# An Innovative Interdisciplinary Approach for Teaching Modern Manufacturing

**M. Y. Zarrugh**
**Integrated Science and Technology, James Madison University,**
**Harrisonburg, VA 22807**

## Abstract

The Integrated Science and Technology (ISAT) program at James Madison University has developed an innovative, interdisciplinary course sequence that introduces the theory and practice of modern production to undergraduates in science and technology. The sequence stresses "information age" manufacturing, which capitalizes on computing and information technology as a tool for increasing labor productivity and enhancing competitiveness. Successfully blending engineering, business, science and information technology, the courses provide a balanced contemporary treatment of manufacturing resource management, design and manufacturing systems, and materials and manufacturing processes. Several laboratory modules and group projects offered throughout the sequence provide opportunities for experiential learning, hand-on experience and teamwork. The sequence addresses many of the critical competency gaps in manufacturing engineering education reported in recent national surveys of manufacturing managers and practitioners.

## I. Introduction

Engineering education throughout its history has emphasized preparation for professional practice. But engineering curriculum has not kept up with unprecedented economic, technical and political changes.[1,2] The gap between what is being taught in the classroom and the skills needed for contemporary engineering practice is threatening the nation's technical leadership and its ability to compete in global markets for industrial and manufactured goods.[3,4] The primary trends to which educational reformers must respond are[5]

1) *Globalization* of markets, labor and capital that requires companies to operate on a much broader scale than they have been accustomed to operate in the past.
2) *Decentralized management* and flattening organizations are replacing hierarchical organizational structures and centralized control. This management style requires diversified and distributed skills that promote local decision-making and control.
3) *Mass customization of products and services* increasingly provides the variety of choices that the customer wants and expects.
4) *Responsiveness* and rapid adaptation to changes in markets, technology and regulatory requirements.

These trends and gaps have prompted all stakeholders to question the relevance and effectiveness of current approaches to engineering education. Engineering education itself faces significant challenges. These include: (1) economic factors, such as escalating costs and rapid obsolescence of technology and infrastructure; (2) increased participation of nontraditional students who require balance between class time, work schedule and family demands; and (3) traditional classroom teaching that may not be the most compatible with the learning styles the contemporary college students who typically possess short attention spans and a heavily visual orientation.[2]

An effective response to these challenges is to make a commitment to life-long learning that will allow for smooth career shifts as the needs of society and jobs change. Calls for educational reform have advocated that engineering programs produce graduates capable of adjusting to many career changes in their lifetimes through independent study habits and integrated multidisciplinary exposure.[4] Koska and Romano[6] have called for similar improvements in manufacturing education. They recommend that curricula cut across disciplines in an integrated fashion and place more emphasis on the acquisition of softer skills, such as critical thinking, communication, tolerance of ambiguity, teamwork and sensitivity to social issues. By emphasizing processes and experiential learning, curricula impart generic skills that can be extended to many contexts and endure many career changes.

The new evaluation criteria of engineering programs established by the Accreditation Board of Engineering and Technology (ABET) reflect the need for reform and call for total overhaul of traditional engineering curricula.[7] ABET's Criterion 3, Program Outcomes and Assessment, describes eleven specific outcomes in the skills of graduates of accredited engineering programs. In addition to traditional "hard" skills involving mathematics, science and technology, the criteria require the "softer" abilities of functioning in multidisciplinary teams, understanding ethical and professional responsibility, communicating effectively, understanding the impact of technology on society, life-long learning, and knowing contemporary issues.

A survey conducted in 1996 has quantified the attitudes of practicing engineers to ABET's Criterion 3 requirements.[3] Respondents assigned degrees of importance to 172 skills (that map directly to the eleven outcomes of Criterion 3) required of entry-level engineers, as well as engineers with three to five years of experience. Not surprisingly, all items were ranked as slightly more important for experienced engineers than for new engineers. Criterion 3 outcomes that were ranked indirectly as having "High" to "Very High" importance are (listed in descending order of importance): applying mathematics, science and engineering, understanding professional and ethical responsibility, seeking life-long learning, designing and analyzing experiments, formulating and solving problems and communicating effectively.

## II. Professional and Technical Competency Gaps

In 1994, Mason[8] surveyed 47 different companies about their then current manufacturing practices and how these were expected to change over the next five years. The survey also

solicited recommendations for improving manufacturing engineering curriculum. Respondents ranked 21 manufacturing technologies as to degrees of importance to their current and future professional needs. Fifty percent of the respondents ranked six technologies: Manufacturing Resource Planning (MRP), Statistical Process Control (SPC), CAD, Numerical Control (NC), Just-In-Time (JIT) scheduling, and concurrent engineering as "very important." None of the technologies were ranked as "essential" then, but projecting the time horizon five years hence, the rankings of all six technologies were raised to "essential." When asked about the job of the manufacturing engineer, respondents indicated that in addition to their traditional roles of selecting, developing and improving manufacturing processes and operations, manufacturing engineers should also understand the impact of their decisions on job schedules, inventory levels and cost. The respondents also gave at least "very important" ratings to engineering economics, design for manufacturing, manufacturing processes applications, SPC, use of computers in manufacturing, and process control and automation. The results of this survey have significant implications for curriculum design of modern manufacturing courses. Consideration of such recommendations is particularly crucial when educators are upgrading courses to fulfill the newly revamped ABET evaluation criteria.[7] The ABET criteria of manufacturing programs, as well as earlier calls for reform in manufacturing engineering education[9,10] specifically call for extending the traditional evaluation requirements that emphasized materials, manufacturing processes and product engineering to student proficiency in manufacturing competitiveness and manufacturing systems design.

The Society of Manufacturing Engineers (SME) has recently commissioned a survey to identify gaps in the competency of recent graduates[11]. Nearly 400 engineering practitioners responded with their assessment of how well have graduates met employer's expectations. The professional competency gaps identified, listed in order of decreasing importance, are as follows: business knowledge/skills, project management, written communication, supply chain management, specific manufacturing processes (hands-on experience in at least one process), oral communication/listening, international perspective, manufacturing process control, problem solving, and teamwork/working effectively with others.[11] The five most critical gaps in technical competencies are: supply chain management, specific manufacturing processes, manufacturing process control, manufacturing systems, and process quality management.

## III. The Integrated Science and Technology (ISAT) program

In 1990 James Madison University completed a study of how its degree offerings might be extended into the areas of applied science, engineering and technology. The decision was made to create the College of Integrated Science and Technology offering a Bachelor's of Science degree by the same name. The Integrated Science and Technology (ISAT) program educates students for positions that are often filled by graduates of the traditional sciences, engineering, and business programs. ISAT graduates, however, are educated in a broader sense to be technological problem solvers, communicators, and life-long learners. They are unique in having: (1) breadth of knowledge and skills across a variety of scientific and technological disciplines; (2) formal training in collaborative and leadership methods, problem-solving techniques from many disciplines, and use of the computer as a problem-solving tool; and (3) the

ability to integrate scientific and technological issues with political, social, economic, and ethical considerations in problem solving.

Curricular breadth is provided through study in Strategic Sectors that reflect national critical technologies; these include Biotechnology, Energy, Engineering and Manufacturing, Environment, Information and Knowledge Management, Health Systems, and Telecommunications. Depth is provided through studies in an area of concentration and through a capstone senior project. Permeating the entire curriculum are information technology, the systems approach and laboratory experiences. The course sequence blends theory with hands-on practice in such areas as electron microscopy, computer-integrated manufacturing, multimedia production, lasers and optics, and environmental field studies.

The structure of the program is shown on Figure 1. The ISAT topics presented to students during the first two years are grouped under the following four clusters:

**Analytical Methods** (13 credits): A sequence of four courses designed to provide students with basic methods and tools for understanding and analyzing problems in science and technology.

**Issues in Science and Technology** (12 credits): A four-course sequence that treats science and technology in the context of current issues critical to the national economy and in an engaging and inspiring delivery.

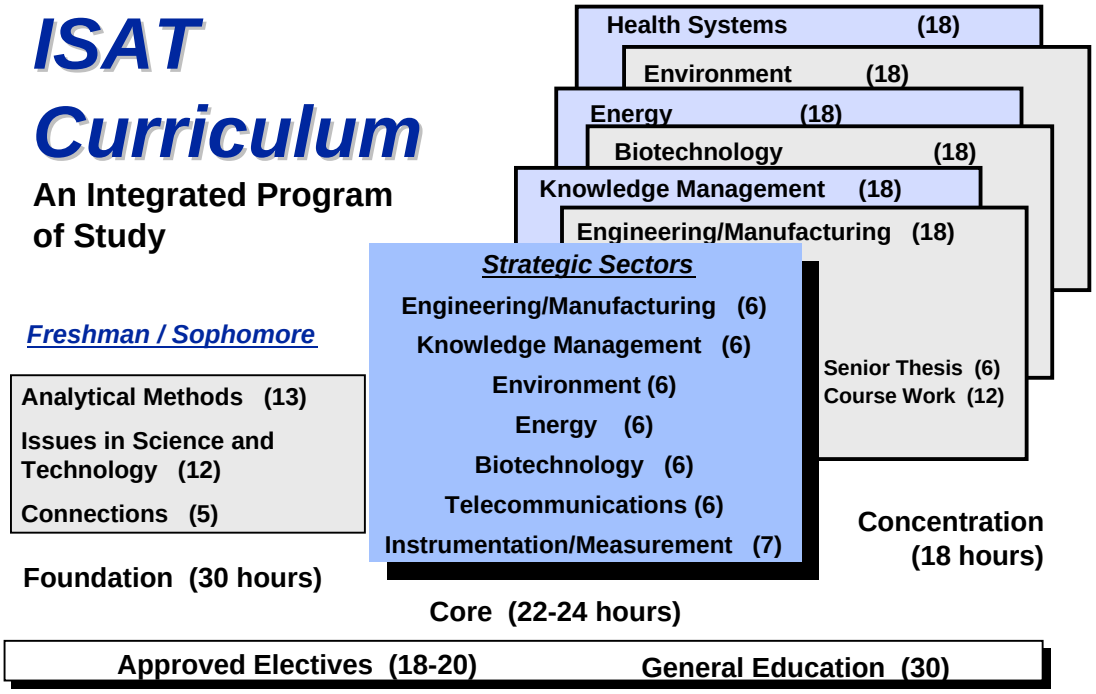


*Figure 1. The ISAT curriculum is designed around three sequences: the lower division foundation, the junior-year "strategic sectors," and the senior-year concentration.*

**Connections** (5 credits): Two courses that introduce social, ethical and legal issues and the impact of science and technology on society.

**Instrumentation and Measurement** (3 credits): A fundamental course introducing students to theory and applications of instrumentation and measurement in the practice of science.

In the upper division, students must complete 22-24 credit hours in at least three strategic sectors during their junior and senior years. The sectors represent areas of current strategic importance to the national economy. Specifically, students are required to complete at least three of the seven sectors available in their junior year and to concentrate in at least one sector in their senior year, depending upon their interest and individual academic plan. Most students (78%) voluntarily elect to extend their interdisciplinary experience further and concentrate in two sectors instead of only one as required.

## IV. Manufacturing Sector and Concentration

The manufacturing sequence of courses offers a framework for understanding, integrating and applying the many disciplines required to design, analyze, manage and improve manufacturing processes. The courses cover a broad set of topics ranging from product design and development to process selection and development to final production operations. External factors, such as safety, environmental regulations, and economic feasibility are also considered. The impact of new technologies on manufacturing processes is stressed. Among design and manufacturing automation techniques presented in the sequence are computer-aided design, computer-aided manufacturing (CAD/CAM) and computer integrated manufacturing (CIM), which includes NC programming, real-time process control, instrumentation and measurements and automated materials handling and robotics.

As shown in Figure 2, the manufacturing sector and concentration sequence in the upper division build on the broad integrated foundation established in the lower division by providing some degree of technical depth. Students consider the entire product realization process, from concept development, through product design and development, to manufacturing process design and implementation. Students learn about the use of computing and information technology in operations integration and process automation within a manufacturing enterprise, which include integration of design, manufacturing, people, parts, equipment, and information.

In addition to automation, the manufacturing sequence focuses on manufacturing systems, materials, manufacturing processes and improvements to implement competitive strategies, such as superior quality, faster time to market, greater flexibility, reduced cost and better compliance with environmental and safety regulations.

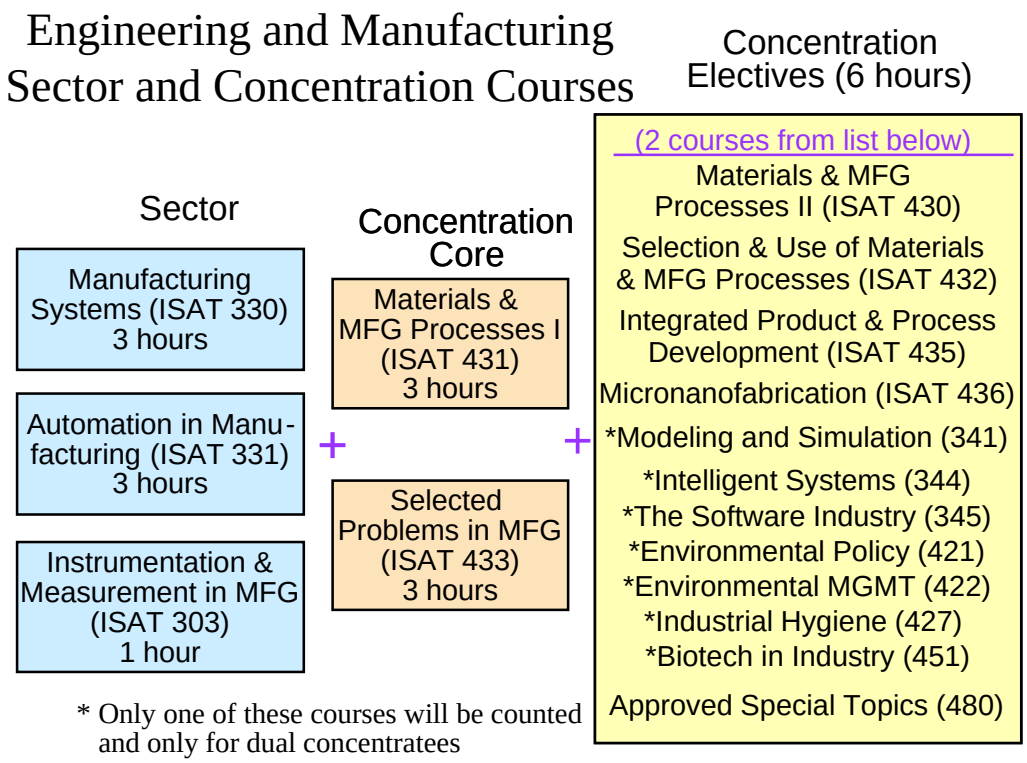


*Figure 2. The manufacturing sector and concentration course sequence.*

## V. Competency Gaps And Curricular Improvements

The novel course sequences outlined in the preceding sections not only address the basic topics of mathematics and the sciences, but also the non-technical softer areas called for by the educational reform and ABET's accreditation evaluation criteria. In particular, topics in manufacturing courses in the ISAT curriculum squarely target and fill the gaps in manufacturing engineering education identified in the two surveys previously discussed. Table 1 summarizes how the different manufacturing courses in the curriculum build student skills and competencies in both technical and non-technical areas.

Whenever possible, course materials integrate mathematics, science, technology, business and social contexts. Topics such as calculus, physics, biology, chemistry, design and manufacturing systems are not treated in isolation. Coherence is provided largely by a context of applications. Solutions to real problems generally draw from many disciplines, and students are confronted with this challenge early and throughout their four years of study.

| Topic or Skill | COURSE | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Foundation | ISAT 211 | ISAT 330 | ISAT 331/303 | ISAT 430/431 | ISAT 432 | ISAT 433 | ISAT 435 | ISAT 436 |
| ***Non-Technical*** | | | | | | | | | |
| Formulating and solving problems | X | X | X | X | | X | X | X | |
| Written and oral communication | X | X | X | X | X | X | X | X | X |
| Project management | X | X | | | | | X | X | |
| Teaming and working in teams | X | X | X | X | X | X | X | X | X |
| International perspective | X | X | X | | | | | | |
| Social, economic and poltical sensitivity | X | X | X | | | | X | X | |
| Ethical responsibility and values | X | X | | | | X | X | X | |
| ***Technical*** | | | | | | | | | |
| MFG processes and applications | | | | | X | X | X | | X |
| MFG planning and control | | | X | | | | X | | |
| MFG system design, analysis and operation | | X | X | X | | | X | | X |
| Quality management and SPC | | X | | | | | | | |
| Design and MFG automation (CAD/CAM/CAE) | | X | | X | | | | X | X |
| Product engineering and design for MFG | | X | | | | X | X | | |
| Engineering economics | | X | | | | | X | X | |
| MFG process control | | | | X | X | | X | | X |
| Computing literacy | X | X | X | X | | | | X | |
| Supply chain integration and management | | X | X | | | | X | | |

*Table 1. Technical and non-technical skills addressed by the manufacturing course sequence*

Not only are problems in real-life interdisciplinary in nature but the solutions to these problems are also often constrained by political, economic, ethical, or other non-technological factors. This social dimension of science and technology is a theme that carries through all courses of study in the program.

## VI. Pedagogical Improvements

In addition to fundamental reforms in curriculum content, the ISAT program is committed to improving pedagogy in the following ways:

*1) Team Teaching:* It is extremely difficult for a faculty, educated in narrow specialties, to provide integrated instruction that cuts a wide swath across traditional discipline boundaries. Thus, many courses (particularly in the lower division) are developed and taught by interdisciplinary faculty teams. This approach has the advantage of simulating actual problem solving in the professional world.

*2) Working in Teams:* Students, both in the foundational and the sector/concentration courses, are usually encouraged and often required to work in formal teams to complete projects or in ad hoc groups to work on homework problems. By working in groups, students can collaborate and learn from each other in relaxed informal settings. Such experiences help develop collaborative

skills and further prepare students for the modern workplace where most problems are typically solved by teams rather than by individual contributors.

*3) Experiential Learning:* Through ubiquitous use of laboratory exercises, students learn first-hand how to collect, analyze and present data in a variety of contexts, ranging from basic sciences (biology, physics, chemistry and materials) to the more specialized technology areas, such as biotechnology, manufacturing systems, environmental systems, energy systems, information technology and business.

*3) Intrinsic Use of Computing Tools*: Use of the computer and information technology as tools for problem solving permeates the curriculum. Students are given email accounts and access to computers the first day of class. Students receive broad exposures to simulation, analysis, measurement and database management tools as part of almost every course they take.

*4) Modern Pedagogical Methods:* Student-centered teaching and inquiry-based methods that force students to be active learners are known to improve competency and to increase student motivation and interest. In the ISAT program, these approaches are coupled with visual instructional techniques, such as multimedia, live demonstrations and props, to communicate difficult concepts to today's undergraduates who generally have short attention spans and a strongly visual learning style.

*5) Context Driven "Pull" Delivery:* In foundation courses, in particular, special attention is given to motivating students to learn. Topics are "pulled" in a "just-in-time" manner when needed by the applications or context. So the relevance and importance of the subject matter are always clearly evident to the student. For example, calculus concepts are taught in the context of one- and two-dimensional motion applications and the concepts of statistical variation and confidence levels are "pulled" by process control contexts. Thus, strong student motivation is cultivated by avoiding the traditionally dry and rigidly sequential delivery.

## VII. Implementation Considerations

The process of building a novel integrated science and technology program from "scratch" has been exhilarating and rewarding, but at the same time challenging and risky because the program was designed as an alternative to traditional curriculum and teaching methods. There are several lessons learned from this process[12]. First, growing an innovative, distinctly different program from traditional programs using existing faculty is not likely to succeed. It is critical that interdisciplinary faculty enter the program from the outside so that they regard it as their collective home to be built and nurtured, rather than a temporary assignment from their original departments.

The second tactical observation is that developing such a non-traditional program will be questioned and challenged, especially from traditional quarters. To succeed, the development efforts must receive the unwavering support of the highest administrative levels and the strongest commitment from the faculty developing the program.

Lastly, cultivating a special faculty culture is necessary in order to overcome the inertia of traditions and to sustain the spirit of reform and innovation. Faculty hiring practices that

emphasize the value of recruiting well-rounded and diversified professionals is a key prerequisite for sustaining the integrated vision. Faculty search committees need to look at more than the professional credentials of faculty candidates. Past performance and special expertise are important, but the fundamental motives, interpersonal skills, and teaming ability of the candidates are essential considerations. Faculty members who consider themselves integrated scientists first and regard their own discipline as secondary offer the best fit with the teaching and delivery philosophy of the program. Only interdisciplinary-oriented faculty can effectively draw and explain connections between different disciplines to students who are generally unable to integrate multidisciplinary materials on their own.

## VIII. Conclusions

The course sequences presented above effectively respond to calls for reform and to challenges to produce graduates capable of adjusting to many career changes in their professional lives. The curriculum cuts across disciplines in an integrated fashion and pays special attention to the softer skills, such as critical thinking, communication, tolerance of ambiguity, teamwork, and sensitivity to social and political issues. By emphasizing processes and experiential learning, the innovative program imparts generic adaptive skills that can be extended to many contexts and endure many career changes.

The success of the ISAT program in general and the manufacturing sequence in particular, required the presence of several critical elements that ranged from sensitivity to existing political forces and establishing an appropriate program culture, to demonstrating an ability to develop a curriculum of integrated instruction that provides an "essential depth" of knowledge across broad fronts of science, technology and business. Perhaps the critical element to a successful reform in teaching science, technology, or even engineering is the faculty that creates the program.

The program is currently in its ninth year. The number of entering students has grown from 62 in fall 1993 to 230 entering in fall 2000. Over 800 students are currently enrolled as ISAT majors. The program has had five graduating classes. Graduates have been very successful in finding professional placements at salaries consistent with BS engineering graduates, and achievement levels suitable for acceptance into graduate school. The average starting salary for the five classes is $42,000. Typically, about 10% of the graduates have continued in graduate school. There are about 100 businesses, industries, and government agencies interested in hiring ISAT graduates.

While these outcomes indicate that the program has been very successful to this point, the curriculum is still evolving, new faculty members continue to be hired, and additional infrastructure continues to be built. One enduring goal of the ISAT program is to remain innovative and responsive to changes in societal and career needs by making appropriate adjustments to its curriculum. Over the long-term, as the nation's need in certain technology areas waxes and wanes, the ISAT program and its graduates will be better prepared to accommodate such changes than most traditional science and technology programs and their graduates.

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**M. Y. ZARUGH**

Dr. Zarrugh is a professor of Integrated Science and Technology. He is also the executive director of Virginia's Manufacturing Innovation Center (VMIC) that helps smaller manufacturers increase competitiveness through advanced technology. Dr. Zarrugh teaches manufacturing, engineering design, instrumentation, and operations management. His research interests include, manufacturing systems, robotics, product design methodology and rapid prototyping.