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The Four Pillars of Manufacturing as a Tool for Evaluating Course Content in the Mechanical Concentration of a General Engineering Curriculum

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The Four Pillars of Manufacturing as a Tool for Evaluating Course Content in the Mechanical Concentration of a General Engineering Curriculum

Abstract

The four pillars of manufacturing have been developed as a framework to promote understanding of the ideal content of an undergraduate program in manufacturing engineering. It has been proposed that the four pillars could also provide direction for enhancing the content of other related engineering programs (e.g. mechanical engineering) in order to better prepare these engineering graduates for entering the manufacturing workforce. This paper describes the application of the four pillars as a tool for analysis of the curricular content of a general engineering degree with a concentration in mechanical engineering. Many graduates from this program (located in the state of Michigan) have gone on to work in various manufacturing industries, even though the concentration has not previously been tailored specifically toward the preparation of manufacturing professionals.

In particular, the content of a required manufacturing processes course was evaluated using the four pillars structure in order to ensure that students are exposed to the best possible combination of manufacturing topics. A comparison of previous course content with the content areas of the four pillars, in the context of the rest of the program course requirements, helped to identify opportunities for improvements. This paper will describe the evaluation process and present conclusions regarding proposed changes in course content. The analysis resulted in a new course plan which will be implemented in the spring 2013 semester. This work also clarified where in the curriculum, outside of the manufacturing course, students learn skills that are aligned with the four pillars. The four pillars structure proved to be an accessible yet detailed standard that facilitated a better balancing of topics in the manufacturing processes course. This exercise demonstrates that the four pillars model can be successfully applied in settings outside of manufacturing programs to better prepare students for manufacturing-related engineering careers.

Introduction

The “four pillars of manufacturing” model for manufacturing engineering education was brought to this author’s attention at the 2012 ASEE conference.[1] As the faculty member with primary responsibility at Calvin College for maintaining and enhancing the manufacturing aspects of the mechanical engineering curriculum, the idea that this model could be helpful in guiding curriculum content in a setting other than a manufacturing engineering program was a very intriguing one. Further research revealed that the originators of the four pillars had also proposed that the model could and should be used for this purpose. In the Curricula 2015 report issued in June of 2011, two specific recommendations converge to provide the motivation for the analysis described in this paper. Recommendation 7 under Curriculum Revision and Development specifies that engineering educators should “encourage the use of the Four Pillars for curriculum design” and Recommendation 6 under Reaching Out to Other Disciplines specifies that “non-manufacturing programs should include manufacturing content.”[2]

This suggested a synergistic intersection of professional interests: continuous improvement of a standalone manufacturing course for mechanical engineers, and a new application of the four pillars model of the manufacturing engineering body of knowledge. Having seen an example of the four pillars applied to evaluation of a manufacturing engineering program also presented at the 2012 ASEE conference (paper)[3], this method showed promise for also critiquing the manufacturing content within a mechanical engineering concentration.

Project Goal

The goal of this project was to evaluate the content of a manufacturing processes course for mechanical engineering students using the content areas of the four pillars, in the context of the rest of the program course requirements, to help identify opportunities for improvements. The results of this work could then be used as a template in other mechanical engineering programs to ensure adequate exposure to manufacturing topics for those that require a manufacturing processes course. This paper will begin with a presentation of the project background, including a brief history of the four pillars as well as more detailed information about the engineering program analyzed. It will then describe the evaluation process and present conclusions regarding proposed changes in course content.

Four Pillars History and Purpose

Manufacturing engineering education practitioners, spearheaded by the SME Manufacturing Education and Research Community, have been involved in curriculum planning and improvement over the last several decades. Manufacturing engineering at the undergraduate level is a relatively new discipline (compared to other traditional engineering disciplines), with the first program being accredited by ABET in 1971. Figure 1 shows the number of programs accredited by EAC of ABET over time, revealing a general growth trend.[4] This graph only includes programs that are currently accredited, and therefore may miss some programs which began and ended during this time frame. Manufacturing engineering is also interdisciplinary in nature, involving a combination of mechanical engineering, industrial engineering, and business-related topics. For both of these reasons, manufacturing engineering has struggled to define itself. So, while the essential elements of the mechanical engineering curriculum are well established (although not entirely non-controversial) the essential elements of the manufacturing engineering curriculum have been somewhat in flux as the discipline attempted to respond to industry demands. A great deal of effort has been expended over the last several years in defining and communicating curricular expectations.

The four pillars of manufacturing engineering model emerged as a result of the most recent manufacturing engineering education evaluation begun in 2008 and culminating in the Curricula 2015 report released in June 2011. The goal of curricula 2015 "was to examine the state of manufacturing education and develop a plan for revising manufacturing education." [5] The consultative process involved representatives from the Manufacturing Education and Research community of SME, in communication with various other SME members, manufacturing practitioners and related organizations including ASME, IEEE, IIE, and government agencies. The many activities undertaken as part of this process resulted in a detailed report, primarily consisting of a large set of recommendations for improvement activities.

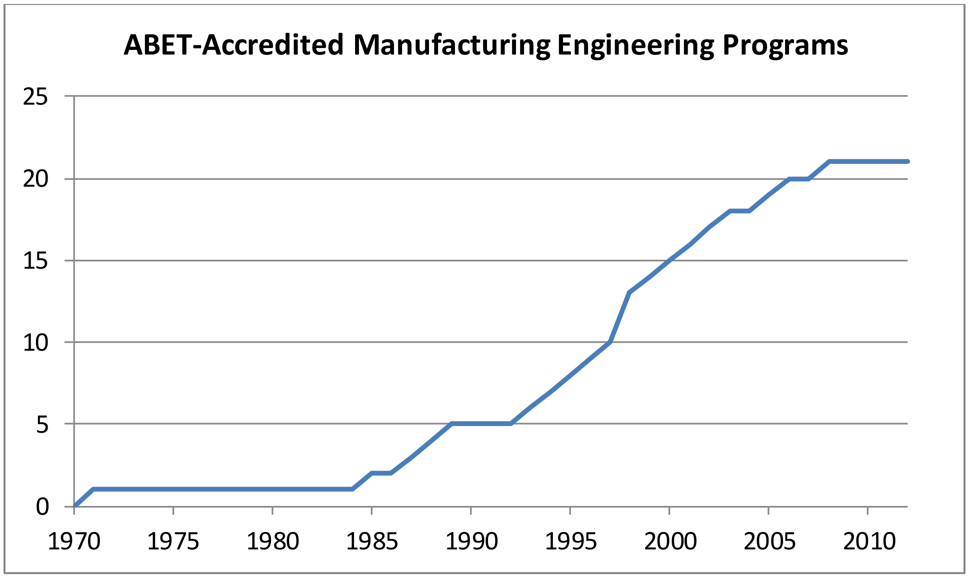

Figure 1. Number of ABET-Accredited Bachelors-Level Manufacturing Programs

The four pillars model that emerged from the Curricula 2015 evaluation is an attempt to clarify the boundaries of the manufacturing engineering discipline and to provide a “tool for promoting greater understanding of the breadth and depth of the field of manufacturing engineering.”[6] It was also meant to be descriptive, defining the body of manufacturing knowledge as reflected in ABET’s manufacturing program accreditation criteria and SME’s manufacturing engineering certification criteria, to create a model useful for describing manufacturing education. The current version of the model was modified somewhat in format from the version described in Curricula 2015 report. The top level diagram (not including specific sub-topics) of the version presented at ASEE 2012 and available on-line is shown in Figure 2.

For the purpose of curricular revision, the four pillars bridges the gap between the very detailed requirements list for the SME Manufacturing Engineering certificate and the much more general ABET manufacturing engineering program criteria. The graphical format is also helpful for a big picture approach to balance of general topics (as can be seen in Figure 2) and for a more specific topical curriculum analysis (as will be seen later in the paper). The intentions of the model developers included that it “be used to identify gaps in the current curricula content and resources so that educators will be supported in endeavors to fill the gaps.”[7] This indicated a good fit for the intended purpose of curriculum revision with the goal of producing mechanical engineers who are well-rounded in their exposure to manufacturing topics. The four pillars were developed with the goal of identifying overarching fundamental manufacturing principles rather than more narrowly focused industry-specific knowledge. This approach seemed an ideal fit for analyzing a general mechanical engineering program with respect to manufacturing content.

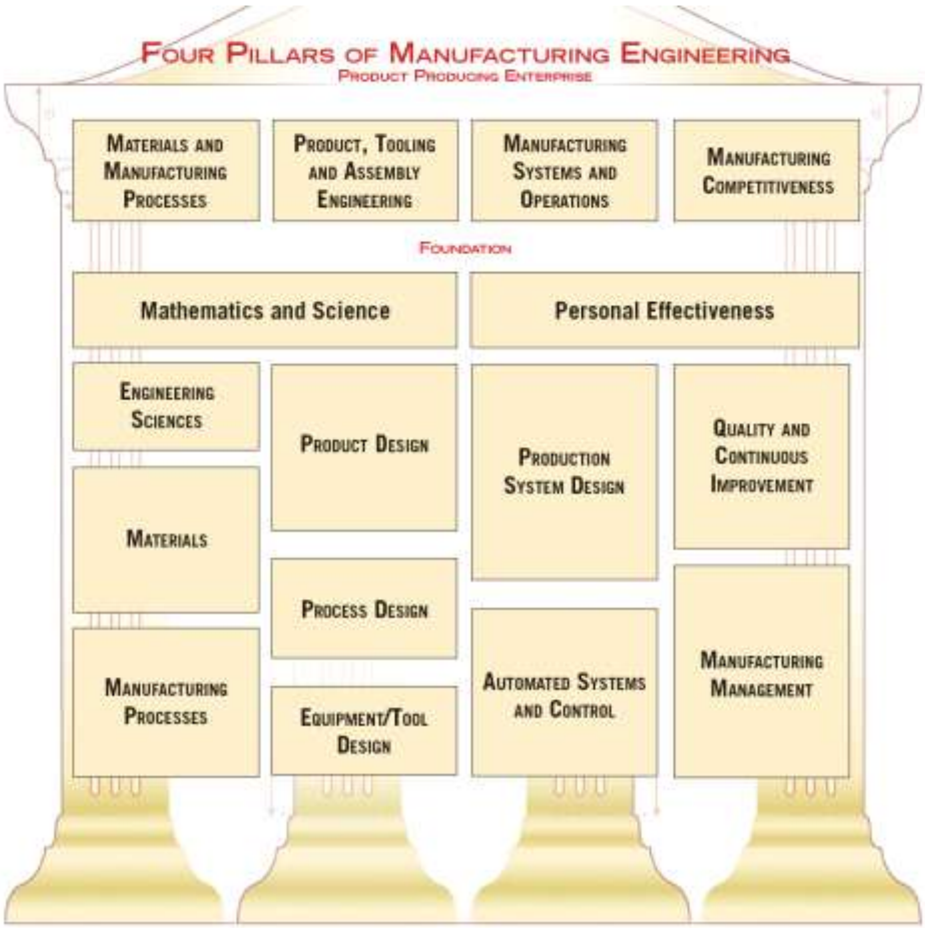

Figure 2. The Four Pillars of Manufacturing Engineering[8]

Since the four pillars have been rather recently introduced, there is almost no evidence of the model being applied for evaluation of existing curricula in the available literature. One exception is the work of David Wells in mapping the four pillars onto the existing manufacturing engineering curricula at North Dakota State University. After noting some minor shortcomings, the conclusion was that "the model remains a powerful and effective tool for analyzing, guiding and assessing curricula in Manufacturing Engineering."[9] This conclusion supported the idea that the four pillars model would serve well in the task of evaluating curriculum, even for a program that is more general than the model was designed to serve.

Program Institutional Context

This paper describes the application of the four pillars as a tool for analysis of the curricular content of a general engineering degree with a concentration in mechanical engineering. This section describes the nature of this program in more detail. By shifting from the context of the four pillars to the context of the program being evaluated, some essential background to the course and curriculum evaluation efforts will be provided.

The institutional setting is that of a comprehensive Christian college with a liberal arts focus. The engineering program at Calvin College is housed in the Engineering Department and consists of a single Bachelor of Science in Engineering degree accredited by ABET under the general engineering criteria. ABET lists these types of programs under the (somewhat unwieldy) general heading of "Engineering, Engineering Physics, and Engineering Science Engineering." The program has four options, or paths, by which students may satisfy the requirements of the program: 1) chemical engineering concentration, 2) civil and environmental engineering concentration, 3) electrical and computer engineering concentration, and 4) mechanical concentration. The mechanical concentration is the program option evaluated in this paper. The philosophy of the program emphasizes design and problem-solving skills based on mathematical analysis and fundamental engineering principles which will provide a foundation preparing students for work in a broad array of mechanical engineering disciplines. The objectives of the program are that recent graduates will…

> …apply and develop the basic principles and skills necessary for engineering (including mathematics, the sciences, business and the humanities) for appropriate assessment and analysis of current and complex problems.
> …creatively generate innovative solutions to problems and move them toward successful implementation.
> …contribute and communicate ideas successfully in multidisciplinary environments, exhibiting awareness of cultural context and team dynamics.
> …demonstrate commitment to social responsibility, sustainability, and the continued learning necessary to address the pressing problems of our contemporary world.[10]

A small but significant portion of mechanical engineering concentration graduates have gone on to work in various manufacturing industries, even though the concentration has not previously been tailored toward the preparation of manufacturing professionals. Based on alumni surveys of graduates 3-years and 10-years out of the program collected from 2009-2012, 21% of mechanical engineering concentration graduates list a job title and/or job description that indicates direct involvement in manufacturing engineering work (including quality and process engineering). Of the 19 mechanical engineering concentration students who had job offers in May of 2012, 42% were in manufacturing or production engineering roles. Many of the others work as mechanical design engineers for manufacturing companies where knowledge of manufacturing concerns is essential to cost effective design work. Given the documented possibility that many of our mechanical engineering graduates will be involved in manufacturing enterprises, both directly and indirectly, it is the program's responsibility to ensure that the curriculum is aligned to a standard that will best prepare students who choose to pursue this work. Obviously, a general program such as Calvin's cannot hope to cover all of the four pillars topics, or cover them to the same depth as a specifically manufacturing engineering program. However, the four pillars can provide guidance in balancing topics within the constraints of the program.

Program Local Educational Context

As further background and motivation for this project of mechanical engineering curriculum evaluation with respect to manufacturing knowledge requirements, an investigation of the range of accredited programs available in the state of Michigan to train students for mechanical and manufacturing engineering work was performed. Currently, there are only two institutions that offer accredited manufacturing engineering degrees (Grand Valley State University in Grand Rapids and The University of Michigan – Dearborn). Not all students who anticipate a career in manufacturing will have access to programs that specifically train students in the manufacturing engineering discipline. Arguably, there simply are not enough of those programs to fill the need for qualified manufacturing professionals in industry. Therefore, it is important for related disciplines (particularly mechanical engineering) to include a minimum level of manufacturing content as a foundation for future learning on the job. Table 1 presents the results of an analysis of mechanical engineering (and general engineering programs with a mechanical emphasis) with respect to available courses related to manufacturing topics. Web-available curriculum descriptions were used to compile the table. Institutions in Michigan offer a total of 15 undergraduate programs accredited under the mechanical engineering criteria, plus 3 additional programs that are accredited under the general criteria which have a mechanical engineering focus. Of these 18 programs, 11 require a course in manufacturing processes for all graduates. This is the only required subject that is clearly identifiable as a manufacturing topic, other than a CAD course (which is required by nearly all programs). Some manufacturing content may also be embedded in product design or other similar courses, but since identifying the extent of manufacturing in those courses would have been very difficult, that category was not included in the table.

Table 1. Mechanical/Manufacturing Engineering Programs in Michigan

		Required Mfg Processes Course?	Mfg Electives Available?	Mfg Emphasis Available? (description)
	Mechanical Engineering Programs			
1	Baker College – Flint	Yes	No	No
2	Central Michigan University – Mt. Pleasant	No	No	No
3	Grand Valley State University – Grand Rapids	Yes	Yes	Yes (program)
4	Kettering University – Flint	No	Yes	Yes (specialty)
5	Lake Superior State University – Sault St. Marie	Yes	Yes	Yes (specialty)
6	Lawrence Technological University – Southfield	Yes	Yes	Yes (concentration)
7	Michigan State University – East Lansing	No	Yes	Yes (concentration)
8	Michigan Technological University – Houghton	Yes	Yes	Yes (emphasis)
9	Oakland University - Rochester	No	Yes	Yes (option)
10	Saginaw Valley State University – Saginaw	Yes	Yes	No
11	University of Detroit Mercy – Detroit	Yes	Yes	Yes (non-accredited degree)
12	University of Michigan – Ann Arbor	Yes	Yes	Yes (concentration)
13	University of Michigan – Dearborn	Yes	Yes	Yes (program)
14	Wayne State University – Detroit	Yes	Yes	No
15	Western Michigan University – Kalamazoo	Yes	No	No
	General Engineering Programs with Mechanical Engineering Emphasis			
16	Andrews University – Berrien Springs	Yes	Yes	No
17	Calvin College – Grand Rapids	Yes	No	No
18	Hope College – Holland	No	No	No

The table indicates that the results of this paper could be directly applicable to the approximately 61% of mechanical engineering programs which include a manufacturing processes course in their curriculum. It should also be noted that many programs (13) offer additional manufacturing-related electives to students, although none are required for graduation. Of those programs, a majority (10) also offers some collection of elective courses that make up a manufacturing emphasis. The potential exists for the four pillars to also be used as an evaluation tool for the manufacturing specialty/concentration options listed in the table in order to optimize manufacturing preparation for mechanical engineering students who know they will be headed for a manufacturing career. By assessing the manufacturing processes course content in direct comparison to manufacturing curriculum standards, along with making sure the program as a whole teaches basic professional skills (that are not manufacturing-specific), Calvin's program can become an example that is successfully "incorporating manufacturing content required of their graduates and demanded by their constituencies into existing programs"[11] as recommended in the four pillars document.

Curriculum and Manufacturing Processes Course Background

The mechanical engineering concentration curriculum at Calvin includes a number of required engineering courses as listed in Table 2. Currently there is only a single course required (and offered) for engineering students that involves manufacturing. This course is officially titled "Materials and Processes in Manufacturing". It is typically taken by students in the spring of the senior year and has a materials science course and a mechanics of materials course as pre-requisites. This is not the ideal timing for the course. Pre-requisites and level of content presented would allow it to be taken earlier by students, but other constraints in the sequencing of mechanical engineering courses have resulted in this schedule. The advantage is that students come into the course with more experience in product design and analysis. The disadvantage is that students are very busy with senior design projects and close enough to graduating that they may not take the course with the seriousness it requires.

Table 2. Mechanical Engineering Concentration Curriculum (Engineering Courses Only)

Semester Hours	Course Title	Year Taken	Engr Discipline
2	Introduction to Engineering Design	1st	Common
2	Engineering Graphical Communication Lab	1st	Common
4	Engineering Chemistry and Materials Science	1st	Common
4	Statics and Dynamics	2nd	Common
4	Circuits Analysis and Electronics	2nd	Common
4	Introduction to Conservation Laws and Thermodynamics	2nd	Common
4	Introduction to Thermal/Fluid Sciences	3rd	Mech/Civil
4	Intermediate Thermal/Fluid Sciences and Design	3rd	Mechanical
4	Thermal Systems Design	4th	Mechanical
4	Mechanics of Materials	3rd	Mech/Civil
3	Dynamics of Machinery	3rd	Mechanical
4	Machine Design with Finite Element Analysis	3rd	Mechanical
1	Instrumentation Laboratory	3rd	Mechanical
4	Materials and Processes in Manufacturing	4th	Mechanical
4	Vibration Analysis OR Control Systems	4th	Mech/Elec
6	Senior Design Project	4th	Common

Course Content. When the course was first developed, it included only topics directly related to materials and processes. However, over the last 20 years the content has been expanded to include more topics relevant to contemporary manufacturing competitiveness, such as quality and design for manufacturing. The official course description reflects this mix of content.

> ENGR 324. Materials and Processes in Manufacturing (4) S. This course introduces students to the various mechanical and management issues involved in the fabrication of manufactured goods. scientific and engineering principles are applied to fabricating processes such as casting, forming, and machining so as to determine the relation of process to material properties, economics, dimensional accuracy, and energy requirements. Topics such as computer-aided manufacturing (CAD), numerical control (NC), statistical quality control (SQC), and quality management are also explored. Field trips and laboratories are used to support the lecture material.[12]

The goals of the old version of the course (as taught in the spring of 2012) focus on exposure to a variety of manufacturing processes with deeper analysis of a particular subset of processes. The course learning outcomes are listed in Table 3.

Table 3. Manufacturing Processes Course Outcomes

By the end of the course students will be able to…	
1	Recognize and describe the interactions between material structure, material properties and manufacturing processes
2	Recognize and distinguish between terms and concepts used to describe a wide variety of manufacturing processes, process steps and related manufacturing issues
3	Evaluate alternative manufacturing methods for a given component or product based on suitability, cost, and sustainability
4	Design a manufacturing process for a given product, including specification of sequence of operations, description of tooling and estimation of costs of production
5	Tweak the design of a given component to make it easier to manufacture
6	Evaluate the design and manufacturing process of a given product for better sustainability
7	Calculate unknown values from parameters related to the following topics: Material properties, Casting, Forming, Statistical process control, Machining

The course has used a comprehensive manufacturing textbook (Groover's "Fundamentals of Modern Manufacturing[13]) supplemented with some additional materials to support topics not included in the text. The primary challenge in planning and teaching the course consists of picking and choosing an appropriate set of relevant topics from the vast array of possibilities, both in the textbook and beyond. There was concern that the course configuration might represent the personal experiences and preferences of the instructor, rather than focusing on the best possible combination of topics to prepare students for jobs in manufacturing or product design.

Course Structure. One of the course re-design constraints is the total amount of available course teaching hours. Calvin has a 13-week long semester (not including the final exam period). The course meets three times a week for 50 minute lecture periods and has the option to meet for an additional two hour lab period each week. Approximately half of the lab periods are filled with tours of local manufacturing companies and lab activities. This results in a total of roughly 39 lecture periods and 13 hours of lab time, for 52 student contact hours (4 SH x 13 weeks). Some lecture periods (~5) are used for tests and project work days and are therefore not available for presentation of course content. In terms of allocating topics, 34 (39 – 5) class periods were assumed to be available for teaching and in-class student activities. A summary of the distribution of topics is included later in this paper under the course analysis heading.

Four Pillars Curriculum Analysis

Before considering the four pillars for comparison, it is necessary to recognize that a general engineering curriculum will not be able to address all aspects of the four pillars. While it is reasonable to expect comprehensive coverage of the listed topics (breadth and depth) for a named manufacturing program, the constraints of the mechanical engineering curriculum are such that it would not be possible to fit in every topic or teach many of the topics to the depth indicated. Particularly for this program, whose strength continues to reside in general analysis and design focusing on fundamentals in the two tracks of traditional mechanical engineering, thermal fluid systems and machine design, choices of which manufacturing-related topics to include has to be done very carefully. The goal is to identify the bare minimum of content that a mechanical engineer needs as a foundation to better learn on the job, so as to contribute in a manufacturing environment.

The method of curriculum analysis consisted of comparing the detailed version of the four pillars graphic with the courses and topics of the required engineering courses in Calvin's curriculum. In this way, it would become obvious where the gaps in coverage were. Having identified the gaps, decisions could be made about including additional topics, recognizing that doing so would require dropping of other traditional mechanical engineering topics. Any new content identified as necessary by this comparison would need to be covered in the manufacturing processes course or micro-inserted into other required courses in the curriculum. Figure 3 shows the four pillars model compared to Calvin's program requirements. The darker highlighted topics are those that are already addressed in the program (light gray). The darker gray boxes indicated four pillars topics that are currently included in the manufacturing processes course.

The Mathematics and Science topics identified as the foundation of the four pillars are common to mechanical and manufacturing programs and are covered in the required cognate courses for all students in Calvin's engineering program. The cognates include an introductory chemistry course, two calculus-based physics courses (mechanics/gravity and electricity/magnetism), calculus 1, 2, and 3, differential equations, and engineering statistics. Students must also take an advanced math/basic science elective. Although the college core includes study of the living world (bioscience), most engineering students are exempt from taking this course if they have taken three years of regular science study in high school. Given the inclusion of bio-science in the four pillars, students interested in manufacturing may be best advised to choose a biology course for this elective. A suggestion for future revision of the pillars might be to clarify the extent to which bio-science is necessary.

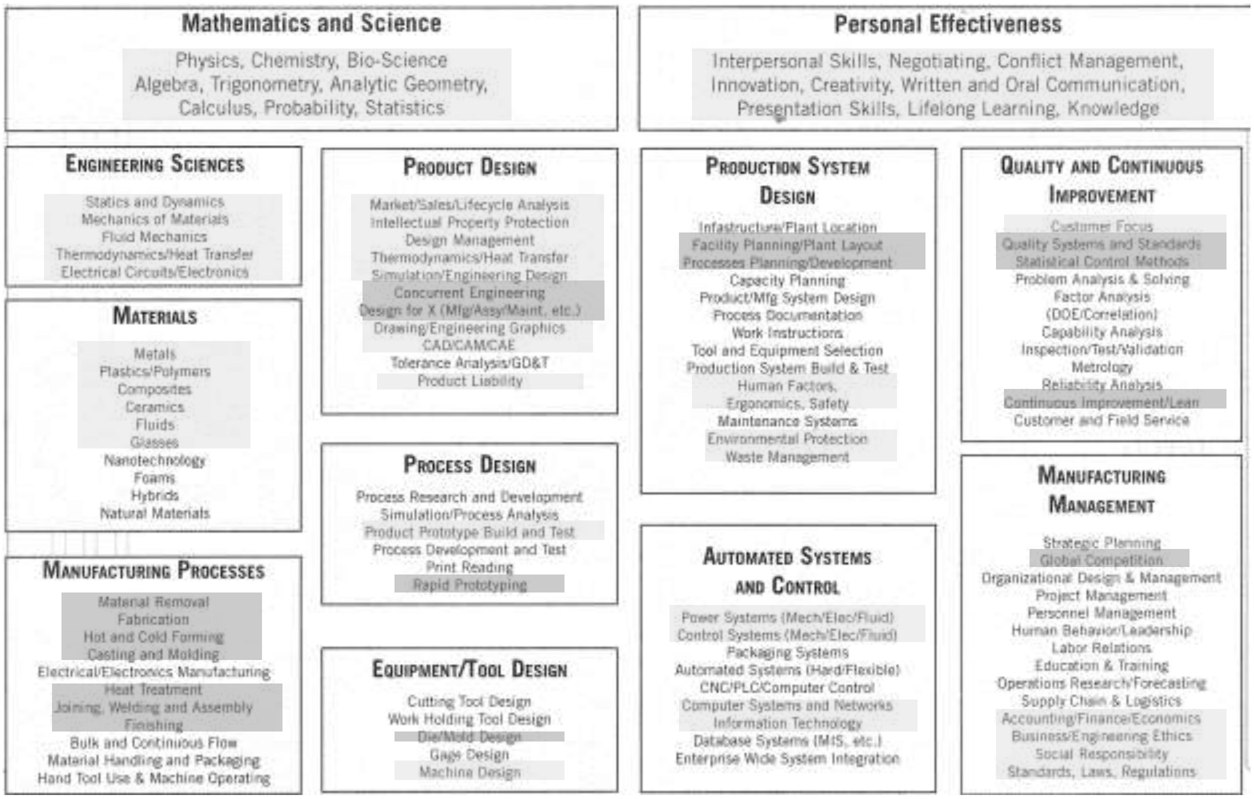

Figure 3. Four Pillars and Calvin's Curriculum

The Personal Effectiveness topics are also addressed effectively in other areas of the engineering curriculum at Calvin. Interpersonal skills, conflict management, innovation, creativity, and life-long learning are initially addressed in the introductory engineering design course and are re-enforced in the senior design capstone experience. Writing and presentation skills are presented and assessed in at least four engineering courses (the first year introduction to engineering design course, the sophomore circuit analysis and electronics course, a junior level lab course specific to each discipline, and the capstone design course). All engineering students are required to take a speech course involving professional use of presentation software. The relatively large liberal arts component of the core also functions to hone students' writing skills, self-awareness and self-management.

The first pillar on the left is referred to as Materials and Manufacturing Processes. This pillar has the most overlap with traditional mechanical engineering concepts. The engineering sciences at Calvin are introduced at the sophomore level, including statics and dynamics, thermal/fluid sciences, and electrical circuits/electronics. Students in the mechanical engineering concentration continue deepening their knowledge of these topics, as well as mechanics of materials and heat transfer, in their junior and senior level concentration-specific courses. All students take a required advanced chemistry and materials course in the second semester of the first year. This course includes study of metals, polymers, and ceramics, with only minimal exposure to some of the other material categories on the list. This is an area where perhaps the materials course could be updated, although the course needs to address materials in a way that makes sense for all the concentrations, so it might be more appropriate to include these in the manufacturing processes course. The highlighted topics in the manufacturing processes box are currently covered in the manufacturing processes course and detailed consideration of potential changes which might better match this list will be described in the next section.

The second pillar includes Product, Tooling, and Assembly Engineering and encompasses both product and process design. In Calvin's mechanical engineering program, product design and analysis is a major focus area.. All engineering students take a course in graphical communication which includes mechanical drawing and 3D CAD. Lifecycle design, including some marketing concepts, intellectual property, and design management are featured in the capstone design sequence. Thermodynamics and heat transfer are taught in a three-course intro/intermediate/advanced sequence that culminates in design and optimization of energy generation systems. The machine design track of the mechanical engineering curriculum includes various types of analysis and simulation, as well as design projects focusing on mechanical elements. Matching of topics indicates that our program is weak in tolerance analysis and GD&T. This is something that should be considered when evaluating the manufacturing processes course content. While the freshman and senior design courses support strong product prototype build and test sequences, very few opportunities are provided for process design and test. This should be considered as a possible addition to the manufacturing processes course, since this topic does mesh well with any of the other current courses offered. Rapid prototyping is currently covered in the manufacturing processes course, and the recent purchase of a 3D printing system by the department will allow this topic to be emphasized more. As for equipment and tool design, the program has a strong emphasis on machine design and there is some attention paid to die/mold design in the manufacturing course.

With respect to the third pillar, Manufacturing Systems and Operations, it is clear that our general engineering program addresses fewer of these than of the first two pillars. In the judgment of the author, the knowledge and skills indicated in this pillar are more specific to manufacturing engineering. It is therefore less surprising to see more gaps in coverage relative to this pillar. The program does provide limited exposure to facility and process planning with some consideration of human factors and safety in the senior design course. Calvin has a strong emphasis on sustainability, which includes aspects of environmental protection and waste management. Mechanical engineering students have the opportunity to take an environmental engineering elective and the manufacturing processes course includes some consideration of green manufacturing methods. With respect to automated systems and control, students must currently choose between controls and vibrations to fill an engineering elective. Students with an interest in the manufacturing field should be encouraged to choose controls, since that course meshes better with the topics of the four pillars.

Pillar 4, Manufacturing Competitiveness, lists many topics that are specific to manufacturing and that relate to engineering management. Most of the manufacturing management sub-topics are beyond the scope of our general program, although engineering students get some exposure in a required two semester hour Business Aspects for Engineers course. If students have enough space due to AP credit or willingness to take summer courses, they can opt to add a business minor which would include courses that address many of these topics. Engineering ethics is a feature of our program and is integrated into the curriculum. A recently implemented academic ethics policy for students reinforces the importance of ethics to professional practice. Social responsibility is part of the mission of the college. Standards are emphasized in the senior design course in response to ABET's reinforcement of the need for this knowledge in the student outcomes.

Overall, our current curriculum does align with many of the most basic aspects of the four pillars with emphasis on those on the left side of the graphic. The comparison exercise identified some potential gaps, which can be addressed with advising choices. However, most of the material currently not addressed would have to be added as content in the manufacturing processes course.

Four Pillars Manufacturing Course Analysis

Continuous improvement of courses and programs is always an important goal for engineering educators, but often it is challenging to keep up-to-date with new requirements and to find the time to evaluate and re-prioritize course topics. The awareness of the four pillars provided a resource and a trigger for a re-balancing of topics in the manufacturing processes course, since the four pillars provide a nationally accepted benchmark. The goals of this course redesign included: 1) increasing engineering student learning of concepts and skills important to success in a manufacturing environment, 2) increasing student perceptions of the relevance of the course material to engineering practice, and 3) increasing the motivation of students to pursue manufacturing careers (and therefore increase overall manufacturing competitiveness. The current distribution of lecture topics (as taught in the spring of 2012) within the time framework described earlier is included in Table 4.

A comparison of the list in Table 4 with the four pillars topics reveals that there are no topic areas within the course that are NOT included in the four pillars model. While it was a relief to discover that the course was already directed toward goals that were in synch with the manufacturing engineering community's needs, it was also a disappointment to realize that there were no obvious topics which could be eliminated. Because there were so many more course topics identified in the four pillars model than could possibly be included in this single course, hard choices would still need to be made. These choices would depend not on the four pillars model itself, but on the judgment of the instructor in interpreting the priority of the various elements in the model. For this analysis, priority was given to items that were deemed more basic (more mechanical engineering in nature) as opposed to more specifically manufacturing-related. Promoters of the four pillars model may wish to devote some attention in the future toward prioritizing the curriculum contents, if the model is to be more useful for evaluating programs that are not defined to be comprehensively manufacturing in nature.

A general consideration of the model and previously described curriculum comparison pointed to the following proportional distribution of the course content among the four main pillars: 70% addressing pillar one (materials/processes) and 30% addressing the other three pillars (roughly equally divided). The justification for this decision was two-fold: first, pillar one has the most in common with a general mechanical engineering topics and second, the course description should retain manufacturing processes as the primarily focus.

Table 4. Summary of Manufacturing Processes Course Content

Topic	Lecture time (days)	Textbook (pages)	Quiz	Homework	Other Activities
Intro/Concurrent Engineering	4	27	✓		Tours
Materials Review	4	125	✓✓	✓	
Heat Treating	2	12	✓		
Casting	5	53	✓	✓	Tour
Costs	2	NA		✓	
Quality	2	13	✓	✓	Project
Forming	3	60	✓	✓	
Sheet Metal	2	39	✓	✓	Tour
Surface Treatment	1	10			Tour
Machining	2	58	✓	✓	
Design for Recycling	1	NA			Lab 3
Welding	1	38	✓		
Plastics	1	76	✓		Tour
Composites	1	34			
Design for Mfg	1	NA			
Rapid Prototyping	1	14	✓		
Process Planning	1	7		✓	Lab 1, 2, Project
Total Content	34				
Tests	3				
Project Work Days	2				
Total Non-Content	5				
Total	39 (3x13)				

Based on this analysis, the course re-design consisted of a balancing exercise in terms of adjusting the course content to fit the general proportions noted above, as well as integrating in specific topics from the four pillars that were deemed to fill the most crucial gaps identified. Of the non-highlighted items in Figure 3, the most crucial topics were deemed to be those listed in Table 5 as proposed course additions. Some could be added to the new version of the course without additional lecture material, while others would require trade-offs in the form of elimination of some material covered in the older version of the course. Most of the proposed additions consisted of re-integrating material that had been taught in previous years but was eliminated more recently due to time constraints and shifting interests. It should be noted that the learning goals for this particular course have always been very ambitious. While it is likely true that a student will not be able to develop a deep understanding of a topic like welding (for example) in one lecture period, it is hoped that a pedagogical model based on the student learning basic terms and background from the textbook outside of class, combined with in-class time for process illustration and discussion, will contribute to at least a basic level of understanding of these topics.

Table 5. Proposed Course Additions

Add for Spring 2013	
Topic	Method
Nanotechnology	Add half lecture, textbook chapter and video
Electrical/Electronic Manufacturing	Add half lecture, textbook chapter and video
Tolerance Analysis and GD&T	Add a homework assignment
Factorial Design of Experiments	Add a lecture, homework, and supplementary material
CNC	Add a textbook reading and laboratory activity
Remove for Spring 2013	
Costing	Remove one lecture
Finishing	Remove one lecture
Consider for future addition	
Simulation/process analysis	Add software and laboratory activity

Summary of Proposed Changes

The proportionality choices described above result in the need to allocate 75% of the 34 content days for materials and processes (24 lectures). This would leave 4 class sessions for product, tooling and assembly engineering (specifically process design and concurrent engineering), 3 class sessions for manufacturing systems and operations (process planning and automated systems), and 3 class sessions for manufacturing competitiveness (quality systems and lean manufacturing). The new course topic list which fulfills this scheme and includes the topics of Table 5 is shown in Table 6.

Some ideas for more subtle changes to the course that better reflect the needs of manufacturing practice were also generated. It was noted that the negotiation and conflict management aspects of personal effectiveness could be emphasized more in the manufacturing course by providing additional context to one of the assigned case studies. The course project could be refined to emphasis the need for customer focus and also provide an option for students who could choose a process research and development, rather than a process design focus. Also, the industry tours typically highlight many of the manufacturing management topics. Additional resources could be provided in the on-line course management system to allow interested students to explore those topics in more detail.

Conclusion

The four pillars model provided a useful framework for evaluating manufacturing course content within the mechanical concentration of a general engineering degree. A comparison of previous course content with the content areas of the four pillars, in the context of the rest of the program course requirements, helped to identify opportunities for improvements. The analysis resulted in a new course plan which will be implemented in the spring 2013 semester. This work also clarified where in the curriculum, outside of the manufacturing course, mechanical engineering concentration students learn skills that are aligned with the four pillars.

Although the four pillars were developed predominantly for designing and evaluating manufacturing engineering curriculum, this exercise shows that it can also be useful at the course level for ensuring comprehensive student exposure to topics that will equip students with the skills and knowledge to contribute to a manufacturing enterprise. Since the model contains many more topics that can realistically be covered in a broader program, it did not directly solve the trade-off problem. It would be especially helpful to have some ranking of the importance of the knowledge areas within the model (highest to lowest) to allow a prioritization that best reflects the needs of industry and avoids the possibility of individual instructor bias towards favorite topics. However, the model was successful in providing curricular guidance and should continue to be part of the dialog between manufacturing and mechanical engineering.

Table 6. Proposed Manufacturing Processes Course Content

Topic	Pillar	Lecture time (days)	Textbook (pages)	Quiz	Homework	Other Activities
General Processes Intro	1	1	5	✓		Tours
Concurrent Engineering	2	2	24			
Materials Review	1	4	125	✓	✓	
Heat Treating	1	2	12	✓		
Casting	1	5	53	✓	✓	Tour
Costs	4	1	NA		✓	
Quality	4	2	13	✓	✓	Project
Design of Experiments	4	1	NA		✓	
Forming	1	3	60	✓	✓	
Sheet Metal	1	2	39	✓	✓	Tour
Machining	1	3	58	✓	✓	
Design for Recycling	2		NA		✓	Lab 3
Welding	1	1	38	✓		
Plastics	1	1	76	✓		Tour
Composites	1	1	34	✓		
Design for Mfg	2	1	NA		✓	
CNC	3		13	✓		Lab 4
Rapid Prototyping	2	1	14	✓		
Electronics and Nano	1	1	46	✓		
Process Planning	3	2	7		✓	Lab 1, 2, Project
Total Content		34				
Tests		3				
Project Work Days		2				
Total Non-Content		5				
Total		39 (3x13)				

To further that dialog, it would be very useful for the authors of the four pillars to also consider defining which features are essential for mechanical engineers. The fact that students from some mechanical engineering programs can graduate without taking a manufacturing processes course (essentially no exposure to manufacturing topics) is disturbing. The manufacturing community may need to lobby for mechanical engineering curricula that include some minimum level of exposure to four pillars topics.

Finally, the four pillars model should be useful to those programs that offer a combination of manufacturing-related elective courses that make up a manufacturing option within a mechanical engineering program. If Calvin's program, in response to student demand, were to allocate resources toward adding manufacturing-related elective courses or a manufacturing-focused concentration or specialization, the four pillars construct would be a useful guiding document.

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[1] Robert L. Mott, Ronald J. Bennett, Hugh Jack, Steve Wendel, Mark J. Stratton, V. Raju, Winston F. Erevelles, and Phil Waldrop, "The Four Pillars of Manufacturing Engineering: What Engineering and Technology Graduates Should Know About Manufacturing," Proceedings of the American Society of Engineering Education (ASEE) Annual Conference, June, 2012.

[2] Hugh Jack (editor), "Curricula 2015: A Four Year Strategic Plan for Manufacturing Education", Society of Manufacturing Engineers (SME), June, 2011. Accessed at http://www.C2015.com

[3] David L. Wells, "An Example Mapping of the Four Pillars of Manufacturing Engineering onto an Existing Accredited Program," Proceedings of the American Society of Engineering Education (ASEE) Annual Conference, 2012.

[4] Data obtained from the ABET accredited programs search website using manufacturing engineering as the program area (http://main.abet.org/aps/Accreditedprogramsearch.aspx)

[5] Hugh Jack, Robert L. Mott, Mark J. Stratton, Phil Waldrop, and Karen Wosczyna-Birch, "Curricula 2015: An Update for 2012", Proceedings of the American Society of Engineering Education (ASEE) Annual Conference, June, 2012.

[6] Robert L. Mott, Ronald J. Bennett, Hugh Jack, Steve Wendel, Mark J. Stratton, V. Raju, Winston F. Erevelles, and Phil Waldrop, "The Four Pillars of Manufacturing Engineering: What Engineering and Technology Graduates Should Know About Manufacturing," Proceedings of the American Society of Engineering Education (ASEE) Annual Conference, June, 2012.

[7] Hugh Jack, Robert L. Mott, Mark J. Stratton, Phil Waldrop, and Karen Wosczyna-Birch, "Curricula 2015: An Update for 2012", Proceedings of the American Society of Engineering Education (ASEE) Annual Conference, June, 2012.

[8] Obtained from SME website http://www.sme.org/uploadedFiles/Forms/Four%20Pillars%20of%20Manufacturing%20Knowledge.pdf on 1/4/2012.

[9] David L. Wells, "An Example Mapping of the Four Pillars of Manufacturing Engineering onto an Existing Accredited Program", Proceedings of the American Society of Engineering Education (ASEE) Annual Conference, June, 2012.

[10] The Calvin College Engineering Department Mission Statement, including educational objectives, can be found on the web at http://www.calvin.edu/academic/engineering/about/mission.html.

[11] Robert L. Mott, Ronald J. Bennett, Hugh Jack, Steve Wendel, Mark J. Stratton, V. Raju, Winston F. Erevelles, and Phil Waldrop, "The Four Pillars of Manufacturing Engineering: What Engineering and Technology Graduates Should Know About Manufacturing," Proceedings of the American Society of Engineering Education (ASEE) Annual Conference, June, 2012.

[12] Calvin College Catalog 2012/2013 available at http://www.calvin.edu/academic/services/catalog/2012-2013/Catalog1213.pdf

[13] Mikell P. Groover, Fundamentals of Modern Manufacturing: Materials, Processes, and Systems, 4th Edition, John Wiley & Sons: New York, 2010.