2006-17: A FRAMEWORK FOR STUDENT LEARNING IN MANUFACTURING ENGINEERING

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A Framework for Student Learning in Manufacturing Engineering

Abstract: The framework proposed in this paper offers a compact outline for transforming traditional process-dominated manufacturing engineering curricula into comprehensive learning in product realization. The outline includes four stages: product engineering; process engineering; quality engineering; production engineering. The paper presents an application of this learning progression that is implemented within a traditional set of courses -- an approach that can be adapted and adopted by other faculty virtually instantaneously. Also presented is a suggestion for thorough overhaul of manufacturing engineering curricula into a substantively new format. The paper concludes with observations and measures of student response gathered in application of the four-stage model in the author's classes.

Context and Continuity: As a formal field for academic preparation, the discipline of manufacturing engineering has been evolving for only two or three decades. Through the sponsorship and leadership of the Society of Manufacturing Engineers, documents offering curricular structuring, suggested course content and focused central learning objectives appeared from the mid-1980's through the 1990's.[1,2,3] Likewise, over the past ten years, competency maps and gaps for various stages of manufacturing engineering careers have been published by SME and others.[4,5,6]

Following a landmark SME publications in 1985 and 1988,[1,7] each of the historical documents has offered guidance for developing curricula and specific course content in an incremental evolution. These recommendations maintained a constant focus on manufacturing engineering as a dominantly process-oriented discipline, enhanced with soft-skills. This paper suggests a more comprehensive framework for the manufacturing engineering discipline encompassing the full spectrum of product realization.

The Essence of Manufacturing: The essential nature of manufacturing is the creation of products. Indeed, no products (outside of raw vegetables, perhaps) exist that are not manufactured. Although global information exchange and market competitiveness in all corners of the world are vital and pervasive issues, manufacturing enterprises exist to produce products -- and to do so in a fashion that generates current and continuing profit. Thus, it is contended that the learning of manufacturing engineering must begin with deep understanding of products of a variety of genres. Subsequent learning about value-added processes for material transformation, quality measurement and management, and design of production systems and enterprises are all, then, accomplished in the context of the creation of products and from the foundation of strong knowledge of materials processing.

Despite the plethora of management tools that have flooded the market-place over the past decade or so, manufacturing remains at root a materials processing enterprise. Manufacturing occurs when a material is altered in some way that adds value.[8] The workpiece materials evolve into the product, and the product is the entire purpose of the manufacturing enterprise. The procedures through which the material is altered are what we know as 'manufacturing processes'. The requirement that value be added necessarily implies that the altered material is of appropriate quality and worth. The set of activities through which value is added via various stages of processing and to a variety of parts is the production system.

It is germane to note that this definition of manufacturing is completely general. Any material to which value is added through application of a process of some kind has been manufactured. This rubric can be as easily applied to production of silicon wafers or cardiovascular stents as to internal combustion engines and automobile bodies. It follows that the principles of manufacturing engineering ought to be applicable as general practice, not prescribed by particular materials, processes or product forms.

The Essence of Manufacturing Engineering: All engineers solve problems, and all engineers design things. What differentiates the engineering disciplines is the type of problems addressed and the objects of the design activity. Some engineers design products; some design processes. In the main, manufacturing engineers design processes. However, the purpose of these processes is the production of product. Following the logic of manufacturing traced in the previous paragraph, 'design' in manufacturing engineering spans the product realization spectrum. A logical extension to the fundamental definition of manufacturing is to identify sub-disciplines in manufacturing engineering.

Product Engineering
Process Engineering
Quality Engineering
Production Engineering

Figure 1: Four Sub-disciplines in Manufacturing Engineering

These sub-disciplines can be defined a bit more thoroughly. There is a logical path to be followed in the realization of the product. The rubric can be most readily illustrated through the following instructions that are issued to students undertaking a project to design a manufacturing system for a given product.[9] The context is that student teams in a 'production engineering' class fulfill the learning objectives for the course through a semester-long project. Student teams design a production system for an existing product. The products have been as varied as cast steel flow control valves, printed circuit boards and fishing reels. Integrated into the fabric of the project, students are challenged to critique the product design to improve manufacturability and reduce cost. The first three stages of the project are reported in progress-report format, and the overall system design is presented in a comprehensive final report.

Product Engineering: Develop a complete bill of materials for the product family. Determine a preliminary make-or-buy differentiation for all parts. Document the reasoning underlying these determinations. For the parts selected for purchase from vendors, describe specifications suitable for action by a company purchasing agent. For parts selected for in-house manufacture, identify the feature characteristics of each part (or family) that determine the manufacturing processes and process parameters to be employed. Assemble the parts to be produced into groups of similar manufacturing processes. This will look like a table of parts, features, sizes and processes.

Process Engineering: Develop process flow mapping to define the manufacturing processing necessary to produce the families of parts. In these maps, identify the specific manufacturing processes to be employed in each stage of material alteration. Devise analytical models for machining[i] each feature, and select the primary process parameters to be used (depth of cut, feed, cutting speed, cutting tool). Compute the necessary values for spindle speed, machine feed, material removal rate and spindle power consumed. Determine the specifications of the machine tools needed (machining envelope, speeds, power, tool capacity and change time). Estimate cycle times for machined parts. Select specific machine tools (make and model, specifications, footprint, operating floor area).

Quality Engineering: Identify the specific measurable features that determine 'quality' in these products. Define a quality management strategy. Determine what measurements are necessary and when during the production processing the measurements are to be taken. Determine the specifications of the inspection equipment (part capacity, characteristics measured, precision). Select specific inspection apparatus (make and model, specifications, footprint, operating floor area).

Production Engineering: Define production strategy (production quantities, shift arrangement, etc.). This will require further research to determine a reasonable annual production quantity for the assigned products.[ii] Include in the production strategy, an identification of the quantity of each machine tool and inspection station required. Define material handling and inventory storage methods. Determine staffing requirements. Design a floor plan. Identify bottlenecks and methodology for continuous improvement. Estimate throughput and inventories (raw materials, work-in-progress, finished goods).

It is certainly true that manufacturing engineers, in practice, will be called upon to contribute to concurrent engineering product development teams. Successful modern manufacturing stems from iterative and parallel thinking, not serial procedures. Part of the manufacturing engineer's responsibility lies in influencing product design for designed-in quality and ease of manufacture. Anecdotal evidence strongly indicates that mastering process and production system design through a product-centric lens provides a very strong understanding of such crucial issues as design-for-manufacturing and designing quality into the product. Students who have learned manufacturing engineering through the framework outlined above have been sought after for attractive and competitive career positions, and they report rapid progress in their companies.

A Minimalist Application: A course framework for teaching manufacturing engineering in the four sub-disciplines suggested in Figure 1 can be either very compact to fit as a concentration within another major or purposefully designed as the core of a stand-alone major.

A minimalist methodology could involve as little as only two purpose-specified courses beyond traditional fundamentals. As such, specialized instruction in manufacturing could be crafted as an option or concentration within mechanical engineering or industrial engineering or agricultural engineering or another major. In this scenario, courses in 'process engineering' and ‘production engineering’ would be comprised of intermediate-level analysis and design, based on a traditional introductory course in ‘manufacturing processes’, such as has been taught for many years on many campuses. Such an option would also draw upon other commonly offered courses in mechanics, materials, electronics, quality control and engineering economics. The investment for the minimalist scenario is quite small

The ‘process engineering’ course in this scenario should focus on product engineering and process engineering. The product engineering portion of this course would concentrate on parts that would be fabricated and subsequently assembled into usable products. Parts would be defined in some detail as to features, dimensions, tolerances, fits, finishes and the processes through which the material transformations are affected. Basic concepts of group technology are quite useful in this regard. The bulk of this course should concentrate on modeling and analysis of manufacturing processes and upon design of processing solutions for selected parts or products. The focus is at the machine tool and the tool-workpiece interface.

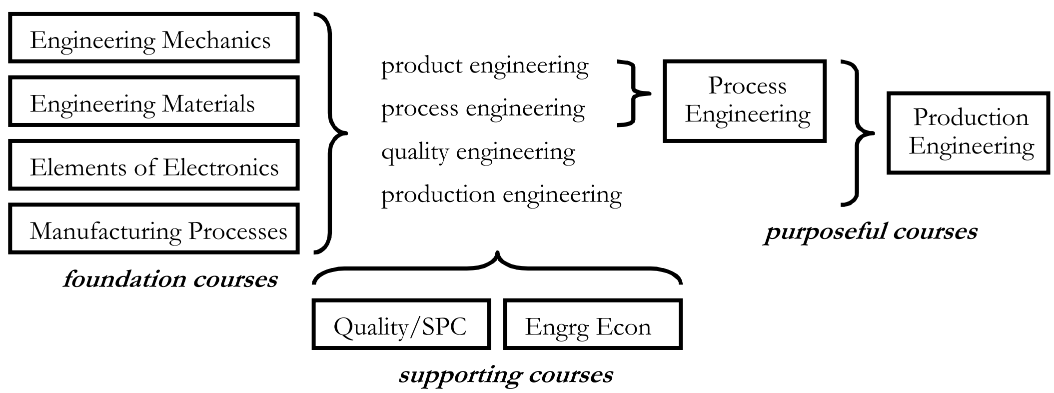

Figure 2: A Minimalist Instruction Pattern for Manufacturing Engineering Instruction

The ‘production engineering’ course would reprise the product and process engineering facets with multiple parts that make up a complete product. Then, quality engineering considerations would be added. Finally, the entire production system would be designed. Issues such as ergonomics, energy efficiency, safety, environmental impact and ethical issues are readily interwoven with this ‘systems design’ effort. The principal metrics used to evaluate the resultant production system designs are throughput, inventory and time (used as a surrogate for operating cost).[10]

Throughout both process design and production system design, the projects should always include time and cost estimating as fundamental elements of manufacturing engineering. In process design, such basic notions as estimates for cycle time, tool life, and material and tool ordering quantities should be present in all projects. Design of a production system incorporates more sophisticated considerations of time and cost. In addition to cycle time and purchasing quantity estimates, project work must extend to integration of quality assurance, workpiece and tool movement through a factory, inventory placement, production planning, staffing, shift strategy and other factors. The end goal is a production system design with carefully estimated throughput and cost structure. The relevant aspects of lean manufacturing are easily woven into the 'production engineering' course.

Depending on the level of interest in manufacturing, curricular constraints and other circumstances, this bare-bones manufacturing engineering content could be supplemented through additional coursework in process science for relevant classes of manufacturing operations (e.g., physics of machining, plastic deformation, solidification, etc.), realization of particular types of products (e.g., electronics manufacturing, plastics processing, composites manufacturing, etc.), tool engineering and/or other coursework that suits the particular institution.

A Different Path: In order to address the imperatives of twenty-first century manufacturing, it would be far better to re-consider the traditional basis for manufacturing engineering education and re-structure the undergraduate program from the ground up. Four fundamental premises drive this train of thought: (1) All of the products that are necessary for modern life are manufactured. (2) The array of products that require competitive manufacturing engineering design is now far broader than in prior years. (3) A high standard of living for any society is unsustainable without a vibrant local manufacturing sector. (4) Maintaining a dynamic manufacturing sector in the American economy requires competition in innovation and design, rather than in low-wage application of old technologies.

In this scenario, instruction is purpose-designed for manufacturing engineers in their own right, rather than as adjuncts to older engineering disciplines. It is designed as three-legged in products, processes and production systems,[iii] and begins with an introductory course in 'product engineering' in the freshman year. Thus, the entire program is flavored with a product orientation from the start.

This instructional concept continues with a significant departure from the normal practice of introducing fundamental acquaintance with manufacturing processes. A review of the principal texts now available for courses in basic manufacturing processes suggests that the norm is a single course that attempts not-very-deep introduction to a very wide variety of processes. While this is a creditable strategy for acquainting other engineering disciplines with the basics of manufacturing, it is arguable that manufacturing engineering students should be equipped with both broader and deeper understanding.

A sampling of popular textbooks reveals a very heavy concentration in traditional metal processing. This orientation strongly suggests that introductory courses are mostly, if not entirely, limited to turning, milling and, perhaps, grinding, with a little forming and joining appended.[11,12,13,14,15,16,17] The more recent of these popular texts include single chapters on electronics fabrication, plastics manufacturing, automation and related topics that are balanced against a dozen or so chapters on metals processes. However, as manufacturing has become more diverse and the vision of manufacturing engineering both broader and deeper, concentrated focus on metal chip-making is increasingly unsatisfactory for manufacturing engineers.

The concept outlined here calls for three separate courses -- one each concentrated on metal processing, on plastics and composites and on electronic products. Ceramic products and processes are a much smaller category at this time and could be included in one of the other courses (e.g., that on metal processing). Each course is conceived as a modular presentation of focused product engineering, applicable materials description, relevant process science, operational modeling and analysis, and description of representative machine tools. Each would also include an appropriate laboratory component.

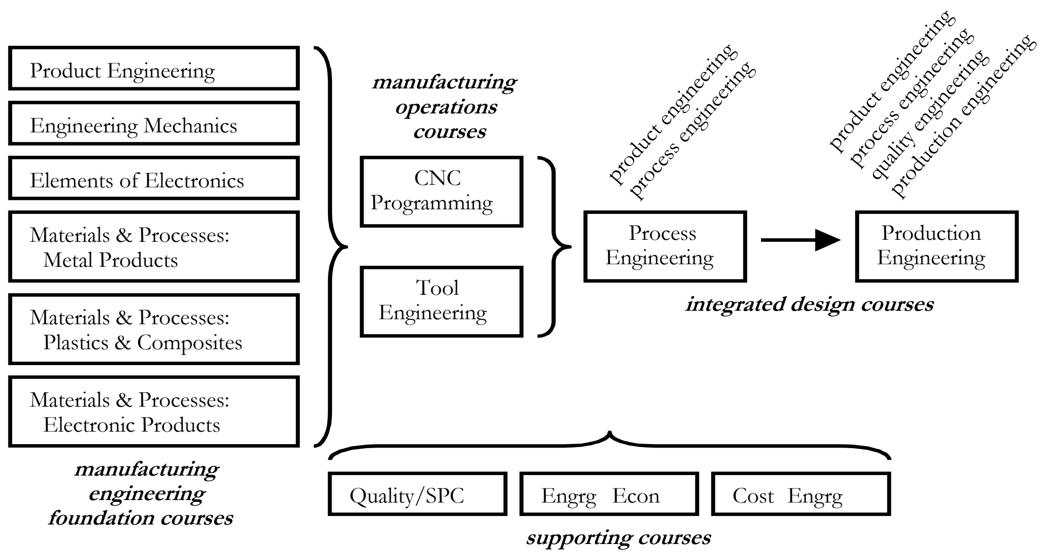

Figure 3: An Instructional Pattern for a Manufacturing Engineering Major

Thus, each manufacturing engineering student acquires a foundation for a breadth of manufacturing industries and is reasonably well-prepared to enter a wide choice of career fields. These particular product focal points were selected because they are the most important in the region served by our university. While they are generally applicable nationwide, selection of core products can, of course, be tailored to the industrial constituency of a particular school. The key notion is the strong content over a range of relevant products and processes.

This scenario continues with operational courses in programming of machine tools and robots and in tooling and fixturing -- two important topics deserving of individual attention in undergraduate manufacturing engineering programs. 'Process engineering' and 'production engineering' courses remain in the mix, but with stronger foundations, these can embrace more significant design content. Finally, junior and senior students would be prepared for elective coursework in any of the three industry threads -- metal processing, plastics and composites manufacturing, or electronics fabrication, packaging and assembly.

Again, it is important to note that the strong themes of quality, cost and lean that have so permeated the manufacturing world in the recent decade or so are not treated as separate subjects, encased in their own distinct packaging. With some basic procedural instruction in methods of statistical quality and engineering economic analysis, these measures are integrated throughout the curriculum -- beginning, conceptually, in the freshman introduction to product engineering. The idea is to instill in undergraduates the habits of thinking of quality, cost and throughput issues as normal and customary in every situation.

Local Status: The concept of manufacturing engineering as a deep and diverse discipline is the root of the notions discussed in this paper. The central idea is the materials processing nature of manufacturing. What happens within the machine tool -- the science-based operations through which inputs are converted into outputs -- is of paramount importance. It is postulated that in no other way can manufacturing processing innovation continue to trump low wages.

Coursework following these precepts and in a middle ground format is currently offered in North Dakota State University's BS program in Manufacturing Engineering. The core courses are in 'manufacturing processes', 'process engineering' and 'production engineering', along with 'computer aided manufacturing', 'automation', 'statistical process control', and 'production and inventory control'. Virtually every major course incorporates industry-oriented project-based instruction. Likewise, every course includes substantive written and oral reporting, as well as comprehensive examinations. As is usual, support is provided through a strong core of engineering sciences, engineering materials, and engineering economics.

'Process engineering' is concentrated in metal processing and is conducted through four projects -- typically in machining, plastic deformation, welding and "anatomy of a machine tool".[iv] 'Production engineering' uses a semester-long project to design a production system for a real product, which varies each offering between metal and electronic products.[v] Specialty manufacturing courses are offered in 'composites manufacturing', 'plastics processing' and 'electronics manufacturing', each of which adheres to the same rubric as is presented here.

Student response has been gratifying. As instructional experience has been gained in managing learning through the project motif, quality of project output has steadily improved. Results in the 'production engineering' course are excellent. In one recent offering, the student project was the design of a production line for assembling small runs of prototype printed circuit boards. The customer's needs are in tens to perhaps a thousand boards, and flexibility and quick turn-around are far more important than high-speed optimization. The system design produced by the students in this class was adopted and built by the customer. It is now in its second iteration.

Another evidence of quality in student work occurred in a 'plastic processing' course. The result of the class project was disclosed as an invention, and the university's technology transfer office is now pursuing patent protection. Naturally, such noteworthy results do not always ensue. However, the customer focus introduced by the project structure offers a platform that encourages commercially usable output.

Student perceptions are also very interesting. In the end-of-semester Student Rating of Instruction, these project-driven courses rank very highly. In recent years, student ratings have been consistently well-above university averages. This is in stark contrast to the usual case, where the more challenging courses in science, math and engineering tend to be rated significantly below the university mean values. Typical commentary offered (anonymously) on the rating forms indicates the student perception is that these project-driven manufacturing courses are more challenging and the work harder than in other classes. Nonetheless, these courses are still very highly rated.

Acknowledgements: The concept of a providing separately-focused instruction in three basic styles of manufacturing originated with my good colleague at North Dakota State University, Dr. Valery R. Marinov, in the 2002-2003 academic year. He devised the notion of coordinated instruction that would include elements of process science, materials, manufacturing operations and production equipment in separate courses for each of the industrial threads that are important in our geographic region. Dr. Marinov also provided leadership in the dialogue that led to the initial description of the overall concept of a preferred structure for undergraduate education in Manufacturing Engineering. There is much more to that story.

Independently, Dr. Hugh Jack of Grand Valley State University has developed concepts for integrating manufacturing engineering with product development. While he has not published a cohesive presentation of his views, his remarks at various manufacturing engineering conferences have been very well structured. Dr. Jack's ideas have been influential in the recent evolution of the process engineering and production engineering courses.

In both cases, the debt to creative minds is gratefully acknowledged. However, this paper and the ideas contained therein the author's creation, and any errors are mine alone.

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[i] This version of the instructions was for a project to design a production system to produce flow control valves from steel castings. When the product is different, the wording is modified to suit the type of manufacturing processes relevant to the topical product.

[ii] Specifications for some problems include production volume requirements. In other situations, the student teams are tasked to develop realistic estimates of production quantities.

[iii] In this context, production systems design includes both quality engineering and cost engineering.

[iv] The text used is Beddoes and Bibby; Principles of Metal Manufacturing Processes; Arnold & John Wiley; 1999

[v] Texts used are Goldratt and Cox; The Goal, 3rd revised edition; North River Press; 2004 and Black and Hunter; Lean Manufacturing Systems and Cell Design; Society of Manufacturing Engineers; 2003