Using the Fundamentals of Engineering Exam to Assess Student Performance in a Chemical Engineering Curriculum

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Abstract

The Chemical Engineering Program at the United States Military Academy is relatively new. Formed in 2002, the program was recently accredited by ABET in 2014. From the three students enrolled in the program in 2002, the program has grown to 67 students with 23 graduates in the Class of 2016 and 33 freshman, or "Plebes," enrolled as of May of 2016. During those years, the program has evolved considerably. Many of the structural changes in the curriculum were due to direct assessment of student performance. Our most fruitful assessment data has come from the Fundamentals of Engineering Exam. The exam exhibits a high degree of fidelity from year to year, allowing us to identify trends in student performance. We have also associated various features of the exam directly with student outcomes, so that these trends feed directly into our continuous improvement efforts for ABET Criterion 4. One advantage of this approach is that the resulting assessment is then based on a comparison of our students with nationally normed test scores. The use of external data holds significant weight at our institution when we request permission to make curricular modifications. Therefore, using this data, we have been able to introduce several courses into the curriculum and then monitor student performance before and after the changes. In this article, we summarize these results with specific examples. We also show that targeted introduction of new courses can successfully impact performance on student outcomes.

Keywords

Assessment, ABET, fundamentals, engineering, FEE.

Introduction

The chemical engineering program is relatively new at West Point but chemical engineering as a component of the education has a long history. To more fully understand the program, it helps to have some perspective regarding the overall academic culture in which the program exists. We begin this paper with a brief discussion of how some of the aspects of that culture have evolved over time. We then give an overview of the chemical engineering program at West Point. Finally, we will show how the chemical engineering curriculum continues to grow and change to meet the needs of our students. This provides a view of where we came from, what we look like now, and where we are going.

The formation of the chemical engineering program at West Point occurred within the context of the overall academic reforms and changes in the institution over the last 85 years.

Institutional changes at West Point tend to be initiated at the upper levels of management and happen at discrete time periods rather than gradually over time. However, there is a long-term trend in the nature of the changes that can best be summarized as a movement toward curricular diversity. This trend began roughly in the middle of the twentieth century and continues right up to the present day. The starting point is approximately when West Point began offering a Bachelor of Science degree in 1933.[1] This year forms a reference point in the discussion since it indicates the point at which West Point adopted civilian academic standards to its own curriculum. The merits of conferring an academic degree at the Military Academy have been debated and will not be discussed here, but it appears to be a result of the desire to enhance the ability of graduates to attend graduate school, among other factors. Since 1933, arguably the most significant aspect of the changes to the academic program has been the movement away from a common curriculum and toward the development of an increasing number of electives and elective programs. This has been a gradual but very deliberate process.

Up until 1952, all graduating cadets received a single B.S. degree, and all cadets took exactly the same 44 courses, without electives. The curriculum has always included courses that would normally be found at civilian institutions, including chemistry, physics, and mathematics, as well as humanities such as philosophy and foreign languages. However, the dominant educational philosophy of the institution during the first half of the twentieth century was that the firm grounding in problem solving found in quantitative coursework was the optimal preparation for military officers. This philosophy dates to the opening of the institution in 1802 as the nation's first engineering school. Also, consistent with the predominant educational philosophy, the majority of the courses in the academic program were in mathematics, science, and engineering (MSE). Of the 44 required courses in 1952, 25 were in MSE and 19 were in Humanities and Social Science.[2]

The process of evolving from a prescribed curriculum to one containing a wide array of electives and academic majors resulted from a recognition that not all students were inclined toward the engineering and science disciplines, and that some students had a natural inclination for humanities and social sciences. This recognition has brought significant benefits to the cadets. As the modern curriculum has emerged, it has been argued that enrichment of the curriculum, thus allowing more student choice in curricular planning, was one factor in the reduction of the high attrition rates of about 37% that characterized the institution well into the 1970s.[3] While other forces were also at work that led to high attrition rates, and this point can be argued, there is no doubt that the enriched curriculum has stimulated intellectual growth by allowing depth of study in areas of student interest. This idea took hold and continues to influence the ongoing curricular reforms.

The curricular evolution that led to the creation of an elective program began in the mid 1950's, so that by 1962, cadets could take two electives out of 48 required courses. The academic diversification process continued through the 1960's, going from two electives to six electives in 1968 and to 10 electives by 1982. The 1972 curriculum allowed the cadets to concentrate electives, and by 1982, fields of study had fully emerged. The cheating scandal of 1976 was a significant driving force for change. The academy responded to this incident with substantive curricular reforms to improve the conditions that led to the cheating. Sixteen majors were introduced in 1983, including chemistry, civil engineering, computer science, electrical engineering, engineering management, engineering physics, mathematical science, mechanical engineering, behavioral science, economics, foreign language, geography, history, literature, management, and political science.[4]

The Accreditation Board for Engineering and Technology (ABET) figured prominently in the early planning of the engineering programs at West Point. Engineering management, and civil, electrical and mechanical engineering were accredited by ABET in 1985.[5] Each of these programs, prior to accreditation, were cited in the initial Redbook entries as "proposed for accreditation," and were specifically designed around the ABET accreditation criteria. Other programs soon followed. Systems and environmental engineering majors were introduced in 1990.[6] Computer Science, along with the two new majors, are accredited as of 1995. Information technology, nuclear engineering, and chemical engineering were introduced in 2002.[7] The former two programs are accredited as of 2007 and chemical engineering as of 2012.

Although the academic majors are relatively new, the study of chemistry and applied chemistry at West Point goes back as far as the beginning of the academy in 1802. Prior to 1820, the subject was studied informally through independent reading or attendance at guest lectures.[8] Chemistry as a distinct course was formally introduced into the curriculum by Sylvanus Thayer in 1820.[9] Throughout the 19th century, cadets studied inorganic, organic, and applied chemistry in their third and fourth years.[10] Standard chemistry textbooks from the time period were used for the courses, and new books were chosen to reflect changes in the field.[11] Applied courses in minerology and geology were offered in the fourth year. These courses made sense at the time as many military officers were involved in surveying vast new territories in the western part of the country. The cadets obtained additional practical chemical instruction in the ordnance laboratory during their senior year, preparing all manner of incendiary compositions and materials used in the artillery service.[8] Chemistry was considered to be an important subject for placement into the "scientific corps" that consisted of engineering, artillery, and ordnance. The latter was the branch most associated with chemistry; its officers supervised munitions production at the various arsenals and made advances in munitions, weapons and methods of production.[8]

Interestingly, serious coursework at West Point in the manufacture of ordnance predates the first recognized courses in chemical engineering at other institutions by several decades. For example, in his memoirs, John C. Tidball, Class of 1848, describes the ordnance laboratory in some detail.[8] His experiences include preparation of various propellants and explosives and assembling them into working munitions. Both Henry[12] and Henry A. DuPont[13] were alumni from this time period (classes of 1833 and 1861, respectively), and were almost certainly influenced by their experiences in ordnance courses at West Point. Externally, industrial chemistry and chemical engineering were beginning to emerge in the last quarter of the 19th century. What has been described as the first true chemical engineering course was given at the University of Manchester in 1887,[14] and Lewis Norton's four-year curriculum at MIT was offered for the first time in 1888.[15] The American Institute of Chemical engineers was founded in 1908.[16] So, while chemical process engineering and the introduction of unit operations and unit processes was emerging in various civilian institutions, a significant amount of product engineering in explosives chemical manufacturing appears to have been part of the curriculum at West Point during the early part of the 1800's.

Chemical education at West Point continued more-or-less the same pattern until the late-twentieth century. Modern chemical engineering electives began to emerge as a result of the curricular reforms of the 1980's, and the first formal chemical process engineering elective (CH476 Introduction to Chemical Engineering Analysis) was offered in 1983.[4] Other electives appeared shortly afterward. A material and energy balances course was first offered in 1991,[17] and courses in reaction engineering and plant design followed in 1993.[18] The appearance of these courses was more-or-less contemporary with the rapid increase in the number of electives that accompanied the introduction of majors at West Point in 1983.

The current chemical engineering program appeared at West Point in 2002 and the program had its first graduates in 2005. The program was specifically developed during the curricular reforms of 1999-2000 and was a result of the continuing movement toward more academic diversity. The timing also had to do with changes in the ABET program criteria that were occurring around that time, as discussed in the next section. These changes amounted to a reduction in the number of chemistry courses required for chemical engineers, allowing the design of a major that fit into the overall West Point curriculum.

Chemical Engineering at West Point

The chemical engineering curriculum at West Point is derived in part from comparison with programs at civilian institutions. This is done for various reasons, but mostly to ensure that our graduates can transition smoothly into graduate programs in these institutions or civilian engineering jobs after their five-year military obligation, should they decide to do so. The credit hour content of the program is summarized in Table 1 for the graduating class of 2016. Table 1 also shows a comparison of the West Point chemical engineering program with other chemical engineering programs accredited by ABET. The credit hours in 2012 for other institutions were determined by examining published materials on department web sites and university catalogs. Credit hour averages from 1994[19] are also shown for comparison to give an idea of how the nationwide chemical engineering curriculum is changing over time.

For the most part, West Point chemical engineering follows the overall pattern of credit hour coverage seen in the nationwide averages. We are very similar (within about 0.5 credit hours) in much of the fundamental coverage, including material and energy balances, separations/unit operations, chemical reactor design, and control. We provide more than the average credit hours in the areas of transport phenomena, mathematics (including statistics), and electrical and civil engineering. Less time is spent in the design, laboratory, chemical engineering thermodynamics, and chemistry subjects.

There are some interesting trends in the data shown in Table 1. Predominantly, the table shows how specific topics and experiences have gained or lost coverage, and thus, one may assume, gained or lost importance as a critical skill expected of undergraduate chemical engineers. In the 18-year span between 1994 and 2012, design, laboratory work, reactor design, control, and thermodynamics all gained 10-30% average coverage, as measured by credit hours. Noticeably, these are all chemical engineering-specific topics, with the biggest gains being associated with design. Nearly all of the significant coverage lost over those same 18 years has been in general engineering or background science. All chemistry topics have dropped more than 30%, while statistics, electrical, civil, and material engineering topics have nearly disappeared. An additional trend is in the total number of credit hours allotted to all engineering related topics. In 1994, an ‘average’ program required more than 97 credit hours of related engineering, math, and science content. By 2012, this had dropped to just over 81 credit hours.

The decline in chemistry credit hours is an interesting trend that has emerged in recent years. Nationwide, pure chemistry content in chemical engineering programs is dropping, as can be seen in the shift from 19.0 to 14.7 credit hours from 1994 to 2012. West Point is at 10.5, which is somewhat low compared to either benchmark. In addition to the drop in credit hours, our study shows that 47 out of 159 chemical engineering programs no longer required physical chemistry in 2012. This drop in requirements is probably due to realization that programs can satisfy ABET requirements in math and basic science without a large number of elective chemistry courses. In our case, while our credit hour coverage is low, performance indicators, which will be discussed in the next section, show that our students’ performance in chemistry is strong, giving us some confidence that the coverage is sufficient.

One likely reason for the reduction in chemistry credit hours is that ABET changed the chemical engineering program criteria significantly in 2000. The program criteria for 2000-2001 required that

> “Chemical engineers must receive thorough grounding in chemistry, and the chemistry courses they take should be the same as, or equivalent to, those taken by chemistry majors. An accreditable chemical engineering curriculum *must include at least one-half year of advanced chemistry in addition to the usual two-semester (or three-quarter) freshman-level course in general chemistry*.”[20]

By 2001-2002 the program criteria had been changed to

> “The program must demonstrate that graduates have: *thorough grounding in chemistry and a working knowledge of advanced chemistry* such as organic, inorganic, physical, analytical, materials chemistry, or biochemistry, selected as appropriate to the goals of the program.”[21]

The program criteria underwent a few more minor changes between 2002 and 2012. The most current version, which went into effect in 2012, includes the requirement that

> *“The curriculum must provide a thorough grounding in the basic sciences including chemistry, physics, and/or biology, with some content at an advanced level*, as appropriate to the objectives of the program.”[22]

Essentially, ABET has moved away from prescribing curricular content or credit hours in chemistry, with the result that more and more programs are finding that they can meet ABET accreditation criteria with fewer chemistry courses. This change is clearly reflected in the data in Table 1.

The reduction in chemistry content in the program criteria also allowed the formation of a chemical engineering program at West Point. As discussed earlier and also shown in Table 1, our core course load is high compared to the general education requirements at most civilian schools. We also have a strict 47-month time limit for graduation, which, combined with the heavy core course load, effectively prohibited a chemical engineering program under the old criteria.

Table 1. United States Military Academy (USMA) credit hours compared to national average credit hours in key chemical engineering subjects.

Course Content	*USMA*	*2012 Avg*[a]	*1994 Avg*[b]
Design	3.5	5.7	4.9
Laboratory	3.5	4.1	3.7
Reactor Design	3.5	3.1	1.9
Separations/Unit Operations	3.5	3.0	3.2
Control	3.0	3.0	2.3
Material & Energy Balances	3.5	3.6	3.6
Transport Phenomena	7.0	6.3	11.7
Chemical Engineering Thermodynamics	6.5	4.8	4.2
Chemistry (excl. Phys. Chem.)	10.5	14.7	19.0
Physical Chemistry	0.0[c]	3.0	6.4
Physics	7.0	7.7	7.7
Mathematics (to ODEs)	16.5	14.8	14.5
Computer	3.0	2.4	3.6
Statistics	3.0	1.0	3.0
Electrical Engineering	3.5	1.0	3.8
Civil Engineering/Materials Science	3.0	0.9	3.8
Philosophy and Ethics	3.0		
Economics	3.5		
English Composition	6.0		
Physical Geography	3.0		
American Politics, Intl Relations	7.0		
Psychology	3.0		
History, Law	15.5		
Foreign Language	6.0		
Physical Education	3.0		
Military Science	4.5		

[a] Average of 159 schools in the Unites States in the ABET database.
[b] From Occhiogrosso and Rana. [19]
[c] Physical Chemistry dropped to 0.0 in 2015.

Another area in which we are somewhat low in terms of credit hours is design. The West Point program has 3.5 credit hours, while the national average is 5.7. This is essentially the difference between ~1 and ~2 semesters. Also of note is that the national average is up from 4.9 credit hours in 1994, and the trend seems to be toward 2 full semesters of design. However, in this case, benchmarking credit hours is not enough. Even with relatively fewer credit hours than our peers at other institutions, our students continue to perform reasonably well in this section of the FE exam, as discussed in the next section.

West Point chemical engineering also differs in the amount of civil and electrical engineering required by the program. Combined, these courses amount to 6.5 credit hours, compared to 1.9 credit hours in the national average. These courses used to be quite common in engineering programs. We note that the 1994 average was 7.6 credit hours, close to where West Point is now. Although somewhat old-fashioned in this respect, we feel that knowledge of circuits and civil engineering are essential skills for graduates of our program.

Assessment Methods and the FE Exam

The chemical engineering program at West Point is benchmarked against content areas within the Fundamentals of Engineering (FE).[23] The FE exam represents a synopsis of relevant engineering skills, with both general engineering and chemical engineering content. The exam content is provided by professional and academic practitioners, and passage of the exam is required for licensure in all 50 states. The exam is also nationally normed, allowing us to compare the performance of our students with their peers at other schools. For these reasons, the FE Exam is an excellent benchmark for a public institution such as West Point, and our program curriculum is aligned with it.

The FE Exam can be used to assess some of the ABET a-k outcomes. Barrett, Whitman and Steadman[24] claim that FE exam results can be used as one measurement in the assessment of the following student outcomes from ABET General Criterion 3: (a) an ability to apply knowledge of mathematics, science, and engineering; (b) an ability to design and conduct experiments, as well as to analyze and interpret data; (c) an ability to design a system, component, or process to meet desired needs within realistic constraints; (e) an ability to identify, formulate, and solve engineering problems; (f) an understanding of professional and ethical responsibility; and (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Our institution makes heavy use of the exam for program assessment. We use the exam for partial assessment of each of the outcomes mentioned above, with the exception of (b). We measure experimental design directly, and the connection with analysis and interpretation of experimental data on the FE exam is not clear enough to us to justify using the exam for this outcome. However, we use the exam to assess other outcomes not mentioned in the list above. For example, we use the exam to assess (h) understanding the impact of engineering solutions in a global economic, environmental, and societal context. We feel that the economic component of this outcome is related to engineering economics, which, on the FE exam, include interest and time value of money, as well as other common financial instruments such as cash flow patterns and capitalized cost. We also use the FE exam specifically to assess ABET outcome (i). We view the percentage of our students who take the exam as a measure of recognition of the need for lifelong learning.

The reinforcement of the role events such as the FE exam can have for a career is very important for new engineers. West Point is unique in that our students have a military obligation for at least five years after graduation. Although the ABET student outcomes are an excellent preparation for this part of their career, the students generally will not be performing technical engineering assignments until after this time. Interestingly, the Army publishes extensive literature on officer professional development after graduation from college. This literature explains the importance of the FE exam, particularly for officers in the Engineer Branch.[25] Also, to emphasize the importance of the exam, our institution pays the cost of registration. Despite this, our students' participation in the FE exam was not 100%, primarily because the exam is voluntary at our school.

In an effort to modify this performance, a new course was introduced into the program in 2010. The new course, CH400 Chemical Engineering Professional Practice, was created specifically to expose students to longer-term professional experiences, including, among other topics "continuing education, global and societal issues within chemical engineering, and professional plant engineering." The course also contains a significant amount of preparation exercises for the FE exam. These exercises are aimed at improved technical skills and also are intended to develop a group culture that emphasizes the importance of the exam.

Figure 1 shows participation rate and pass rate by year from 2006 to 2016. As can be seen in the figure, since the introduction of the professional practice course in 2010, the percentage of students taking the exam has risen from an average of 86% to 100%. Also, not surprisingly, the pass rate on the exam rose from an average of 77% to 86% over the same time period. Since the inclusion of the course, the participation and improved average pass rates suggest the change has been a good one.

ABET outcome (i) requires that students possess "a recognition of the need for, and an ability to engage in life-long learning." Interestingly, Barrett, Whitman and Steadman[24] do not mention this outcome in their discussion of the relevance of the exam. Our use of the exam to assess this outcome is based on the career counseling literature published by the Army, discussed earlier. Within this literature, each branch suggests activities that army officers should be engaged in for "self-development" at each stage of their career, from lieutenants immediately after graduation on up to colonel. For example, in its self-development sections, the engineer branch states, "Officers who have a Bachelor of Science degree from an ABET accredited institution are highly encouraged to take the Fundamentals of Engineering exam."[25] Later in their career, at the captain and major levels, they are encouraged to take the Professional Engineering exam and to obtain a PE license.[26] Since the Army is the primary constituency of our institution and our program, literature published by the Army is considered by us to be authoritative. Since the exam is voluntary, the percentage of students taking this exam indicates how many of our students are willing to engage in the professional licensure process, and is therefore one aspect of students' ability to recognize the need and develop the skills required for life-long learning.

Our program has created a twelfth student outcome that specifically targets ABET's chemical engineering program criteria. Specifically, for program student outcome 12, we have, "the program provides the graduate with a thorough grounding and working knowledge of chemical engineering sciences, including general and advanced chemistry, material and energy balances, safety and environmental factors, thermodynamics of physical and chemical equilibria, heat, mass and momentum transfer, chemical reaction engineering, continuous and stages separation operations, process dynamics and control, modern experimental and computing tools, and process design." These topics also map almost directly to the specifications of the FE exam. ABET makes allowance for this in the Criteria. According to ABET, "Student outcomes are outcomes (a) through (k) plus any additional outcomes that may be articulated by the program."[27] So, by articulating the exam content as an additional student outcome, we have thoroughly connected the FE exam to our program's student outcome assessment process.

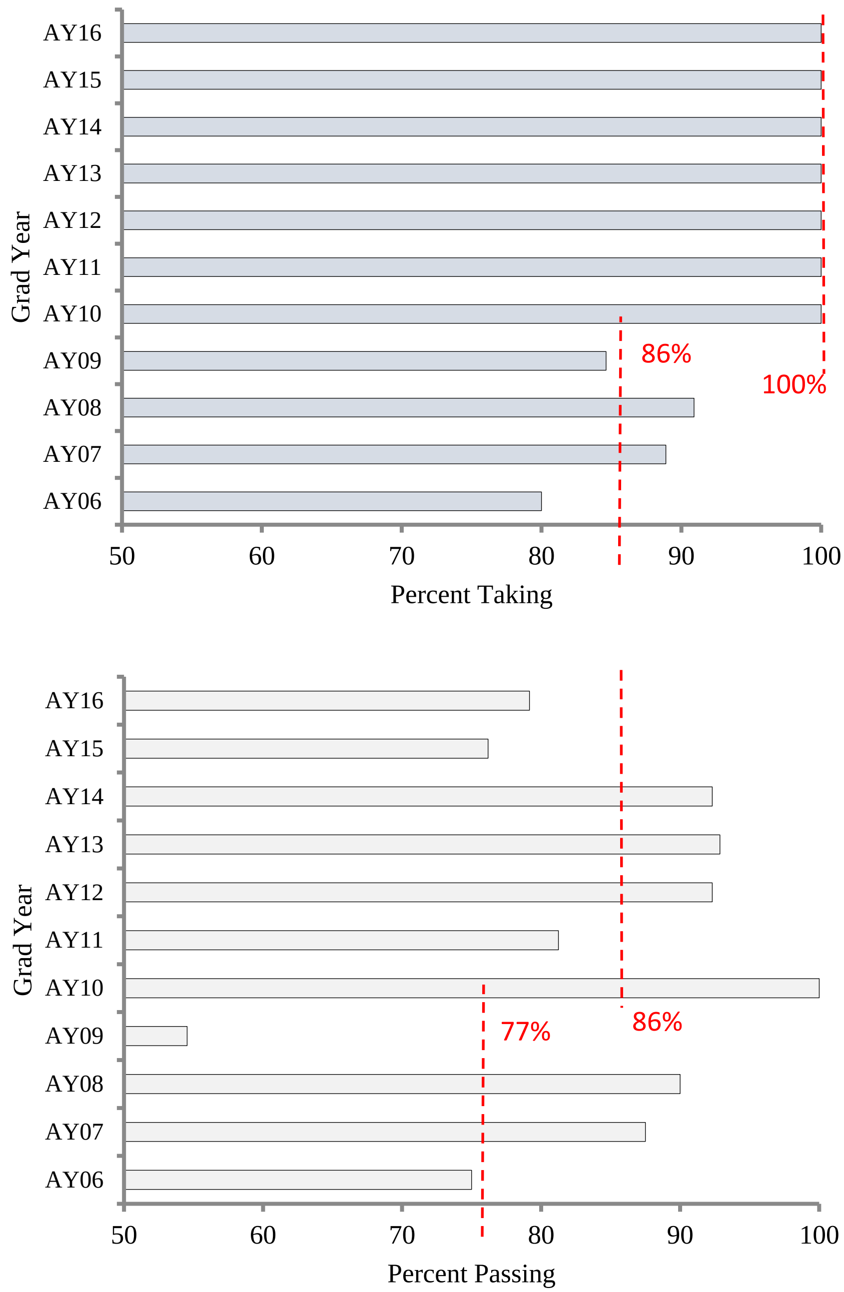

Figure 1. (a) Percentage of West Point chemical engineers taking the FE exam, and (b) percentage of students passing the exam.

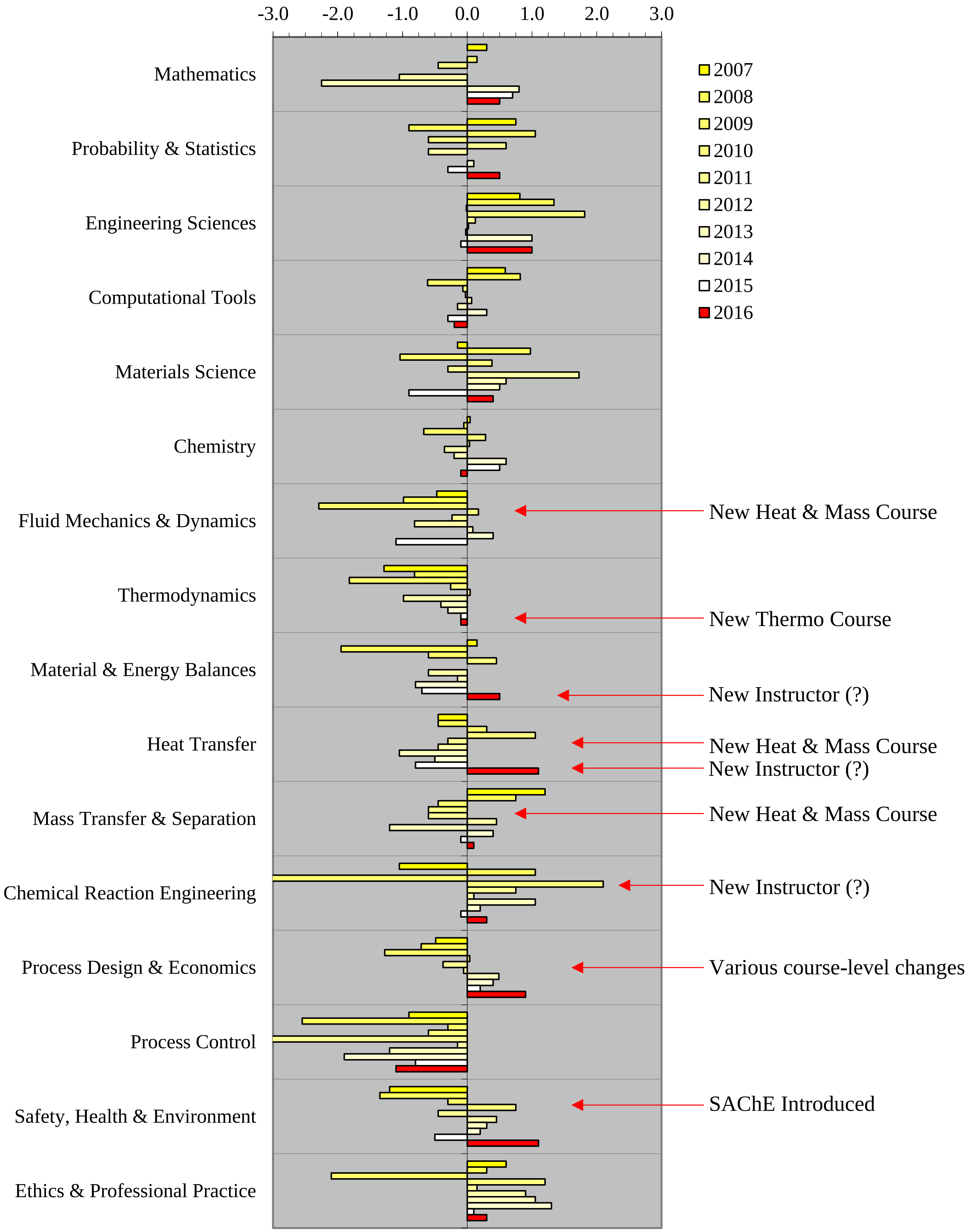

Figure 2. Year-to-year performance in subject areas on the FE Exam.

A very useful feature of the FE exam is that the National Council of Examiners for Engineering and Surveying (NCEES) provides a performance report to the students' institutions. The report shows the average program performance in each topical area as well as national averages in each of the content areas of the exam. The report does not indicate how individual students performed. Figure 2 shows data from the reports for West Point chemical engineers from 2007 to 2016. The data in the figure are plotted as differences between West Point cadets and the national average. The vertical line at 0 represents zero difference in scores.

At the top of the figure, the data in the topical areas demonstrates trends we expect and would like to see when assessing performance. The data from the Probability and Statistics area, for example, shows that in some years students exceed the national average and in others they do not, with no clear positive or negative trend. This is an expected pattern. When assessing the overall program, this pattern is generally interpreted as not requiring significant adjustment, though some course-level changes may be warranted. The trend shown in the Engineering Sciences area demonstrates a trend that we would like to see – each year at or above the national average. As a desired trend, this can also be used judiciously to influence course or program content. For example, one conclusion could be that the apparently more-than-sufficient coverage of this topic might be an area from which a number of lessons in one or more courses could be used instead for topics that are not consistently so strong.

The more critical and difficult trends to address (both logistically and emotionally), however, are those demonstrated first in the Fluid Mechanics and Dynamics and Mass Transfer and Separations topical areas. Between 2007 and 2009, student performance showed consistently low achievement compared to the national average. To address this, we proposed, and on the strength of this trend data, got approved, a new course within the program to address these assessed shortcomings, specifically, CH485 Heat and Mass Transfer. Since then, performance in these areas shows more of an expected trend – some years higher, some lower, than the national average.

A similar trend was shown in the Thermodynamics area during the same years. By 2013, as the trend continued low, another new course, CH365 Chemical Engineering Thermodynamics, was proposed and accepted. The first class experiencing this course took the FEE in the spring of 2016 and graduated shortly afterwards. The results on the FEE that year were very nearly the national average, and the results over the next few years will be examined carefully, hopefully for a changing trend.

Yet another strong trend shown in this data is the consistently below-national-average performance of West Point chemical engineers in the area of process control. As demonstrated, students have performed below the national average in this topic since the program's inception. In the 14 years the current course has been part of the Chemical Engineering major, several attempts have been made at both the program and course levels to make changes intended to improve cadet performance in process control. These changes included creation of chemical engineering content for the current course, re-alignment of the process control thread in the chemical engineering curriculum, movement of the controls course from senior year to junior year, introduction of process control content in the follow-on unit operations course, and inclusion of review topics in the professional practice course.

More invasive attempts have been made within the program to improve our students' performance in process control. For example, in 2006-2008, a chemical engineering professor worked closely with the course faculty to modernize the course and make it more relevant for the chemical engineers.[28] He was constrained, however, to maintain the overall lesson plan and sequence provided for the general course. The result was that a number of lessons were allotted for chemical engineering-specific topics. Additionally, in 2010, about 2 lessons within the program's 1.5 credit hour CH400 Chemical Engineering Professional Practice course were designated specifically for reviewing process controls topics. Finally, in 2011, approximately 15% of the unit operations course was allocated for discussion and reinforcement of controls topics. This time is allocated to applied process control within the overarching goal of designing and executing unit operations experiments.

Improvement in performance in process control has been particularly challenging, as the West Point program (uniquely among US ABET accredited chemical engineering programs relies on a course taught in another department to convey the necessary background in controls theory and practice.[28] The course is thus responsible for desired topics for any disciplines requiring or desiring controls theory, not just chemical engineers, and may include mechanical, electrical, and aeronautical engineers. Making changes to the course for the specific needs of chemical engineers, therefore, could not detract from the material provided to other disciplines, a difficult proposition. Moving forward, our efforts will most likely ultimately culminate in the creation of a new course, where more targeted content can be created.

Summary and Conclusions

Chemistry and chemical education have a long history at West Point. Early in the 19th century, academic studies in chemistry were strongly coupled with what would be defined in modern times as product engineering, particularly in ordnance manufacturing. The current chemical engineering program emerged after academic majors were created at West Point and after ABET relaxed the program criteria in chemical engineering, allowing the course load to be added to the already heavy common or core curriculum. The current version of the chemical engineering program has credit hour coverages that compare well with national averages in each of the topical areas. The FE Exam and performance on the exam has been used with some success to make modifications to the curriculum. In particular:

- Creation of a review course led to increased participation and pass rate on the FE exam.
- Creation of a course in heat and mass transfer was based in part on performance data on the exam and has led to improved performance in fluid dynamics.
- Similarly, creation of a course in chemical thermodynamics was also based in part on performance on the exam and has led to somewhat improved performance.
- Currently, relatively poor performance in process control is being used to create a new course in this area.
- Various changes at the course level usually lead to improved performance when they are carefully targeted and executed.

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