AC 2010-33: A STRATEGY FOR INCORPORATING ADVANCED MANUFACTURING TECHNOLOGIES INTO UNDERGRADUATE EDUCATION

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David L. Wells has been Professor of Industrial and Manufacturing Engineering at North Dakota State University since January 2000. He teaches undergraduate and graduate courses in process engineering and production engineering systems design and in product innovation and entrepreneurialism. His instruction is characterized by heavy reliance upon project-based, design-centric learning. Course projects are drawn from real industrial applications with real industrial constraints, often interactive with a corporate sponsor. Students are challenged to design effective and efficient part manufacturing methods and complete production systems for commercial and industrial products. The common theme for students is mastering process, production system and enterprise design procedures that are applicable to any product in any industry. Graduates have been successful in manufacturing enterprises that produce virtually every type of product -- literally, from spacecraft to foodstuffs. In addition to traditional courses, Dr. Wells leads innovation teams in two engineering venues: product realization and transforming laboratory research into commercial products.

Dr. Wells' active research lies in orthopedic implants, micro-assembly, micro-machining, circuit board process engineering, printed electronics, applications of RFID technologies and manufacturing engineering pedagogy. Through his research, Dr. Wells has supervised the completion of twelve graduate degrees in the past six years. His publication history includes nearly seventy print publications and over forty invited presentations. He has addressed professional audiences in Ukraine, Japan, India, Brazil, Peru, Mexico and Canada, as well as in many United States venues. For many years, he has been active in the national leadership of Society of Manufacturing Engineers, American Society for Engineering Education, and ABET. Over the past twenty-six years, he has been a central figure in the design, development and articulation of curricula for educating manufacturing engineers in the United States and in selected off-shore venues. He also participates in Surface Mount Technology Association and Institute of Electrical and Electronics Engineers.

Prior to joining NDSU, Dr. Wells held manufacturing engineering and management positions in energy, aerospace, commercial sheet metal and automotive industries for twenty-six years. He also held a faculty position at University of Cincinnati for fifteen years, including thirteen years as chair of a department of some five hundred student head-count. He has also served as an academic dean in an experimental manufacturing engineering education program at Focus: HOPE (Detroit, Michigan) and as chair of the IME Department at NDSU. Dr. Wells is a certified manufacturing engineer and earned the BS and MS in Mechanical Engineering from Stanford University and the PhD in Engineering Management from the Missouri University of Science and Technology.

A Strategy for Incorporating Advanced Manufacturing Technologies into Undergraduate Education

Abstract: The face of manufacturing has been steadily and rapidly changing for many years. From about the mid-1980's, concepts of cost control, quality and overall efficiency have become an increasingly sharp focus. In recent years, many companies have tunneled in on lean manufacturing as their savior. It is certainly true that the precepts and procedures of lean, ToC, TQM and other regimens are essential for modern manufacturing competitiveness, and instruction in these matters has become a fundamental component in manufacturing education. With far less visible excitement, however, another 'revolution' has entered the scene. The fastest growing sectors of product type are those that require new processing technologies. In 21st century technical dialogue, product and process identification are intermingled. Among the new technologies that demand attention are nanotechnology, MEMS, biologically-focused products and a host of 'micro'-featured products and processes. This paper will explore the product and process issues that are relevant for undergraduate education in manufacturing engineering and manufacturing engineering technology and propose a timeless set of manufacturing principles that transcend evolutions in product and process development. The discussion will draw on classroom and laboratory content applied at the author's institution, as well as observations gleaned from the literature and from the Society of Manufacturing Engineers' leadership forums during 2008 and 2009. The paper will conclude with an outline of one possible step towards incorporating advanced manufacturing technologies into an undergraduate curriculum, without displacing instruction on timeless fundamentals.

Historical Perspective for Introduction of New Technologies: For at least the past three decades, the face of manufacturing has been in flux. The workplace in 2010 looks very much different than its counterpart in 1980. Tools and practices have evolved enormously. In response, so has been the need for definition of manufacturing engineering education[1] and the design of both undergraduate and graduate curricula.

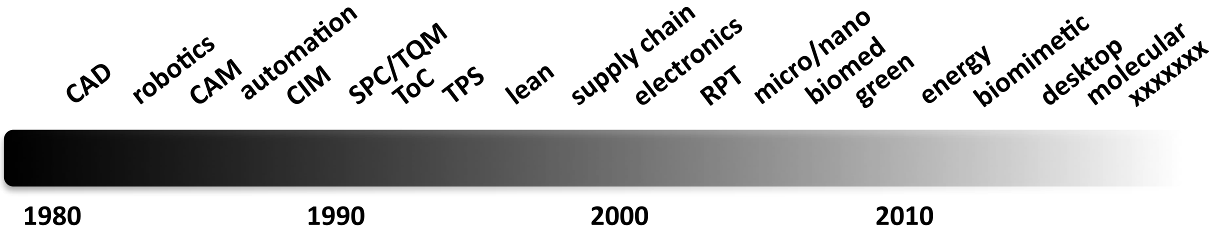

Figure 1: An abbreviated view of the introduction of new required topics into manufacturing engineering education over three decades-plus

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[1] It is fully recognized that university-level programs in both manufacturing engineering and manufacturing engineering technology are viable for providing professional staffing for industrial companies. In order to shorten the adjectives and other modifiers throughout this paper, whenever 'manufacturing engineering' appears, 'manufacturing engineering and manufacturing engineering technology' is meant, in almost every case. There are a few references (e.g., reference to accreditation criteria) where this inference is not the case, and these cases will be clear in the context.

❖ In the 1980’s, the rapid introduction of computerized tools in virtually every category of product-based industry led to an onslaught of new concepts in manufacturing education. Computer-aided-design transformed the industrial workplace. Many new software tools were created -- by many new (and some existing) companies. Compatibility became somewhat daunting -- most CAD drawings created on one system could not be read by another system. Then, software capabilities leaped forward, and the application of ‘design’ in CAD was expanded beyond drafting into analysis. Distinctions were made between CAD and CADD, and between CAD and CAE. Capabilities of computer-numerical-control exploded, and computer-aided-manufacturing was invented. Linkages between part drawings and machine controls emerged, and CAD/CAM entered the lexicon. Soon, computer-aided-design was overtaken by computer-aided-everything.

Manufacturing educators were flooded with new demands -- teach a new course in CAD; teach a new course in CAM; teach a new course in robotics; teach a new course in (topic of the current fad). Serious debates ensued on such minutia as which was the ‘best’ CAD system to teach. Curriculum design became somewhat extreme is spots. Curricula for degrees specifically in CAD began to surface, especially at the associate level. Whole separate degree programs in operational robotics proliferated, to the point where projected graduates would exceed the total number of positions throughout the economy in this narrow specialty every year.

❖ The 1990’s brought us more in the way of methodologies than in new technology. By the end of the 1980’s, American industry was beginning to recover from the high quality-low price onslaught of Japanese and other off-shore competitors. Quality had become a watch-word in virtually all product manufacturing industries, and educators spoke sagely of new courses in SPC, TQM, quality circles, voice-of-the-customer and the like. Globalization entered the mainstream of thinking in both industry and on campus.

As the decade progressed, *The Goal* of Eliyahu Goldratt and *The Machine That Changed The World* impacted manufacturing education.[1,2] Curricular elements introducing the concepts of Theory of Constraints and the Toyota Production System began appearing. Topics such as kanban, just-in-time, pull systems and ISO certification proliferated in papers presented at educational conferences. Towards the end of the decade, the list of new methodologies tended to coalesce around ‘lean manufacturing’ and ‘supply chain management’. The current-state focus in manufacturing and in manufacturing education had shifted to a noticeable degree from the technologies of how goods are produced to methods through which the production of goods is organized and managed.

❖ As the new century dawned, the methodologies of lean manufacturing and of supply chain management remained on center stage. Lean thinking continued to provide cost controls in production of virtually every conceivable type of goods, and spawned Six Sigma and other derivative concepts. Educational curricula followed suit. Research reports on ‘optimization’ of virtually every possible aspect of production systems seemed to become the staple of thought about manufacturing. Attention had shifted from the physics of altering a material in a way that adds value to an array of mathematical algorithms that attempt to describe the flow of materiel through a production system, virtually independent of 'manufacturing method'. The infrastructure of manufacturing seemed to have overshadowed the technologies for adding value.

As the concentration of attention remained glued to methodologies for organizing existing technology, a product revolution was arriving. Driven primarily by the electronics industry, features, parts and whole products had been getting smaller for years. By the early years of the 21st century, the shrinkage trend had reached the point where parts were small enough that the physics of tool-workpiece interaction had changed. As it happens, when the workpiece shrinks to about a millimeter in principal dimension, the balance of natural forces that affect material transformation shifts. At about that scale, surface forces become of approximately the same magnitude as body forces.

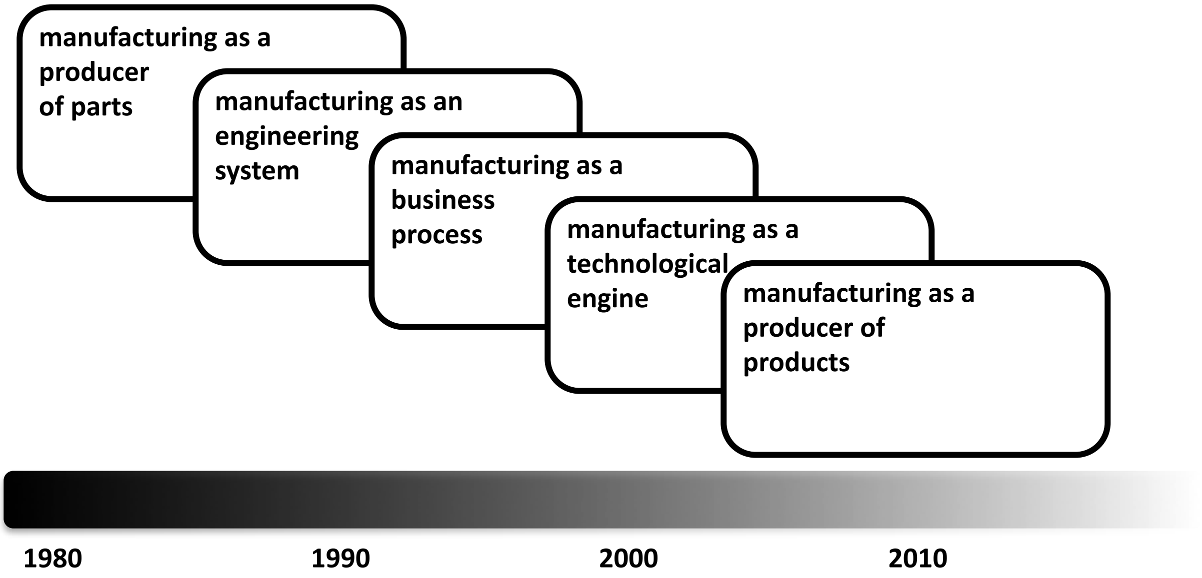

Figure 2: Evolution of 'manufacturing' over thirty years

❖ At the first decade of the new century comes to its end, the spectrum of topics contained in the discipline of 'manufacturing engineering' has shifted once again. 'Lean' and 'supply chain' remain crucial matters for applying technology to the production of goods. 'Quality', 'process flow' and 'value stream' are inextricably embedded in both process and production system design. However, new dimensional scales and product applications and environmental interactions require that science-based instruction be re-emphasized as the core of manufacturing engineering education.

To effectively and efficiently manufacture goods at micro-, meso- and nano-scales requires a return to emphasis on the physics and chemistry -- and increasingly, the biology -- of processing. Chip formation, solidification kinetics and parts assembly are different at sub-millimeter and sub-micron scale than in the traditional dimensional realm. Sound manufacturing process design now requires analysis of previously neglected forces from electrostatic, surface tension and van der Waals effects. Materials simply behave differently at the sub-micron scale, and the processes necessary for altering the workpiece material to add value embrace a far wider array than has been traditionally contained within 'manufacturing engineering'. This re-established emphasis on materials behavior leads us to a broadening of the spectrum of products considered as core topics for manufacturing engineering and a renewed consciousness of manufacturing as any activity that transforms (in any way) a material (of any sort) to add value.[3]

Moreover, the distinction between product design and processing design has become increasingly indistinct. A rush of new products in electronic devices, in medical devices, tools and implants, in novel energy generation techniques and in a seemingly unending array of micro- and nano-sized goods has joined the continuing flood of VLSI electronics. In much of this spectrum, new materials are encountered -- from shape-memory metal alloys to novel ceramics to nano-engineered composites. In virtually every case, product features and process capabilities are inextricably intertwined.

In order to be successful in a product environment of the small dimension and the novel material, manufacturing engineering must re-balance the equation of technology and method of application. To be sure, lean principles and 'supply chains' will remain as crucial aspects of the discipline. These, however, are [a] well-established and no longer new and [b] not fundamental technologies in themselves, but basic ways of thinking about managing technologies. Much as was the case with 'quality' some twenty years ago, 'lean' should distributed throughout the curriculum -- as habits of thought to be thoroughly integrated into the principles for designing processing and production solutions based on necessary value-adding technologies.

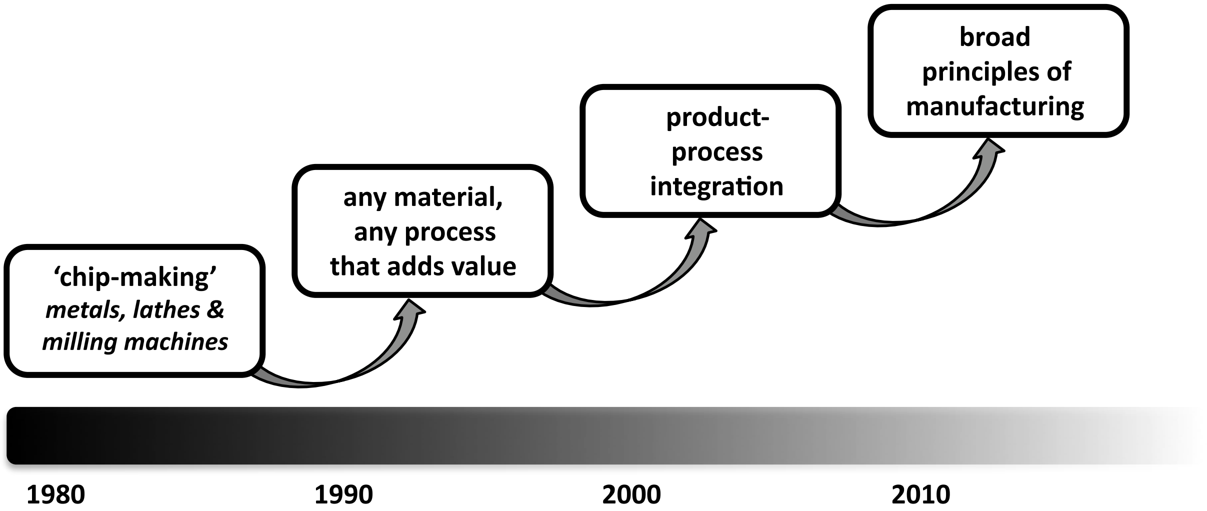

Figure 3: Evolution of manufacturing engineering education

The continuing curricular dilemma: For at least the thirty-year span referenced in the opening paragraphs, educators in every engineering discipline have been faced with the dilemma of too much to teach in too little time. Effective response to this continuing challenge is rooted in some of the basic aspects of many of the methods that have become popular for managing operations of industrial manufacturing facilities -- core competencies and doing more with less.

In manufacturing education, ‘core competencies’ are the fundamental principles of manufacturing engineering -- the science-based analysis and design necessary to create and specify effective and efficient processes and production systems to manufacture high-quality, low-cost goods. In many institutions, the pressure on the core discipline-specific portion of the curriculum is perhaps stronger than heretofore. Many states and institutions have introduced upper limits on total program credits, which in most cases result in reductions. At the same time, pressures to maintain or increase ‘general education’ content remain persistent from both liberal studies faculties and such ‘friendly’ sources as the periodic SME reports citing gaps in competencies of newly-minted engineers.[4]

At about the final decade of the previous century, undergraduate engineering curricula were typically the most credit-heavy programs on the campus, often running to graduation requirements of as much as 20 percent higher than their liberal arts competitors -- the equivalent of nearly an extra year in undergraduate study. Within the engineering education community, this was widely-believed to be justified by the extra rigor and breadth of learning required of engineers. It was also commonly felt at the time that even a credit-heavy curriculum had little room for introducing all of the new subjects that were being demanded by industrial advisors, employers and other commentators from the commercial sector.

topics	semester	credits
general studies		28
humanities; social sciences; communications		
mathematics		21
calculus; differential equations; statistics		
basic sciences		18
physics; chemistry		
engineering sciences		21
mechanics; circuitry; fluids; thermo; programming		
major engineering discipline:		
introduction	3	
core discipline topics	36	
capstone	6	
technical electives	12	57
		145

Figure 4: A ‘typical’ undergraduate engineering curriculum, circa 1990’s

At about the mid-1990’s, a movement began to limit the credit-size of engineering programs. An important element in the early motivation for this change originated in a few state legislatures. As politicians are wont to do, it was believed by these crusaders that one size should fit all -- that there should be guarantees that any college student should be able to achieve a degree in any major within the traditional four, mildly-challenging years. State mandates to limit all undergraduate majors to a common maximum were soon joined to another, somewhat more logically sound, motivation. Engineering deans, with compliance of university administrators, saw that limiting credit-size of their programs might make them more size-comparable with majors in pure and applied sciences and in business, which, in turn, might be an asset in competing for qualified students.

In order to squeeze already-packed curricula down to the newly-mandated limits, some small concessions appeared, at least on some campuses, in the mandated general education content. One such concession was the shifting of introductory freshman English from a first-year course to an entrance requirement. Engineering faculty met the remaining credit reduction requirements through various means. Popular stratagems included … elimination of laboratory requirements from basic and engineering science courses and from discipline-specific content, shifting some mathematics content to engineering courses, elimination of technical elective options for students, and shrinking basic and engineering science content. But a substantive part of the shrinkage burden came from curtailing the number of credits devoted to discipline-specific subject-matter. The net impact on disciplinary content might have reached 15 to 20 percent of the pre-shrinkage credit allowance.

topics	semester	credits
general studies		25
humanities; social sciences; communications		
mathematics		19-21
calculus; differential equations; statistics		
basic sciences		14-16
physics; chemistry		
engineering sciences		17-21
mechanics; circuitry; fluids; thermo; programming		
major engineering discipline:		
introduction	3	
core discipline topics	26	
capstone	6	
technical electives	12	47
		128

Figure 5: A 'typical' undergraduate engineering curriculum, squeezed to an arbitrary credit limit

An attractive next stage of refinement in 'shrunk' curricula would be the elimination of mandated introductory courses. These have become redundant for the majority of entering freshmen. Perhaps today's youngsters no longer need a course in how to find the library and how to use computers, coupled with admonitions that studying is important. Likewise, traditional courses to give students a broad overview of their chosen discipline can be more effectively supplanted by revised core-content coursework. But even these refinements leave most engineering curricula short of the pre-shrinkage discipline content.

Engineering programs are still faced with the deep challenge of introducing revolutionary new technological content into over-loaded curricula. The compulsion to squeeze new content into an already-stuffed curriculum is reminiscent of the onslaught of computer-based-everything that dominated curricular attention some twenty-five years ago. As then, it would seem that one obvious solution would be to change how we teach -- to be innovative in blending similar or parallel subject matter; to find ways and means for improving ‘efficiency’ in teaching. There have been experiments in blending subject matter in introductory engineering sciences that are worthy of attention.[2] In manufacturing engineering curricula, at least, it is more promising to blend at least some of the ‘lean’ and ‘supply chain’ topics into mainstream manufacturing design coursework. This teaching philosophy holds that it is often not so much what we teach, but how we teach.

topics	semester	credits
general studies		24
humanities; social sciences; communications		
mathematics		18
calculus; differential equations; statistics		
basic sciences		17
physics; chemistry; biology		
engineering sciences		21
mechanics; circuitry; fluids; thermo; programming		
major engineering discipline:		
introduction	0	
core discipline topics	30-36	
capstone	6	
technical electives	6-12	48
		128

Figure 6: An effective compromise undergraduate engineering curriculum

There will be cases where some industrial advisors will note that a curriculum may include no courses that contain the term ‘lean’ in the title and conclude that these topics are being ignored. What is often missed by the superficial observation is the more time-efficient and relevant incorporation of lean thinking into several courses. In the integrated approach, the principles of lean, value stream, Theory of Constraints, Six Sigma and other methods for managing technology are treated as integral parts of the thought processes for professional manufacturing engineers, rather than as separate and isolated topics.

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[2] One example that has merit is the combining of introductory fluid mechanics and introductory thermodynamics into a blended course that was piloted at the author’s former school in the early 1990’s. Another notion that has been tried is the blending of statics and strength of materials.

A path to a lasting solution: Of the many ways that have been envisioned and attempted to breach the continuing dilemma of what to teach and what to leave out, it is postulated that the most promising is a re-orientation of manufacturing engineering education from a collection of technologies and methods for their management to a concentration on fundamental and timeless principles. A change from industry-focus to principles-focus.

1. The most fundamental issue is dialogue in and about manufacturing engineering education that centers on the understanding that manufacturing is one of the few occupations that creates wealth -- rather than simply distributes wealth. As a direct result, manufacturing is a dominating social force -- the root of prosperity and what we are accustomed to call 'standard-of-living'. Manufacturing brings more goods and tools within the reach of more people every year. Manufacturing engineering students should be imbued with the sense of contribution to something larger than themselves or their company or the profit margin.

2. Manufacturing engineering, at the end of the day, is about creating products -- things that improve and enrich lives. Every product that touches our daily lives is manufactured. The fundamental description of manufacturing holds that this is what occurs when a material (of any type, form or composition) is altered (in any way) that adds value.[3] The principles of manufacturing engineering emanate directly from that fundamental definition. The central themes of manufacturing engineering are [a] the material that is transformed (a.k.a. the product) and [b] the transformation that adds value (a.k.a. processes for individual parts and production systems for entire products). Quality in the goods produced and lean deployment of assets are integral elements of process and production system design.

3. Manufacturing engineering is a design profession. Educational curricula should stress the blend of science and art upon which creativity grows, for 'design' is a process that creates both new products and new processes. While projects with tangible and realistic products are to be preferred in the learning process, the objective is the development of familiarity with universally applicable design methodology -- that can be applied to any product in any industry.

4. Regardless of size, scale, complexity, material, durability or any other aspect of the product, manufacturing engineering can be categorized into a common framework -- a universal set of principles that are applicable to the manufacture of any product. These can be summarized as three basic components for the discipline: product engineering; process engineering; production engineering.[5,6,7]

5. The competencies of the discipline are well-summarized in the accreditation program criteria for manufacturing engineering. At the end of their undergraduate curricula, newly minted manufacturing engineers should demonstrate proficiencies in …

… materials and processes: understanding the behavior and properties of materials as they are altered and influenced by processing in manufacture;

… process, assembly and product engineering: understanding the design of products and the equipment, tooling and environment necessary for their manufacture;

… manufacturing competitiveness: understanding the creation of competitive advantage through manufacturing planning, strategy and control;

… manufacturing systems design: understanding the analysis , synthesis and control of manufacturing operations using statistical and calculus based methods, simulation and information technology;

… laboratory experience: graduates must be able to measure manufacturing process variables in a manufacturing laboratory and make technical inferences about the process.[8]

Even stripped to the core of fundamental principles, the body of knowledge to be compressed into an undergraduate's curriculum will strain the bounds of any program. Amid much pressure to reduce the number of credits required for a baccalaureate degree and to broaden and expand the 'general' education component of undergraduate programs, the time and space for thorough engineering education recedes, seemingly, yearly. Incorporation of new technologies, along with timeless fundamentals remains a challenge that continues to tax creativity of faculty.

One very promising approach: One very effective method for enriching the learning process is the fundamental innovation referred to as 'project-based learning', sometimes called 'discovery-learning' or 'inquiry-learning'. These methods have been touted in ASEE conferences and other similar venues for well-over a decade, but appear to remain under-used. This pedagogy focuses on learning, rather than teaching. Much self-teaching and peer-teaching occurs.[3] Lectures are minimized and are confined to fundamental processes. Class periods are not used for conveying data or information that can be just as readily acquired by the student through other means. Instead, most class meetings are devoted to discussing how to apply the methods outlined in the text or in prior lecture or in pre-requisite courses or in independent learning to the solution of significant problems. Attention is focused on principles and on generally-applicable methods and procedures --- not on rote examples of 'how to'.

The method of instruction is somewhat challenging for the instructor. First, it is crucial that the instructor be well-versed in a variety of real industrial situations. Traditionally, such expertise comes from instructor experience as a practicing engineer in industrial employment. In modern engineering schools, however, most faculty have little opportunity for industrial experience before beginning on the professorial ladder. In such cases, summer internships may offer a viable path.

Even with a wealth of experience in the practice of engineering, it is difficult to achieve the right balance between general principles and effective execution of basic notions (e.g., how to establish criteria for selection of a machine tool for manufacture of a given part vis-à-vis computation of a prediction for spindle power requirement in milling or of press force required to stamp a sheet metal part). However, with diligent practice and willingness to adapt and modify classroom procedures, remarkable results can be achieved. There is also a significant challenge in managing the classroom. In inquiry-based learning, class meetings are heavy on discussion of issues and practical problems of how to address detailed aspects of the project. For the instructor, this is hard work and should be accompanied by more than usual care in preparation.

Different challenges attend the assessment of learning. When the focus is on designing a manufacturing solution for a practical part of a multi-part product, it is sometimes difficult to

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[3] Incidentally contributing to fulfillment of the ABET outcome for developing competencies for life-long learning.

maintain student attention on the correct causal relationships in the underlying manufacturing science. One of the persistent assessment challenges is centered on how to assure that students truly know the correct relationships between, say, primary cutting conditions and machine tool settings of a lathe -- what parameters are selected and on what reasoning. When the project objectives are framed in the larger terms of process or production system design, the details often get shorter shrift. Students often think they know more than they do. So, assessments must be crafted to [a] purposefully evaluate both the fundamentals and the design application and [b] maintain student focus on both issues simultaneously.

Another part of the challenge is the age-old problem with retention of knowledge and translation from one class to another. A recent classroom experience of the author illustrates: The assignment was to apply beam bending analysis to a press brake in the laboratory, with the objective of establishing achievable part dimensional tolerance limits as a consequence of deflection of the machine tool structure under load, using both concentrated and distributed loading. The expectation was that students would apply beam theory from strength-of-materials (a prerequisite course) to process engineering in predicting effects of process parameters on machine tool deflection and, then, on part dimensional tolerances. Very poor results were obtained, and the post-mortem classroom dialogue revealed a pervasive lack of understanding of how beam theory might be applied. Students reported that their achievement in the prerequisite course was based upon entirely on accurate reproduction of problems solved as examples in their textbook. This experience suggests that two addition notions require attention in inquiry-based learning. One is that the effectiveness of this style of learning is somewhat influenced by its widespread application in the curriculum. Second, the recurrent question of how much review is included in the post-requisite class is still ever-present.

A Suggested Strategy: It must be recognized that there is no single model that will fit every situation, nor is there a fully fleshed-out strategy for incorporating all (or even any) of the new manufacturing technologies into an undergraduate curriculum. However, observations and experiences (both successful innovations and unsuccessful ones) suggest a proposed path through which new technologies can be successfully introduced into an already-packed curriculum. It is suggested that this path is characterized by …

… Insofar as is possible within the constraints of institutional procedural limitations, trim the program of coursework of marginal value-addedness. Such topics as introduction to campus life and to the engineering discipline are prime candidates. Careful program-wise content management can retain those elements of traditional introductory courses that are useful. Credits freed up from elimination of marginal-value courses can be better employed for introducing new technologies.

… Structure a pervasive philosophy of manufacturing engineering throughout all disciplinary course offerings. A product-centric philosophy is suggested. Be certain that students hear the same message from all faculty.

… Present the learning of the discipline of manufacturing engineering in the universally applicable framework of … process engineering; product engineering; production engineering. Be consistent in employing this litany in successive courses throughout the major study. Stress the universality of these fundamentals through repetitious emphasis on the proficiencies defined in program accreditation criteria and through use of projects that draw from a variety of established and new technologies.

… Introduce new manufacturing technologies in two ways: [a] as illustrative project or homework assignments in core courses within the major (requiring supporting change in lecture content) and [b] as advanced-topic elective courses that are based on core fundamentals -- and/or [c] in other, innovative ways devised for the particular program. This remains a difficult task in course and curriculum design. There are no magic paths or ready-to-apply templates. It is probable that not every new manufacturing technology can be included, at least not in any degree of depth.[4] Selection is, and will be, always a challenge. Further, which new technologies to include in core courses and which topics to emphasize in electives must be determined to fit the focus in each program.

Faculty expertise is crucial. In the vast majority of cases, the manufacturing technologies in question will be well-beyond those that were central to initial faculty preparation. Few current faculty will have, for example, developed a level of expertise in medical device manufacture during their graduate study or earlier career; growth in expertise is essential. Introduction of new technologies requires background (from study of new technologies, as well as the fundamentals of the manufacturing engineering discipline), perception (from interaction with the program's industrial constituencies and with trends in the broader national and international arena) and a well-developed program strategy (needed in any case).

… Note that some of the new manufacturing arenas require a different set of preparatory topics -- example: foundations in biology and organic chemistry for study of manufacturing of medical products; molecular-scale physics for study of nano-manufacturing. Changes in the natural science content will likely exacerbate the crowded-curriculum problem, and innovative methods for addressing needs for altered foundations may be the most fruitful approach. Sometimes, enterprising faculty in the natural sciences can be valuable allies.

… The most challenging aspect in the introduction of new manufacturing technologies is the matter of laboratory equipment. Regardless of which technologies are selected for the program, significant experimental work will be beyond the capabilities of the conventional machine tools that populate the typical manufacturing engineering laboratory. Many processes require quite different machine tools (e.g., manufacture of electronic devices or nano-scale products). Others at least require resolution, tolerances and control well-beyond the traditional norms (e.g., micro-manufacturing).

A simple or universal solution to the equipment challenge does not seem to be available. University budgets everywhere are under great pressure, and coaxing out the significant new investments necessary will likely be at long odds. There are very few opportunities to compete for grant funding for teaching apparatus -- not nearly enough to serve the needs of even a significant fraction of manufacturing engineering programs. Still, the ingenuity of

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[4] This is a familiar dilemma from decisions that have to be made regarding coverage of more traditional manufacturing processes. Very few, indeed, are the programs that include comprehensive coverage of every available process for transforming workpiece materials.

individual faculty and programs can make a start, and shortage of appropriate laboratory equipment ought to be a constraint, rather than an absolute barrier.

… Deliver manufacturing engineering in a learning-centric format … stressing design and problems-solving, strong in both fundamentals and applications projects, and including as much laboratory experience as can be mustered -- especially in new technologies. Keep student's attention focused in the creation of products.

… Apply great diligence in transitioning instructors from lecturers to directors of learning and professional mentors for students. Practice a lot.

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