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Personal View
An Integrated Engineering Program in Design and Manufacturing Education*

A. SMAILI
J. SCARDINA
Department of Mechanical Engineering, Tennessee Technological University, Cookeville, TN 38505, USA

A program intended to focus on product realization and to give mechanical engineering students a 'cornerstone' experience in design and manufacturing is presented. Students in the program will engage in real-world problems, preferably obtained from industrial clients for specific human needs. In all courses in the program, students will work individually on the constituent parts of the project relevant to the subject being studied. The program will culminate in a capstone course in which the product that is being designed in the lead-up courses will be realized by different interdisciplinary teams. Students will experience the use of computer-aided engineering and modern manufacturing technologies.

INTRODUCTION

THE RAPID advancement in technology and the shift from a domestic to a global market economy require all concerned sectors in society to address the new realities and modify the current practices in product realization in order to meet the challenges of the competition [1,2]. In this effort, academia should play a leading role. The main challenge for universities is to educate future scientists and engineers who are capable of functioning technically in such a competitive environment. Achieving this goal in the technical era in which we live requires continual enhancement of engineering programs to make them relevant to industry concerns. The central idea is to produce a technical workforce that can commercialize current knowledge and technology in order to produce better, faster and cheaper products than the competition. This requires enormous changes in the philosophical and practical approaches to undergraduate engineering education in the area of design and manufacturing. Engineering programs that focus on the 'product realization process' are needed. Currently, students acquire knowledge in the form of a large volume of seemingly distinct batches of information in the required courses without the experience of integrating this knowledge in a meaningful fashion. The key is to deliver information to students in a way that helps them establish knowledge as a system. The major difference between a list of uncoordinated courses and a set of courses that constitute a systematic program is that knowledge acquired in a coherent program can more easily be applied to new situations. In essence, effective delivery of information should be approached as a chess game as opposed to a jigsaw puzzle. Engineering educators have been working to achieve integrated education. However, much work is still needed.

In an attempt to integrate knowledge and give students a meaningful design experience, most undergraduate engineering programs involve capstone courses in their curriculum, a practice that has been around for a long time. In its new criteria adopted in October 1992, the Accreditation Board of Engineering and Technology (ABET) requires of engineering programs to develop the design experience in a coordinated fashion throughout the curriculum rather than relying on capstone courses only [3]. (ABET is 'the agency responsible for accreditation of educational programs leading to a degree in Engineering' in the U.S.A.) This requirement constitutes a step in the right direction in regard to design education. However, what is required in the current competitive climate are engineering programs that give students a 'cornerstone' experience in design and manufacturing on which the students can build throughout their undergraduate education. This experience would culminate in a capstone project in which a product is realized. Essentially, a total integration of the courses in the area of design and manufacturing in one coherent program is needed. In retrospect, the cornerstone experience merges the best of two worlds when it comes to learning. One was summarized by Leonardo da Vinci: 'Those who rely on practice without science are like sailors without rudder or compasses', and the other one was affirmed by Aristotle: 'Let us first understand the facts and then we may seek the causes.'

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DESIGN AND MANUFACTURING: INTEGRATED APPROACH

Advanced technology manufacturing is regarded as the prime mover of a world-class economy and it is essential for an industry's survival in today's global market [4]. Manufacturing is the link to competitiveness: it is where innovative ideas are transformed to the marketplace. A strong manufacturing base is only affordable if the technical workforce is able to take advantage of new technologies as they become available and apply them to develop manufacturing systems that yield competitive products. The fast pace of technology advancement does not allow enough time for on-the-job training of the workforce. Therefore, engineers must have prior knowledge and experience of existing manufacturing technologies before they assume their responsibilities in the real world. Some of this knowledge and experience must be acquired as part of their engineering education. In this way they can learn and implement specific technologies more quickly once they are employed as practising engineers.

A product must be designed before it can be manufactured. The effort and knowledge required from scientists and engineers prior to manufacturing a successful product is intense. Several studies have confirmed that the major part of 'the life-cycle cost of products is determined and committed during the design process' [5,6]. To insure customer acceptance, the product must be simple, reliable, easy and safe to use, must have an acceptable life cycle cost, and must have acceptable aesthetic features. In short, it must be of high quality. Quality is initiated in the product during its design stage and is finalized during its manufacture. Therefore, including these concepts in design education is a very important step. Engaging in a *meaningful* design experience stimulates students' creativity and perpetuates innovation, which are two necessary ingredients for competitiveness. It allows students to develop abilities to think and reason, conceive ideas, nurture them by a blend of their artistic, scientific and mathematical skills, and translate them into reality with consideration to social and economical constraints [6]. Scholars, industry and governmental agencies always encourage universities to establish innovative, integrated engineering design programs as opposed to relying on the design content of individual courses in the curriculum. In references [6] and [7] undergraduate engineering curricula for design education are proposed. Some scholars advocate Ph.D. programs in design [8]. ABET requires that an engineering curriculum contains an adequate number of design credits that are distributed throughout the curriculum in a manner that culminates in a 'meaningful, major design experience' before it is granted accreditation. Capstone design courses that are integrable with the design content of other 'lead-up' courses in an engineering curriculum have been implemented to achieve the ABET target.

However, efficient realization of a design cannot be achieved in isolation of the design process itself. An innovative and reliable design remains just that if it cannot be efficiently manufactured and realized into a competitive marketable product. Integrating design and manufacturing processes is required. Successful integration requires that the personnel involved in both the design and manufacturing processes regard themselves as two sides of the same coin. Knowledge is the key to successful integration. If the designer understands the manufacturing process, the design would certainly be tailored to make it simpler to manufacture, easier to assemble and cheaper to produce. On the other hand, the knowledge of the manufacturing engineer of the design process enables him or her to have valuable inputs to the design that is being achieved. The knowledge needed to produce a team that can work in this fashion removes the artificial barriers that exist between engineering disciplines. Technology has in effect made barriers between engineering disciplines pale and, in the case of realizing competitive marketable products, barriers vanish altogether. It is no longer valid that only mechanical engineering students learn design and industrial engineering students learn manufacturing concepts, both in isolation from management concerns, marketing concepts and social and economic factors. What is required is an engineer that can work around barriers and is capable of quickly adapting to whatever role he or she needs to play in order for the partnership to succeed. Technology has transformed the work environment and made it interdisciplinary. Universities should respond to the changes by educating engineers that can perform effectively in such an environment. The Report of the 1988 National Science Foundation Workshop On Undergraduate Engineering Education [9] stresses this point by stating that 'the necessity for engineers to change specialties as technologies wax and wane has become more imperative'.

UNIVERSITY ROLE

In his position statement on US Science Education, Watson [10] states that 'courses and curriculum from the first grade through colleges have stagnated, becoming irrelevant and uninteresting'. Certainly, current educational approaches, especially undergraduate engineering programs, are not as bleak. However, innovative approaches are required. In order for the universities to produce a world-class competitive technical workforce, design and manufacturing education must be integrated into one program that focuses on the product realization process. Faculties that are knowledgeable in modern design and manufacturing concepts, equipped with effective teaching methods and capable of coordinating their effort with others are necessary to the success of such a program. Teaching design and manufacturing requires teachers to have a broad knowledge about other fields in addition to their own field of expertise; hence, specialists in one area and generalists in others. This dual nature is essential for developing innovative and optimum ways of delivering information to students and ensuring that practical interdisciplinary examples are presented to the students in the classroom to accelerate their learning process [11]. In addition to their role as deliverers of cutting-edge technologies, teachers are increasingly required to function as motivators for students. This role, in a rapidly advancing technical era, adds an extra burden on teachers to direct time and effort to continually educate themselves, to add or revise existing courses in the curriculum making them relevant to the future, and to search for innovative approaches to deliver information. Only teachers on the cutting edge of knowledge are capable of teaching world-class engineers.

In addition to effective and innovative teaching methods, universities should organize undergraduate design and manufacturing programs that provide students with hands-on experience on machines and equipment related to manufacturing, especially computer-integrated manufacturing and concurrent engineering technologies. For this to happen, the institution and other concerned sectors have to be philosophically and financially committed to develop and maintain modern, well-equipped laboratories. At the same time, the undergraduate program should be strongly linked to master's level studies for students who choose design and manufacturing as their continuing educational goals. The importance of these two factors is underscored in the report on the National Science Foundation Workshop on Undergraduate Engineering Education [9]. The report recommends to 'encourage engineering education institutions to rethink the undergraduate/master's level interface by funding curricular and course development programs which lead to articulation and integration of these programs, as well as enhanced practice-oriented content'.

DESIGN AND MANUFACTURING PROGRAM

The authors are proposing a program aimed at integrating engineering design and manufacturing education. The program will be built around currently existing courses in the ME curriculum and will satisfy ABET requirements in the areas of mathematics, basic sciences, engineering sciences, engineering design, and the humanities and social sciences. The first two years in the program require students to fulfil the requirements for basic sciences, chemistry, mathematics, physics, humanities, and engineering drafting and computing programming. As appropriate, cornerstone projects will be introduced in many of these early courses as carefully formulated example problems to 'preview' their more detailed treatment in subsequent upper-level courses.

The last two years of the program will focus on integrating the concepts of individual courses into a unified solution of cornerstone projects. The courses in the last two years of a typical program based on the ME curriculum at Tennessee Technological University are given in Table 1. The outlined program is not intended to replace the usual ME curriculum. However, it can be regarded as an option program within the ME department with emphasis on design and manufacturing.

The specific courses in the program are not

Table 1. Courses in the last two years of a typical program based on the ME curriculum at Tennessee Technological University

Junior year	Fall semester	ME 301	Concepts of Engineering Design
		CE 311	Mechanics of Materials
		EE 382	Fundamentals of Electrical Engineering II
		ENG 453	Literature and Technology
		ME 321	Thermodynamics
		ME 361	Dynamics of Machinery I
	Spring semester	ME 302	Measurement Systems
		ME 305	Mechanical Vibrations and Simulation
		ME 371	Heat Transfer
		ME 362	Dynamics of Machinery II
		ME 447	Microprocessor Control of Intelligent Machines
		ME 443	Analysis of Manufacturing Processes
Senior year	Fall semester	ME 374	Transport Phenomena Lab.
		ME 372	Fluid Mechanics
		ME 401	Machine Design
		ME 481	Automatic Controls
		ME 445	Design for Manufacturability
		ME 418	Finite Elements Methods in Mechanical Engineering
	Spring semester	Math 451	Advanced Mathematics for Engineers
		IE 310	Engineering Economy
		IE 461	Computer-aided Assisted Manufacturing
		ME 414	Introduction to Robotics and Intelligent Machines Engineering
		ME 467	Integrated Design and Manufacturing for Product Realization

necessarily new, as engineering programs in other institutions include such courses. Neither is the idea of having design and manufacturing programs new. In references [12] and [13] programs of that nature are presented. However, the approach is integrating the courses in the program and the effort in coordinating the engineering experience acquired by each student in all of the courses in the program in order to realize a product is, in the authors' opinion, unique. The program being developed will concentrate not only on the information being taught in the courses, but also in its delivery process, because the way information is delivered has a tremendous influence on student learning abilities. With this in mind, the proposed approach that should be employed in teaching design and manufacturing in a mechanical engineering curriculum is now summarized.

A real-world problem will be obtained from an industrial client. The problem could include creating a system for a specific human need; modifying an existing product in order to improve its safety, cost efficiency and manufacturability; or adapting a product to new standards and regulations. In an effort to optimize the process of delivering information to students, the problem will be broken down by the faculty involved in the program into several parts according to the particular subject matter relevant for its fulfilment. The problem and its constituent parts will be formulated in detail in the Concepts in Engineering Design course at the beginning of the junior year. In this manner the students will be acquainted with a realistic problem that will help focus their attention on the application aspect of the knowledge they will acquire in the future coursework and establish a sense of how courses in the curriculum are integrated toward realizing a product. Each constituent part will then be assigned to students in the form of a sub-project to be completed as a part of the relevant course in the program. The part requiring synthesis and force analysis of a mechanism will be assigned in the Dynamics of Machinery course. Stress and dynamic analysis activities will be given to students in the Finite Elements for Structures and Mechanical Systems course. Design of the required digital controller will be assigned to the students in the Microprocessor Control of Intelligent Machines course. Manufacturing considerations will be addressed in the Analysis of Manufacturing Processes and in the Design for Manufacturability courses. Each student will be required to work individually on each constituent part of the project as relevant courses in the program are taken. This will enhance the student's understanding of methods and techniques, establish self-confidence and maturity, instill a sense of competition and continuity, and develop motivation to learn [11]. As a result, the student will become a better contributor to the efforts of his or her team that are focused toward realizing the product.

The teamwork experience will be acquired in the capstone Integrated Design and Manufacturing for Product Realization course in the senior year. In this course the students will engage in a multidisciplinary teamwork experience where teams are formed to include students from other engineering, technology and business programs. Students respond favorably to teamwork experience as documented by Hodge *et al.* [14] and other references. In this environment the concepts and techniques learned and the knowledge gained by the students in the lead-up courses in the program will be blended with the concerns of other forms of talent that are essential in the product realization process. Equally important are the skills that students acquire while working in teams that allow them to build bridges of communication with those of other expertise, which is an essential ingredient of a professional engineer [15]. The ideas and methodologies devised in the lead-up courses by students to solve the constituent parts of the project represent the initial ideas from which the team decides on the most effective way of fulfiling the stated objectives of the project. In this course also, students will acquire hands-on experience in using CNC machines and will enhance the interface between the graduate and undergraduate programs by allowing first-year graduate students to enroll in it.

The advantages to this approach are enormous. Students will experience, individually and in teams, all phases involved in the product realization process as they solve a practical problem in an educational program that entails coherent progression of coursework.

SUMMARY

A program aimed at giving undergraduate mechanical engineering students a cornerstone experience in design and manufacturing is being proposed. The courses in the program are coherently integrated in a unique fashion in the sense that each course in the program will involve a constituent part of a project that is obtained from an industrial client to fulfil a human need. The program will culminate in a capstone experience in which students in interdisciplinary teams will realize the product they have designed in the lead-up courses. Thus, each student will be required to work individually and as a member of a team in an experience that will focus throughout the program on product realization. Students will also experience the use of state-of-the-art computer-aided engineering concepts, microprocessor control and CNC technologies. It is hoped that the cornerstone integrated experience will help the students perform well in the current climate of fierce competition, in which 'the race is to the technologically swift and commercially astute' is becoming the adage of times.

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Ahmad A. Smaili received from Tennessee Technological University (TTU) a Bachelor's degree in 1979, a Master's degree in 1981 and a Ph.D. degree in 1986. He served on the faculty of the Department of Mechanical and Nuclear Engineering at Mississippi State University (MSU) from 1987 to 1991. While at Mississippi State University he received an outstanding faculty award for the year 1989–1990 and the Purple Shaft Trophy of the MSU chapter of the Pi Tau Sigma for the years 1989–1990 and 1990–1991. Currently he is an Assistant Professor of Mechanical Engineering at TTU where he teaches graduate and undergraduate courses and conducts research in the areas of mechanisms, mechanical design, robotics, and finite-element applications. He is also involved in devising courses and curricula aimed at integrating design and manufacturing education.

Joseph T. Scardina is a Professor of Mechanical Engineering at Tennessee Technological University (TTU), Cookeville, Tennessee. He is a magna cum laude graduate of Vanderbilt University. He received from Vanderbilt University, the Bachelor's degree in Mechanical Engineering (1965), the Master's degree in Materials Science (1967), and the Ph.D. in Materials Science in 1971. In 1984 he initiated the Center for Manufacturing Research and Technology Utilization at TTU and served as its director until 1990. He teaches undergraduate and graduate courses in materials science and manufacturing. His present research interest is in the area of injection molding of plastics.