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Learning to Design Products in Environments with Limited Design Traditions*

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Many researchers agree that 'today's engineer must design under—and so understand at a deep level—constraints that include global, cultural, and business contexts'. In an increasingly global economy, the demand for engineers and technical personnel is increasing in every country. Developing countries which have few internal design traditions are struggling to find a place in the ever growing, ever increasing competitive global marketplace. Even developed countries like the United States are finding increasing challenges to their technological dominance. The ability to design and manufacture timely, needed, and inexpensive products for a large variety of consumers is becoming the great differentiator in controlling the global marketplace. Better design and engineering curriculum is needed in developing countries to improve their ability to compete in a global marketplace and find ways to open their own untapped and waiting markets. The objective of this paper is to provide an overview of our approach to develop more flexible design structures and processes that could be adaptable to environments where there is a limited design tradition. It is anticipated that through the use of appropriate processes, designers in developing countries will be able to effectively learn to design products that have value both inside and outside of their community. We also anticipate that these flexible design structures and processes can be integrated into a formal design curriculum customized to meet specific needs. There are six major topics that are relevant to our research. They are design curriculum outcomes, design processes, design curriculum, learning activities and tools, appropriate assessment techniques, and research in developing countries. Our paradigm is based on the premise that project-based learning is one of the most appropriate and effective means of teaching engineering design principles to students. Furthermore, the authors feel that it is crucial to involve industry with academia. Industry involvement in engineering education improves the relevance of education, better prepares students for employment, provides industry with a better qualified workforce, and creates synergy between industry and academia.

Keywords: engineering design; developing countries; education; design capacity.

INTRODUCTION

IN SOME WAYS developing countries find themselves in the same situation as the fledgling United States did two hundred years ago. The United States had untapped markets that were eager for goods and services, but other 'more developed' countries had the major technology. Manufactured goods were largely imported from Europe, but with the advent of the revolutionary war, Americans started copying imported items. As areas for improvement were found, clever minds developed innovative solutions. This resulted in new technologies with greater opportunities for the American marketplace. The industrial revolution demonstrated how the United States leapfrogged existing technology and became the world leader in manufacturing and technology by the end of World War II.

We see a similar pattern in how rapidly China is developing today. The Chinese are quickly becoming one of the world's best manufacturers of consumer goods. With the largest untapped internal market in the world, Chinese manufacturing companies are beginning to use existing technology to create new products for their internal market [1].

During the 2004 ASEE Conference, Dr. Woody Flowers of MIT in his keynote address stated, 'Hundreds of millions of people in the world want to do what we [engineers] do but are only held back by education.' Education is the key to opportunity and 'the eradication of poverty . . . [is] deeply associated with the building of indigenous capacity for self-growth' [2]. There is little doubt that engineering is a stabilizing force with potential to significantly improve the standard of living in developing countries because it provides important goods and services while creating jobs and businesses.

Developing countries typically have few formal design traditions. For example, a study by Donaldson and Sheppard in Kenya showed there were no formal design processes used in

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any of the companies within that country [3]. Countries with large multi-national companies will likely have more imported design traditions that stem from the United States or European parent companies.

Many researchers agree that 'today's engineer must design under—and so understand at a deep level—constraints that include global, cultural, and business contexts' [4]. In an increasingly global economy the demand for engineers and technical personnel is increasing in every country. Developing countries which have few internal design traditions are struggling to find a place in the ever growing, ever increasing competitive global marketplace. Even developed countries like the United States are finding increasing challenges to their technological dominance. The ability to design and manufacture timely, needed, and inexpensive products for a large variety of consumers is becoming the great differentiator in controlling the global marketplace. Better design and engineering curriculum is needed in developing countries to improve their ability to compete in a global marketplace and find ways to open their own untapped and waiting markets.

Many educators over the past three decades have promoted the relationship of design and engineering. Dieter [5] stated 'the professional practice of engineering is largely concerned with design; it is frequently said that design is the essence of engineering.' The emphasis on design led to the development of formal design structures, processes, and approaches intended to help engineers successfully learn and practice design. However, almost all research in teaching and learning engineering design has been accomplished in the context of a developed country. Many efforts to export design education expertise to developing countries have failed. More effective means of teaching and learning design in environments with limited design traditions, such as those in developing countries, are needed.

The objective of this paper is to provide an overview of our approach to develop more flexible design structures and processes that could be adaptable to environments where there is a limited design tradition. It is anticipated that through the use of appropriate processes, designers in developing countries will be able to effectively learn to design products that have value both inside and outside of their community. We also anticipate that these flexible design structures and processes can be integrated into a formal design curriculum customized to meet specific needs.

In this paper the methodology we will use to study the design process and create an adaptable and customizable design curriculum for use in organizations with limited design traditions is discussed. First, a review of what researchers are doing both in developed and developing countries with regards to design curriculum and the desired outcomes of these programs is presented. Following this review, we present an approach we believe will enable us to develop the proposed design curriculum.

BACKGROUND

There are six major research topics that are relevant to our research. They are: design curriculum outcomes, design processes, design curriculum, learning activities and tools, appropriate assessment techniques, and research in developing countries. Each of these topics is discussed below.

Design curriculum outcomes

The desired outcomes, competencies, and skills of a given activity should be the foundation and motivation for any educational activity. Without a clear statement of what the goal or desired outcome is, it is very difficult to assess the effectiveness or appropriateness of a given set of learning activities.

The ABET accreditation body has articulated eleven general competencies or skills that an engineering student should develop through any undergraduate engineering program [6]. Some schools have given further resolution to the ABET skills [7]. Dym, et al., articulated six additional skills a design engineer must develop [4]. Scavarda do Carmo, Morell, and Jones articulated four additional skills needed for the international engineer [2].

Design processes

There are diverse formal design processes which vary in both content and procedure. There are four major categories of formal design processes discussed: reverse engineering, specification-based, need-based, and artificial intelligence (AI), or mass customization [5, 8–12].

Reverse engineering is the art of replicating or creating a modified replica of a given product [10]. It generally requires less design innovation, research, and development. However, it can frequently involve some innovation in manufacturing engineering. Dym, et al. sites various researchers that have found that reverse engineering exercises 'promote integrative thinking about design and . . .improve student's systems thinking of engineered products when integrated with other design or case study activities' [4]. The Chinese have become very adept at reverse engineering and present an excellent example of how effective reverse engineering is as a learning tool [1, 13].

Specification-based and need-based design processes involve concept-generative activities, the development of the form and function of the end product, and the development of the manufacturing, assembly, marketing and distribution of the product [8, 9].

AI is the automation of the design, manufacturing, and assembly processes to capture engineering knowledge in order to create a family of products that fit within a specific design space [11, 12].

Design curriculum

Design curriculum is most often based on achieving the ABET or other desired program outcomes. The three most prevalent curriculum responses presented in literature have been freshman design courses (cornerstone) [4, 8, 14], senior design courses (capstone) [4, 15–17], and integrated core curriculum where design activities permeate the curriculum [18–21]. In each of these cases, the design curriculum is based on a project-based learning model.

Educators such as Dym have led others to focus on how design might best be taught to those that are learning about it for the first time [8]. In their approach, the essential elements of the design process are taught along with the language and terminology used by the design community. Their focus has been on freshmen, but the principles of teaching design to freshmen might apply to teaching engineering students in developing countries since both have limited exposure to formal design structures and processes.

Many institutions have adapted a senior level 'capstone' course as a way to prepare graduating engineers for the practice of engineering. These capstone programs vary from industrial sponsored projects, to national design competitions, to 'canned' design projects. Numerous papers have discussed the value of industry-sponsored projects [4, 15–17]. It has been noted that one of the greatest challenges in engineering education in developing countries is the apparent lack of industrial–academic partnership or interactions [2].

Learning activities and tools

Current reviews of decades of research are showing that the delivery of material and student engagement (interaction) is more important than specific course content [22]. Further, student learning was significantly better when the engineering instructors were a 'designer and facilitator of learning experiences and opportunities' rather than a lecturer [22]. Project- and problem-based learning activities have been shown to be more effective in teaching both engineering theory and practice than notes-based instruction [4, 22].

Appropriate assessment techniques

In the January 2005 edition of the *Journal of Engineering Education,* a number of articles were devoted to the topic of educational assessment in engineering education. Olds, Moskal, and Millar reviewed the vast body of literature on this subject. They classified each assessment technique into one of two categories: descriptive (find out) or experimental (effectiveness of an activity) [23]. They also discussed how to determine which type of technique should be used in a given situation. Shuman, Besterfield-Sacre, and McGourty discussed methods to assess the ABET 'professional' outcomes criteria which cannot simply be assessed by a textbook, theory-based exam [24]. They classified the professional skills into two skill sets: process oriented, and awareness oriented. They have also given clear evidence that these skills can be taught and assessed.

Research in developing countries

Donaldson and Sheppard performed a study of design practice in Kenya and concluded that there were four approaches exhibited for product design ranging from imitation to original specialty designs [3]. They found that no formal design processes employed in the country. This work makes an excellent case for categorizing levels of design—both in terms of understanding the state of design in a particular environment, and in recognizing what the next level of design might be for that country. The techniques in the paper could be adapted to any country or environment of study. However, they did not address the educational implications of their work.

Johnson examined results of imposing 'first world' design approaches on developing countries and concluded that there has been little success in most cases [25]. She develops the beginning of a modified design process that accounts for the environment in which the design is to be synthesized and produced. Her research concludes that the most leverage for considering the environment in which a product will be manufactured occurs during concept selection.

APPROACH

The goal of the research discussed in this paper is to develop flexible design structures and processes that could be adaptable to environments where there is a limited tradition of design. To reach this goal we must develop a framework for understanding levels and types of designs, as well as methods for students to best learn design at a level appropriate for their environment. It is important to note that this is the beginning of a focused research effort and we are eager for suggestions and input. The following steps have been outlined to achieve this goal:

1. Discover and clearly articulate the desired outcomes, competencies, and skills for engineering graduates.
2. Categorize the levels of design in use within an organization.
3. Identify the thought processes, engineering knowledge/tools, and environmental circumstances required to effectively design at each of the categorized levels of design.
4. Develop an assessment tool that would enable the classification of a given organization in regards to their design capability according to the categorized levels.
5. Identify design processes that are adaptable within the categorized levels of design.
6. Develop design curriculum around the previously identified design processes by:

- developing specific design activities for each desired outcome;
- developing assessment tools for each design activity;
- applying proven experimental research methods to test how effective design activities are at meeting the desired outcomes.

Each of these steps is discussed in further detail below.

Desired outcomes, competencies and skills

The authors feel this is the most important step in creating a truly effective design program. As previously noted, there have been a number of individuals, researchers, institutions, and government bodies that have articulated what an engineer should be able to do. For example, ABET has determined that an engineering graduate should have acquired [6]:

- an ability to apply knowledge of mathematics, science, and engineering;
- an ability to design and conduct experiments, as well as to analyze and interpret data;
- an ability to design a system, component, or process to meet desired needs;
- an ability to function on multi-disciplinary teams;
- an ability to identify, formulate, and solve engineering problems;
- an understanding of professional and ethical responsibility;
- an ability to communicate effectively;
- the broad education necessary to understand the impact of engineering solutions in a global and societal context;
- a recognition of the need for, and an ability to engage in life-long learning;
- a knowledge of contemporary issues;
- an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

These competencies and skills are, in basic terms, the definition of an engineer according to ABET. One of the first challenges for our research team is to evaluate whether or not the ABET criteria fully defines the scope of an engineer and if these criteria are adaptable to environments with limited design traditions. From the desired competencies and skills, educational activities will be developed as well as accompanying assessment tools.

Understanding levels of design

The concept that there are different levels of design was an outgrowth of Donaldson and Sheppard's work in Kenya [4]. Their observations resulted in the classification of four types of consumer products. In order of increasing complexity they are: imitation of foreign designs, imported designs, original basic designs and original complex designs. Their findings suggest there are elements of design know-how and know-why in each of these classes and imply that there are different levels of design required to create products.

To illustrate this concept of design levels, let us examine what is required to create a shovel versus a turbine engine. Clearly the design process required to create a turbine engine would require more detail and complexity than it would to create a shovel. In the same vein, it requires a greater level of thought, analysis and scientific understanding to create the turbine engine. So, how do you accurately assess a given organization or student's ability to design? Can you teach a student who has had little formal design tradition training or experience to design and build a mini-turbine engine regardless of the level of science, modeling and engineering science the student may have had?

These levels of design appear to be closely related to specific design processes. Reverse engineering may be classified as the most basic form of engineering design, which means that the thought processes and skills required to reverse engineer products are a set of basic design skills. It would follow that needs-based design might be classified as the most complex form of design and the thought processes and skills required to perform this kind of design are the most complex skill set.

The authors submit that different levels of design exist and the thought processes, skills, knowledge, and tools that are required to design at a given level can be articulated and linked directly to appropriate design processes. Thus educational activities or curriculum could be built around the desired skill development and design process. We believe this would be applicable to educational institutions in both developing *and* developed countries.

Table 1 is a compilation of documented design process types, some of the skills needed to effectively design within that process type, and a sample of typical applications. The table is not meant to be exhaustive in its scope but rather demonstrate some of the key skills or knowledge that are required to apply the process and some of the typical applications of each process family.

Assessing design capability

It naturally follows that if a given environment is best suited for a certain design level, then it would be foolish to try to implement a design process and curriculum that does not teach the skills needed for that environment. For example, industries within the United States expect engineering graduates to be able do to a wide range of needs-based design and analysis in order to be as innovative as possible. Chinese engineers need to be experts in manufacturing and assembly processes. Many engineers in developing countries are expected to manage repair and maintenance schedules and factory workers. Is it really appropriate to teach them all the same design skills?

The authors believe that by developing an assessment tool to rank or classify an organization,

Table 1. Engineering design processes

Process type	Required skills	Typical applications
Reverse engineering	• Knowledge of materials, manufacturing & assembly techniques & processes • Re-creation of detail & assembly drawings • Understanding of engineering sciences & analysis techniques • Logical & systematic documentation	• Copy a product • Copy a product with slight alterations or adaptations to a different environment • Evaluate a competitor's product & try to determine ways to improve on it (to gain additional intellectual property) • Evolutionary designs
Specification-based design	• Knowledge of when to look to an outside source to meet an internal design need • Decomposition & decision making • Conceptual design methods • Conceptual & physical embodiment methods • Analysis, experimentation, & validation techniques • Implementation strategies (manufacturing & distribution)	• Government related contracts—both military & municipal • Company to company related contracts • Vendor acquired products • These are cases where the specifications & acceptance criteria are completely defined by an outside source or entity. The product is a direct reflection of these inputs.
Needs-based design	• Need recognition, evaluation techniques & methodologies • Need-to-specification translation techniques • Marketing, business, & economics • End use, societal, life cycle, environmental impact, & other ethics related skills • All skills listed in reverse engineering & specification based engineering	• Consumer products • Specialized, customized equipment • New product development/research
Artificial intelligence	• Computer programming • Extensive understanding of engineering sciences, mathematics, & modeling • Extensive knowledge of computer software applications • Knowledge of economical, business, & manufacturing controls (similar to the knowledge required in needs-based engineering) • Required engineering knowledge to be able to create a family of products that fit within a given design space	• Mature & well understood products • Turbine & fan blades • Pressure actuation valves • Waste water treatment equipment • Automobile components

or environment's design capability, the most appropriate design process can be recommended and implemented. It is expected that this tool would incorporate a descriptive assessment technique [23] that maps into a matrix or index which would indicate the types of design processes and skills that are required to design within that design level. It is not yet understood what this tool should include and how it should be organized.

Creating design curriculum

Our paradigm is based on the premise that project-based learning is the most appropriate and effective means of teaching engineering design principles to students. Project-based learning can be further refined to include design-oriented projects (practical) and problem-oriented projects (theory) [4]. Furthermore, the authors feel that it is crucial to involve industry with academia and thus many of the design-oriented projects should be industry sponsored or have some significant level of industry involvement and support. Industry involvement in engineering education improves the relevance of education, better prepares students for employment, provides industry with a better qualified workforce, and creates synergy between industry and academia.

Since the specific outcomes and desired skills have not been fully articulated to a satisfactory state, many of the proposed educational activities the authors are planning to create and evaluate are not in a presentable format. However, randomized controlled trials (RCT) and other formal methods for experimental assessment will be used in conjunction with various descriptive assessment techniques [23].

It is expected that there will be a series of educational activities developed for each level of design to meet the objectives and skills that specifically deal with that level of design and its accompanying design processes.

CONCLUSIONS

This paper has outlined an approach to developing design process and educational systems that would be appropriate and efficient for environments where there is little tradition of design.

If an instructor is able to evaluate the level of design complexity his or her students are capable of applying, a tailored design process and teaching approach could be used to assist the students to be successful in learning both the art and science of design. These tools also have the potential to improve engineering education and teach students how to adapt the design process to a given need or situation. This skill will better enable students to make meaningful contributions in the industries where they are employed.

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