample problems does not develop students’ skills to solve problems they have not seen before (Woods, et al., 1997). Design problems require students to transition from repetitive, single-solution problems to iterative, multi-solution problems (Starkey, et al., 1994; Harris and Jacobs, 1995). Koen (1994) emphasizes that this transition requires a change in behavior, and develops a strategy to teach engineering design based on changing student behaviors to reflect those of professional engineers.

Reading textbooks on engineering problem-solving can improve work quality and increase thought processes (Atman and Bursic, 1996). However, some authors feel learning effectiveness improves more rapidly through active learning (Parcover and McCuen, 1995). This approach challenges students to think and discover engineering principles for themselves (for example, having students experiment with different materials to determine their properties and functions). Atman and Bursic (1998) researched student design processes through verbal protocol analysis and found a correlation between the problem solving process and the final outcome, namely that students who spent more time in information gathering tended to produce more thorough design solutions.

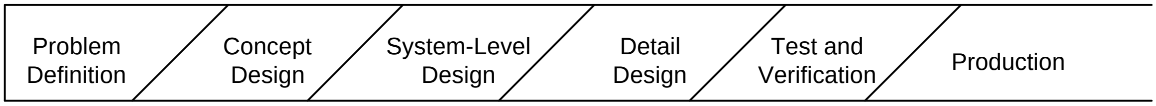

Figure 1: Six Phases of the Generic Development Process

In summary, this literature tends to focus on individual course development and on curriculum issues related to design. Much of this literature is anecdotal—engineering educators writing about their experience—with little academic rigor. A few researchers have attempted to rigorously study the design process itself. These studies tend to focus on individual designers (not design teams), a single discipline, and small projects that can be completed in a few hours.

Design Theory and Methodology Literature

The current literature generally agrees upon six basic phases of the product development (or design) process (see Figure 1), what Ulrich and Eppinger (1995) term the “generic development process.” The phases typically do not have definite start or end points—the process is both evolutionary and iterative, and the phases meld together—but isolating the different phases is helpful in understanding how an idea gets from concept to final product.

The process begins with defining the problem to be solved. Problem definition usually includes assessing market needs, determining customer requirements, and establishing the broad constraints to which the final design must conform. Once designers understand the problem to be addressed, they explore and generate many potential solutions. These ideas are typically conceptual in nature, often embodied in hand-drawn (sometimes computer generated) sketches.

As designers begin to settle on one or several ideas that look promising, they enter the system-level design phase. Here the product begins to take a more definite shape—the major subsystems and components are identified, their rough geometry is established along with how they will be arranged (often called “configuration” or “layout”), important interfaces are identified and designed, and so forth.

With the product architecture established, designers can begin detail design where they specify the product geometry, tolerances, material, etc. in detail. The design must then be verified through engineering analysis and prototype testing. Once the product and manufacturing process have attained a sufficient level of “production readiness,” the product can be “launched” and the project enters the production phase.

Although the generic process looks sequential on the surface, in practice it involves a good deal of iteration and overlap. The design team typically iterates through many cycles of analysis, testing, and refinement at all stages of development, a fact well-established in the literature and in practice. Furthermore, the process applies not only to the overall product system, but also to the individual subsystems and components that make up the system.

Researchers have developed a large number of tools and methods to aid the design process. They cover all phases of the design process: concept generation (e.g., functional decomposition, brainstorming), concept evaluation and selection (e.g., Pugh selection matrix), system-level and detailed design and analysis (e.g., computer-aided engineering and computer-aided design software, design for manufacturability), and verification (software simulations, rapid prototyping). (See: Burr and Cheatum, 1995; Norton, 1996; Pugh, 1991; Shigley, 1963; others).

Statement of Need

James Adams (1986) says the following on the nature of creativity:

> *…I've become increasingly frustrated with the belief that more ideas alone mean better results. If you're serious about encouraging creativity…then implementing ideas is at least as important as generating ideas. You need to understand the entire process—from concept to reality…. Creativity requires that ideas be implemented, and it is in the pragmatic details of implementation that creativity often fails, relegating the ideas to occasional hindsight discussions at cocktail parties. (Adams, 1986, pp. 6-7)*

Many recognize that decisions on concept and system architecture can have a huge impact on the ultimate success or failure of the new product development project (Smith and Reinertsen, 1991; Ulrich, 1995; Ulrich and Eppinger, 1995; others). However, consistent with Adams's observation above, the literature is surprisingly vacuous on how engineering designers proceed from very abstract, conceptual ideas to concrete, detailed product designs. Ullman's (1992) popular text on the mechanical design process, for example, devotes three chapters to concept design and four chapters to detail design, but spends only a few short pages on how one might progress from concept to detailed design. In fact, many authors barely recognize the vital transition between concept and detail design (see Lindbeck, 1995, Kuczmarski, 1992, and Wheelwright and Clark, 1992 for examples).

The design theory and methodology literature assumes that a good development process correlates to good outcomes (i.e., good designs), but actually connecting the two is non-trivial. Design is a creative, often chaotic process, and simply adopting a cookbook-like method does not guarantee good results. But a haphazard process without a sense of direction does not seem to hold much promise either. Much of current research unfortunately does not consider the fundamental nature of the creative process in engineering design, especially with regard to what Adams (1986) refers to as idea implementation. Coming up with good ideas is necessary, but not sufficient. A need exists, therefore, for more research in design processes that takes into account the fundamental synthesis process—taking an idea from concept to reality.

Furthermore, most engineering programs train undergraduates in a limited set of system representations. At Montana State University, for example, the mechanical engineering and industrial engineering programs require students to take ME 110: Engineering Design Graphics in their first year. ME110 trains students in the basics of computer-aided design (CAD), a tool that requires very precise definition of one's design ideas. Yet students typically receive little training in more abstract or conceptual representations (for example, problem definition or sketching). An inability to conceptualize at high to moderate levels of abstraction may limit the spectrum of design alternatives considered, ultimately to the detriment of design creativity and project outcomes.

A few researchers have found that novice engineers tend to jump quickly to a solution and iterate, while experienced designers spend more time gathering data and conceptualizing before deciding on a solution (Atman and Bursic, 1998; Waldron and Waldron; 1996a). Those more skilled at conceptualizing achieved better outcomes in these studies. Yet most engineering programs do not emphasize abstract, imprecise representations of systems, and do not explicitly develop conceptualization skills. Furthermore, students adept at conceptualization seem to have obtained these skills from experiences outside the engineering curriculum, as evidenced by their grade point average.[1] While the evidence is still anecdotal, it suggests that perhaps the typical engineering program measures (and rewards) a set of skills that is different from that required to be a good design engineer.

It seems, then, that a sizable need exists for research in the area of design synthesis: what process(es) are more likely to lead to positive project outcomes, what role(s) does design representation play in engineering design capability, how does it impact the design process, what representations are most suitable for the different phases of design, what are the implications for training of engineers?

Long Range Plan

My long range goals as an academic and engineering faculty member fall largely into two areas of equal importance. First is teaching. I have a love for teaching, especially at the undergraduate level, and plan to stay active in the education of young aspiring engineers. I take a personal interest in the cognitive development of my students, stretching them in new ways intellectually, challenging them to address difficult and complex problems with a systems perspective, and developing in them the confidence and skills to realize creative and thorough solutions.

The second area is research of the design process. My research agenda falls along two parallel paths. The first is to increase our understanding of the synthesis process—the creation and realization of new solutions. I hope to attain this goal through educational research aimed at students' cognitive processes with respect to design. The second path is the continued study of industrial product development systems and how organizations can realize new products expeditiously at low cost and high quality. This CAREER proposal concerns the former.

The two research paths have a natural synergy between each other and with my educational goals. The effectiveness of a company's product development system hinges to significant degree on how well it aligns with human cognitive processes. At the same time, the vast majority of 'expert' designers are in industry, not in school. So studying the processes of experienced versus inexperienced designers should provide some keen insight into how the educational system can better prepare engineers for a life of problem-solving and design. Having one foot in education and one foot in industry, so to speak, will also help create a stronger linkage between education and professional practice.

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[1] Informal conversations with engineering educators from numerous institutions and engineering disciplines reveals that the best engineers are often not the students with the best grades.

The remaining sections present an emerging theory about design synthesis, then propose a set of activities to test and further develop the theory, and realize the principles from theory in educational materials.

Toward a Theory of Design Representation

Designers use numerous design representations to progress from the initial problem definition through the various stages of the design process to their final product. At first, these representations are quite abstract, such as a written list of design objectives or requirements. Eventually the design representations become concrete and detailed—a fully functional prototype or detailed shop drawings, for example. How should one progress from the very abstract to the very concrete? What types of representations are most useful for different levels of reasoning? Are some progressions more likely to lead to success than others?

Bodker (1998) claims that design representations are the holders of the creator's ideas and decisions. As such, the representation will tend to lead the designer along a certain line of thought. At the same time, however, the next representation may lead to a change in direction. Thus, the first proposition toward a theory of design representations is:

> *Proposition 1: Design representation impacts the design (or synthesis) process.*

Design representations may be good or poor (Johnson, 1998), and many different forms of representation exist, each containing incomplete information about the current level of understanding and the future product (Peschl and Stary, 1998). This implies that different representations require reasoning at different levels of abstraction, and that use of a rich mix of representations yields a more complete picture of the design problem and potential solutions.

> *Proposition 2: Design teams that use a rich mix of design representations have an increased likelihood of achieving positive outcomes.*

The reasons for proposition 2 may be several, as the following corollary propositions indicate:

> *Proposition 3: Design representations impact the ability of individual designers and design teams to communicate design ideas.*
>
> *Proposition 4a: Effective use and interpretation of design representations requires specific cognitive skills.*
>
> *Proposition 4b: Repeated use of a given design representation reinforces/builds specific conceptualization abilities.*

At the heart of these propositions is the idea that designers are most effective if they are able to conceptualize and communicate at many levels of abstraction. The ability to conceive a system architecture and visualize the interaction among the different subsystems is quite different from the ability to conduct a finite element analysis of a part with a precisely defined geometry. Both representations are useful, but applicable to different stages in one's reasoning, thus:

Proposition 5: Design representations at a given level of abstraction are most applicable to specific stages of the synthesis process.

Preliminary Research

It should be possible, then, to map any given design representation to a stage of the design process (previously outlined) and create a picture or "story" of the synthesis process. Furthermore, since we are abstracting to a generic model, we can compare design processes across disparate disciplines; that is, we can compare the design processes regardless of the type of system being designed.

As part of an internal grant,[2] a collaborator and I conducted preliminary fieldwork by interviewing MSU faculty in chemical engineering, civil engineering, electrical engineering, mechanical engineering, industrial engineering, computer science, and architecture. Our objective was to establish "good" design practice as defined in the different disciplines. We did not fully meet in our objective because, apparently, *'good' design processes have not been defined in most disciplines*—a finding that prompted this proposal. However, we were able to establish that it is possible to map design representations to appropriate process stages, as demonstrated in Figure 2. Currently, the classification schema are somewhat subjective, but I plan to develop more objective criteria as the research progresses.

The development of a theory of representation in engineering design is still in its infancy. The proposed work will test these propositions and extend the theory into a rich understanding of the role design representation plays in the synthesis process.

Plan of Work—Research Component

I propose an extensive study of student design projects across 5 engineering disciplines plus computer science and architecture to test the propositions above and further develop a theory of design representation. The proposed study models student design processes by qualitatively characterizing the progression of design representations used, calculating the amount of effort expended in conceptualizing and developing design ideas at various levels of abstraction, and correlating these process attributes to quantitative and qualitative project outcomes.

Since many factors affect the success of a design project, and the relationships among the factors are complex and often subtle, the research design will use a rich data collection method to try to include as many factors as possible. It will be important to account for the effects of, for example, intra-team dynamics, team composition (gender/ethnic diversity, experience levels, grade point, etc.), quality of advising, motivation, resources available, project complexity, and so forth. Such factors may also play in key role in understanding the cognitive skills that lead to better design outcomes

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[2] This proposal extends a Montanans on a New Trac for Science (MONTS) grant entitled "Integration Strategies for Design of Physical Systems." MONTS is a NSF sponsored program to help new Montana State University faculty start their research programs. Proposals are subject to a peer-review process. Grants are limited to $25,000.

Discipline	Problem Definition	Concept Design	System-level Design	Detail Design	Validation
Mechanical Engineering	• Written needs statement. • List of product requirements. • Constraints.	• Written specifications. • Preliminary sketches. • Functional attribute map. • Schematics.	• System configuration. • Layout drawings. • Interface definitions. • Flow charts for system control. • Simple mathematical models	• Precise configuration/geometry of components. • Dimensions and tolerances. • Precise mathematical models (e.g., FEA). • Design for Manufacturability.	• Working physical prototype. • Scale models. • Design reviews.
Industrial Engineering	• Operations process charts • Space limitations and requirements. • Material requirements. • Budget	• Activity relationship matrix. • Transportation frequency chart. • Material handling (MH) concept. • Flow process charts	• Space relationship diagram. • Layout configuration. • Material movement volume/ frequency. • MH technologies and specs.	• Alternative layout designs. • Material handling specifications. • Sourcing documentation • Costing model.	• Scale model. • Computer simulation. • Design reviews. • Financial audit.

Figure 2: Examples of Mapping of Design Representations to Design Process Phases.

The study will be conducted in upper-level design courses (where possible, senior ‘capstone’ courses) at Montana State University in seven disciplines over a 4 year period. A list of potential participating courses appears in Table 1 along with estimated enrollment. The project will involve an estimated 300 students in 70-80 design projects.

Course	Estimated Enrollment	Semester Offered
ARCH 457 Architectural Design V	25	Fall
ARCH 458 Architectural Design VI	25	Spring
CE 457 Senior Project I	80	Fall, Spring
CE 458 Senior Project II	80	Fall, Spring
CH E 411 Design of Chemical & Petroleum Processes I	50	Fall
CH E 412 Design of Chemical & Petroleum Processes II	50	Spring
CS 351 Software Engineering	30	Fall
EE 492 Electrical Engineering Design II	60	Fall, Spring
I&ME 444 Senior Design Project	15	Spring
ME 402 Mechanical Engineering Design	40	Fall, Spring

Table 1: Target Design Courses for Data Collection.

Data Collection

Data collection will be conducted using multiple methods in order to obtain the richest possible description of the design projects. To collect design process data, we will solicit the help of individual instructors to require students to keep design journals.[3] Design journals simply document an individual's design activity over time. This research method is similar to the "retrospective method" which Waldron and Waldron (1988, 1996b) advocate for complex design problems requiring a long period of time to complete. The main shortcoming of this method is significant chance of incomplete written records. This shortcoming can be offset through a training program to instruct students how to write meaningful, complete design journals, including what information to include. Key data from a research standpoint are:

- Representations for all design ideas considered.
- Decisions made.
- Dates on which activities occurred
- Time spent on each activity. Time will act as a proxy for amount of effort, consistent with the use of "engineering hours" in industry to measure development costs.

Additionally, we[4] will remind the students of the importance of rigorous documentation and will continuously monitor the written records throughout the semester. An appropriate incentive system for the participating students must be in place, such as making the design journals a small portion of their final grade (currently 10% in mechanical engineering), offering "Best Design Journal" awards, or other incentives.

In addition to design journals, data will be collected through direct observation and interviews of student teams. Most projects have periodic (i.e., weekly) informal reviews with faculty advisors where we can observe design progress and monitor design journals. We will also observe interim design reviews and final project presentations, and collect written interim and final reports. In addition to observation, we will conduct periodic interviews with the student teams (at least twice per team per semester) using a standard set of interview questions.

Project outcomes will be assessed with multiple measures:

- Final grade for the project.
- Total design hours spent on the project (the sum total of time spent on all project activities for all team members).
- Panel of experts evaluations to assess key aspects of design quality, such as whether objectives were met, creativity, simplicity or elegance of the design, feasibility, etc.

We will assemble a different panel for each discipline consisting of 3-4 discipline experts from industry and academia. Panelists will make their evaluations after viewing the senior project presentations for their discipline. We can control for inter-panel variation to some degree by standardizing expectations across the panels and by using a standard evaluation form.

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[3] The data collection scheme has some synergy with the pedagogical objectives of the faculty we interviewed. They indicated that design notebooks or journals are a "good" practice for engineers at all levels.

[4] That is, the principle investigator and graduate research assistants, and possibly other faculty collaborators.

In addition to the two primary data sets, we will also gather data on control factors, such as: team size, assessment of students' technical skill level, team cohesion and leadership, team ethnic and gender diversity,[5] motivation, industry sponsorship and available resources, quality and nature of faculty or sponsor involvement, etc.

Data Analysis

At the end of the course, we will collect the design journals from the students and copies from final reports, and assemble them with the field notes and interview data collected on that team throughout the semester. The first step of analysis will be to reconcile the various records into a coherent "story" of each project's process and outcomes. Follow-up interviews of students, faculty advisors, or industry sponsors may be required to fill gaps in the data. Then we will conduct a qualitative thematic analysis using grounded theory methods (Strauss and Corbin, 1990). The thematic analysis will look at use of design representations, but with an eye open to other patterns that may emerge.

We will then attempt a quantitative analysis by coding each design journal according to type of design representation and classifying them into the design process phases described previously. The coding will attempt to capture discrete levels of abstraction. Representations will be mapped into the framework as appropriate, and new categories may be created.[6] We will then calculate the time spent on each activity from the journal entries, then calculate the sum total of time for each classification.

Once the data set has been developed, we can then perform a statistical analysis looking at patterns between key design process characteristics (e.g., amount of time spent developing drawings in CAD) and project outcome measures (e.g., degree of creativity of final solution).

Outcomes

Perhaps the most important outcome of the research activity will be a more complete theory of design representation, grounded in empirical data, that will shed some light onto the human synthesis process and the skills required to achieve excellent design outcomes.

A second outcome will be discipline-specific statistical models based on factor analysis that relate process and project attributes to project outcomes. We do not yet know what exact form the models will take at this early stage, but we expect to be able to learn about approximate allocations of time per stage of design that optimizes project outcomes. We can also investigate the effects of control variables on student design team performance, and their interactions with the use of design representations. These models will be the basis for future modeling of design processes used in industry, discussed later.

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[5] The NSF funded Science and Engineering for All office at MSU will be solicited for its help and expertise on assessing the impact of gender and ethnic diversity on process and project outcomes.

[6] Conducting such 'theory building' in parallel with data collection and analysis is very consistent with the grounded theory approach to qualitative research—see Strauss and Corbin, 1990, and Miles and Huberman, 1994.

The second outcome will be a statistical model of similar nature those just described, except generalized over the disciplines studied. This will be our first attempt at a generalized activity-based model of design synthesis. An important part of this activity will be to compare and contrast the design process models used in different disciplines, and see what kinds of cross-learning might apply.

Plan of Work—Education Component

Informally, the education component of the proposed work will be ongoing as I incorporate the lessons and ideas into my existing courses and instructional materials, and as I interact with colleagues about the research results.

Formally, as the research results begin to crystallize, we will begin to identify those skills that seem to lead to exceptional synthesis capability, ideally with some insight into how those synthesis skills can be developed. I expect this to be closely related to use of design representation. In collaboration with appropriate instructors, we will develop intervention strategies, tools, and materials consistent with the research results and theory that will help improve student design abilities. The exact form of intervention strategies is not known *a priori*, but may involve in-class and out-of-class exercises, training of faculty advisors, direct intervention in projects, or training in specific tools/techniques.

These ideas will then be implemented as a small-scale pilot study in one or more courses. The design processes and project outcomes will again be measured, using the same methodology, to determine whether the intervention affected processes, and if so, whether outcomes improved.

Additionally, the research results will be embodied in a tool to help guide student design teams as they plan and conduct their projects, and help instructors evaluate the progress of design teams. Most likely the embodiment of this tool will simply be a written list of “Guidelines for Design Process Planning” that design teams and instructors can use to help plan their processes. A separate grant proposal will seek funds for the development of a computer tool to help design teams plan their design processes.

Finally, we will conduct an assessment of current MSU engineering curricula with respect to design, and recommend changes based on the research results. The outcomes-based assessment can be used to help design curricula to meet the assessment requirements of ABET EC2000 accreditation criteria. It would serve as a model for engineering curricula nation-wide to assess the teaching of engineering design.

Project Timeline

Table 2 summarizes the plan for the proposed activities. The first year involves preparation activities and pilot studies. Years 2-3 involve intensive data collection, analysis, and theory development. Year 4 focuses on refinement of the theory, development of generalized models, and dissemination of research results. Development of instructional methods and strategies for synthesis skill development will begin in Year 4, then implemented and measured in Year 5.

Dissemination of research results will be accomplished at local and national levels:

- Debriefing faculty participants (and students if interested).
- Written summary of results to the Dean of the College of Engineering at MSU, including a list of recommendations for the engineering curricula at MSU.
- Seminar on research results and implications to all interested faculty and students; copies of written final and interim reports made available.
- Development of a web site regarding the study and results.
- Conference submissions to ASEE, design theory and methodology, and other appropriate conferences.
- Submissions to academic journals, such as the *Journal of Engineering Education* and *Research in Engineering Design*.

Year	**Dates**	**Activity**
Year 1	Aug., 2000 – July, 2001	• Research and develop training materials for design journals. • Acquire or develop design journal materials. • Develop data collection instruments. • Conduct pilot studies (mechanical and industrial engineering). • Analyze data from pilot studies. • Re-evaluate, modify training materials and data collection procedures.
Year 2	Aug., 2001 – July, 2002	• Preparation for upcoming semesters: contacting/briefing instructors, revising data collection materials, contacting expert panelists. • Collect data from civil engineering and chemical engineering project teams (and ME/IE courses, depending on quality of data from pilot studies). • Data analysis and model development. • Evaluation of the propositions of design representation theory; refinement of theory.
Year 3	Aug., 2002 – July, 2003	• Preparation for upcoming semesters: contacting/briefing instructors, revising data collection materials, contacting expert panelists. • Collect data from electrical engineering, computer science, and architecture projects. • Data analysis, model development, and theory refinement.
Year 4	Aug., 2003 – July, 2004	• Development of educational intervention strategies and materials. • Identification of pilot course(s), instructor(s) for implementation. • Dissemination of research results (locally via seminars, nationally via conference and journal papers, and globally via web site).
Year 5	Aug., 2004 – July, 2005	• Implementation of intervention strategies. • Assessment of intervention's impact on design processes and project outcomes. • Final project report

Table 2: Proposed Project Timeline

Prior Research and Education Accomplishments

My Ph.D. research involved in-depth case studies of the product development systems of two major automotive companies, one American and one Japanese. The research consisted primarily of qualitative research methods. This work has resulted in several publications in prestigious journals such as *Harvard Business Review* and *Sloan Management Review*, and received numerous awards (see biographical sketch). In addition, I have a solid background in quantitative research methods, having participated in a survey of product development practices in the US and Japan that resulted in a peer reviewed publication.

I have also conducted classroom research using both qualitative and quantitative research methods. This project, funded by our Science and Engineering for All office, investigated the impact of various teaching methods and innovations on student learning, and specifically looked at differences between genders. I have also been accepted as a faculty fellow to Montana State University's Teaching and Learning program, and participated in the NSF-sponsored Engineering Education Scholars Program (1998) at the University of Wisconsin-Madison.

As an educator, I have developed a new introductory course and laboratory to introduce prospective engineering students to the field of industrial engineering. I also advise senior design teams and teach two laboratory courses, and have done extensive work developing classroom and laboratory experiences to enhance student learning. Students voted me Teacher of the Year in 1998 for the Industrial and Management Engineering program.

These experiences, and my strong desire study design processes and integrate this learning into education, gives me a solid foundation from which to conduct the proposed research and education activities.

Complimentary Research

I am currently working to secure research sponsors for a parallel study of design teams from industry and professional practice. This research will characterize the design processes of experienced, practicing professionals and correlate these processes to project outcomes (similar in aim and methodology to the project in this proposal). Such a project will be interesting on its own, but comparing the education results with the industry results will be even more powerful. Do the results coincide? If not, why not? Should we change our design training to better reflect actual practice, or try to influence actual practice through enhanced training programs?

Additionally, I plan to seek funding for implementation and validation of the ideas resulting from both research thrusts, including: development of design process planning tools; pilot projects in industry to redesign product development systems; development of workshops to train faculty, students, and professionals in appropriate design representation skills; and assessment of engineering curricula.

Conclusion

The Accreditation Board for Engineering and Technology is driving engineering education to become more outcomes-based, to assess the quality of education through outcome measures rather than input measures. Design—that is, the conceptualization and synthesis of engineering solutions to prescribed problems—is a central activity to the engineering profession, ubiquitous to all engineering disciplines. And yet, the current state of knowledge on the synthesis process is still incomplete.

This proposal is one step toward filling this gap. It is also the first phase in an effort to assess how well our students are mastering engineering design processes.

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To Whom It May Concern:

Dr. Sobek's current appointment as Assistant Professor in the Mechanical and Industrial Engineering (M&IE) Department at Montana State University began on August 15, 1997. It is his first tenure-track appointment. He is therefore eligible for a NSF Early Faculty Development CAREER Award.

I have read and I endorse this Career Development Plan. Engineering design is a critical component of the professional degree programs within our department and across the College of Engineering. Dr. Sobek's proposal promises important insights into this fundamental engineering activity leading to significant improvements in engineering education. It is thus highly consistent with the institutional goals of providing students with a solid education, grounded in engineering fundamentals, and preparing them for long, productive careers.

In addition, the departments in our college are embarking on an intensive reform initiative in response to new criteria from our accreditation agency, the Accreditation Board of Engineering and Technology. These new criteria call for rigorous assessment of program outcomes. Dr. Sobek's proposed project would provide an assessment of our design curricula far beyond what we can do with our limited resources, and will be of tremendous value to the College as well as to engineering schools around the country.

I have been serving as Dr. Sobek's mentor as part of MSU's Teaching and Learning Faculty Fellows program, and would be happy to serve in a mentoring capacity on the proposed project. As further demonstration of institutional support, the M&IE Department will underwrite the project by cost-sharing academic release time and clerical and logistical assistance, a **total match of approximately $64,000** over 5 years. The knowledge from this exciting project could play an important role in future engineering education reform--I look forward to reviewing and sharing the results.

Sincerely,

Vic A. Cundy, P.E., Ph.D.
Professor and Department Head
July 15, 1999