PRODUCTIVITY AND QUALITY INDICATORS
For Highly Ranked ChE Graduate Programs

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Comparative assessments of graduate programs have been made for at least eighty years. Such assessments are useful to prospective students and to those seeking an academic position. They are also used in the political arena to make or justify policy and appropriations decisions. Within engineering, the most visible rankings are those from *U.S. News*,[1] the NRC Report,[2] and the Gourman report.[3] The *U.S. News* ranking is arguably the best publicized and most widely used ranking today.

U.S. News ranks the graduate programs for individual engineering disciplines. These discipline-specific rankings are based exclusively on a department's reputation as determined from a peer-assessment survey. Engineering deans (or their designees) nominate up to ten departments in a particular discipline (*e.g.*, chemical engineering), and the total number of respondents who nominate a department determines its rank. The most recent ranking[1] of graduate programs was compiled in January 2002, based on data from a survey distributed in the fall of 2001.

This article expands the reputation-based *U. S. News* rankings of chemical engineering departments by providing and comparing quantitative quality and productivity indicators for the top twenty chemical engineering departments in its 2002 ranking. One objective of this study was to determine how well the rankings, which are based exclusively on reputation, correlate with different publicly available productivity and quality indicators. A second objective was simply to assemble the database of quantitative indicators, an exercise that has not been completed for at least ten years.

The productivity indicators examined here are the number of published articles and reviews and the number of bachelor, master, and doctoral degrees granted annually. The quality indicators are the number of NAE members, the number of AIChE Institute awards received, the number of highly cited papers, the number of citations per paper, and the total number of citations to the department's published articles and reviews. This last quantity is an indicator of both quality (citations) and productivity (number of publications).

The study also included data on the research expenditures for each department. Some would contend that total research expenditure is not an indicator of productivity or quality, but research funding is a necessary input for a high-quality graduate program. Moreover, one could argue that the ability to compete successfully for peer-reviewed federal funds is an indicator of quality. Therefore, the study included data for federally funded research expenditures for each department.

None of the indicators used in this study are perfect or complete measures of quality or productivity. They are simply quantities that most chemical engineering educators would likely agree are among the most relevant indicators. Similarly, the indicators used in this study do not constitute an exhaustive set of all relevant indicators. Other relevant indicators (*e.g.*, non-AIChE awards, patents, faculty appointments for PhD recipients, etc.) exist but were excluded here to make the demands of data gathering consistent with the resources available for the task.

Many of the indicators considered here have been used previously to rank graduate programs. Diamond and Graham[4] argued that per capita citation density (citations per faculty member) is perhaps the best single indicator of a program's

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excellence. Their article also provides an interesting discussion of the history and limitations of subjective peer assessments (reputational rankings). Angus, et al.,[5] proposed a ranking system that uses data for publications, citations, research support, and awards. Their system included a greater variety of awards than NAE membership and AIChE Institute awards, which are the only awards considered here.

Both articles provided rankings of chemical engineering programs. These rankings were based on the publication and citation data that appeared in the 1995 NRC report. The data were gathered in 1993, so the rankings in these articles as well as in the NRC report itself reflect the landscape as it existed ten or more years ago. Additionally, there were inaccuracies in some of the citation data in the 1995 NRC report.[4]

It is worthy of note that the NRC is currently evaluating various methodologies for its next comparative study of graduate programs at U.S. universities, release of which is anticipated to be in 2005. Given that at least a decade has passed since a comprehensive set of indicators has been assembled for chemical engineering graduate programs, we set out to develop such a database for the top twenty programs in the *U.S. News* 2002 rankings. One purpose in doing so is to assess the degree of correspondence between the subjective rankings and the various publicly available quantitative indicators.

One objective of this study was to determine how well the rankings, which are based exclusively on reputation, correlate with different publicly available productivity and quality indicators.

METHODOLOGY

This study examines data for both productivity indicators and quality indicators for the twenty chemical engineering departments ranked by *U.S. News*. One of the quality indicators is the number of faculty members in a chemical engineering department who are also members of the National Academy of Engineering (NAE). This information was compiled by comparing the list of NAE members[6] at each institution with the list of faculty in each department.[7] A second quality indicator is the number of AIChE Institute awards that faculty members in a given chemical engineering department in 2002 had received between the years 1992 and 2001.[8]

Additional productivity and quality indicators involve publications and citations. The average annual number of publications from each chemical engineering department was determined for 2000 and 2001. These data were obtained from a search of ISI's Web of Science.[9] The search was conducted by department (or school) and not by each individual faculty member. It provided all publications in which at least one author self-identified with the specific department.

The search included only "articles" and "reviews." It provided no data specifically for the chemical engineering programs at Caltech and at Minnesota. Caltech authors in both chemistry and chemical engineering identified themselves with the Division of Chemistry and Chemical Engineering. Thus, the search returned publications for both departments and no attempt was made to determine the subset that could be attributed to chemical engineering. Minnesota's chemical engineering program is part of the Department of Chemical Engineering and Materials Science, and the search returned papers published by the entire department. These departmental totals were included in this study because the chemical engineering portion of that department is easily the larger of the two.

The ISI database was also used to discover the total number of citations made to each "article" and "review" published by a given chemical engineering department in 1998 and 1999. This search also provided the total number of articles and reviews published by that department during that two-year span. The number of citations reported is the number as of the dates of the searches (May 23-24, 2002). Thus, the citation statistics reported herein are for papers that had been in print for two-and-one-half to four-and-one-half years. There may be a benefit to using a longer time in print for the citation analysis (capture more completely the total impact of the articles), but there also exists a disadvantage (using older papers makes the citation data less reflective of the impact of a department's recent work).

The number of papers published by most departments in 1998/99 was within 10% of the number published in 2000/01. Since the departmental publication rates are similar for these four years, and since the citation statistics are for only a two-year sample, the citation statistics are not likely to suffer from a publication-rate-profile bias.[10] Moreover, the citation statistics presented herein are free of many of the "pitfalls" enumerated by Grossmann.[11] Other authors[4,5] have also discussed the strengths and weaknesses of using citations as an indicator of quality so these issues will not be rehashed here.

Note that ISI computes statistics for the citation impact in chemical engineering for different institutions. These statistics are determined from citations to all publications from a given university in a set of journals ISI classifies as "chemical engineering" journals. Thus, a portion of the data will be from articles contributed by other departments, and more importantly, work published by chemical engineering faculty will be excluded if it is published outside the traditional chemical engineering journals. It is for these reasons that this statistic was not used in the present study. Finally, note that one could devise a scheme to calibrate the citation statistics (perhaps using impact factors for journals or fields) to account for field-to-field differences in citation frequency. This calibrated citation frequency could be a useful complement to the total citation frequency reported here.

Another indicator of productivity is producing engineering graduates. The ASEE website[12] provided the number of bachelor, master, and doctorate degrees, respectively, granted in chemical engineering in 2000 and 2001. The data available for the University of Minnesota includes chemical engineering and materials science together. This site also provided the number of full-time, tenured, or tenure-track faculty in each department for these two years. Note that these data do not account for fractional academic appointments nor do they include non-tenure-track faculty. Accurate data for the number of faculty full-time equivalents in each department would have been useful, but such data do not appear to reside in a publicly available database.

Finally, the study included information regarding research expenditures made by each department. The ASEE website provided the total annual expenditure for 2000 and 2001. These total research expenditure figures include both sponsored and internally funded research. No research expenditure data were available on the ASEE website for Caltech, Georgia Tech, or Northwestern. The National Science Foundation[13] also compiled and reported research expenditure data. The most current data are for fiscal year 2000, and both the total and the federally sponsored research expenditures are available for all of the departments of interest.

RESULTS AND DISCUSSION

Table 1 provides the data for each department. The first column, "Rank," provides the *U.S. News* ranking. "NAE" is the number of faculty members in a chemical engineering department who are also members of the National Academy of Engineering. The next column shows the number of AIChE Institute awards that faculty members in a given chemical engineering department in 2002 received between 1992 and 2001. The column "Pubs" shows the average annual number of publications from each department. "B," "M,", and "D" are the mean number of bachelor, master, and doctorate degrees, respectively, granted annually in chemical engineering for 2000 and 2001. "FTF" is the mean number of full-time (tenured or tenure-track) faculty.

The first "Total Research Expenditure" column is an annual average for 2000 and 2001, as compiled by ASEE, and the other two Research Expenditure columns contain data from NSF[13] for fiscal year 2000. The next column lists the

TABLE 1
Extensive Indicators for Chemical Engineering Departments

		AIChE						Research Expend. ($K)					
Rank	*NAE*	*Awd*	*Pubs*	*B*	*M*	*D*	*FTF*	*Total*[1]	*Total*[2]	*Federal*[2]	*Cit.*	*Cit. per Pub*	*>50 Cites*
1. MIT	9	10	134	79	39	34	33	17,958	16,106	10,131	3751	12.0	8
2. Minnesota[3]	7	2	143	156	10	43	32	7,551	9,057	5,682	2283	6.7	2
3. UC Berkeley	3	2	94	80	7	13	18	13,205	4,842	1,880	1577	8.6	1
4. Caltech	4	4	n.d.	11	6	6	10	n.d.	5,105	2,772	n.d.	n.d.	n.d.
5. Wisconsin	2	1	90	93	6	16	17	8,862	7,317	4,295	1210	7.0	1
6. Stanford	1	1	58	14	31	6	11	6,019	6,424	5,378	1068	10.8	2
7. Texas	3	1	91	126	20	18	20	5,405	7,469	3,823	1412	7.2	0
8. Delaware	2	2	86	45	10	19	21	3,380	5,890	2,940	1168	6.8	2
9. Illinois	1	0	54	79	18	9	13	2,825	5,160	3,001	675	5.8	0
10. Princeton	3	7	70	27	2	11	17	3,644	3,130	1,564	1412	9.8	1
11. Michigan	0	3	79	130	22	10	17	4,143	3,623	2,315	1267	8.6	5
12. UC Santa Barbara	6	2	73	17	3	10	19	4,610	4,995	3,907	2648	15.9	11
13. Georgia Tech	3	2	62	135	10	15	34	n.d.	5,938	2,460	793	6.0	1
13. Purdue	0	1	63	112	8	12	21	6,699	6,624	2,403	655	5.0	0
15. Carnegie Mellon	3	2	78	41	9	13	19	3,603	3,379	2,223	1029	7.3	0
16. Cornell	1	0	36	58	12	8	13	3,397	3,020	1,647	770	7.9	0
16. Pennsylvania	2	2	38	30	14	7	9	1,738	1,777	1,300	638	9.7	2
18. Northwestern	1	2	45	46	6	10	15	n.d.	4,086	2,084	643	7.1	0
19. Penn State	1	1	50	141	8	6	20	3,172	14,257	8,491	718	6.1	1
20. Texas A&M	0	1	49	116	14	15	18	11,826	9,364	1,963	381	4.9	0

[1] *From ASEE data*
[2] *From NSF data*
[3] *For chemical engineering and materials science*

total number of citations to all articles and reviews published by a given department in 1998 and 1999. The mean number of citations per research publication appears in the next column. This quantity was calculated as the total number of citations divided by the total number of articles published during those two calendar years. The final column lists the total number of articles in the sample that had been cited more than fifty times as of the date of the citation search.

Different sources sometimes report different values for the same statistic. A manifestation of this discrepancy is apparent in the "Total Research Expenditure" data in Table 1. Substantial differences between the NSF and ASEE databases appear for four departments (Berkeley, Delaware, Illinois, and Penn State). The NSF data are for fiscal year 2000 and the ASEE data are for the academic year, but it is difficult to envision such large differences being attributable to different ending dates for a fiscal and an academic year. The chemical engineering programs at Berkeley and at Illinois do not reside within the College of Engineering, so this administrative structure might play a role in the discrepancies. Data reported by different sources for degrees granted by a given department also exhibited variability (but not as much as the research expenditure data).

The data in Table 1 afford an opportunity to determine which departments had the highest values for the different extensive quality and productivity indicators. Table 2 lists the top ten departments (of the twenty considered) in several of the categories. For each of the five indicators in Table 2, at least half of the departments listed are also among the top ten in the *U.S. News* ranking. In fact, the only top-ten schools absent in more than two of the columns in Table 2 are Stanford and Illinois. Carnegie Mellon (CMU), Michigan, and UC Santa Barbara (UCSB) are the only schools ranked in the second ten by *U.S. News* to appear in at least two of the columns. Each of these schools appears on three or four of the lists.

All of the data in Table 1 except for citations per paper are extensive indicators of the productivity or quality of each department. That is, they are total quantities and their values can depend on the size of the department. To analyze the data more thoroughly, intensive indicators were obtained by

TABLE 2
Top Ten[1] Departments in Different Productivity or Quality Indicators

	Citations/Pub[1]	*Citations[1]*	*Publications[2]*	*NAE Members*	*Doctorate Degrees*
1	UCSB	MIT	Minnesota	MIT(9)	Minnesota
2	MIT	UCSB	MIT	Minnesota (7)	MIT
3	Stanford	Minnesota	Berkeley	UCSB (6)	Delaware
4	Princeton	Berkeley	Texas	Caltech (4)	Texas
5	Pennsylvania	Princeton	Wisconsin	Berkeley (3)	Wisconsin
6	Michigan	Texas	Delaware	Texas (3)	Georgia Tech
7	Berkeley	Michigan	Michigan	Princeton (3)	Texas A&M
8	Cornell	Wisconsin	CMU	CMU (3)	Berkeley
9	CMU	Delaware	UCSB	Georgia Tech (3)	CMU
10	Texas	Stanford	Princeton	3 depts w/2	Purdue

[1] Of the 20 ranked by *U.S. News*
[2] Excluding Caltech because of lack of data

TABLE 3
Intensive Indicators for Chemical Engineering Departments

Rank		*AIChE NAE*	*AIChE Awd*	*AIChE Pubs*	*B*	*M*	*D*	*Research Expend. ($K) Total[1]*	*Research Expend. ($K) Total[2]*	*Research Expend. ($K) Federal[2]*	*Cit.*	*>50 Cites*
1	MIT	0.28	0.31	4.14	2.42	1.18	1.03	553	496	312	115	0.25
2	Minnesota[3]	0.22	0.06	4.47	4.86	0.30	1.33	236	283	178	71	0.06
3	Berkeley	0.17	0.11	5.22	4.42	0.36	0.69	734	269	104	88	0.06
4	Caltech	0.40	0.40	n.d.	1.10	0.55	0.55	n.d.	511	277	n.d.	n.d.
5	Wisconsin	0.12	0.06	5.42	5.64	0.36	0.94	537	443	260	73	0.06
6	Stanford	0.09	0.09	5.27	1.23	2.82	0.55	547	584	489	97	0.18
7	Texas	0.15	0.05	4.55	6.28	1.00	0.88	270	373	191	71	0.00
8	Delaware	0.10	0.10	4.17	2.17	0.46	0.93	165	287	143	57	0.10
9	Illinois	0.08	0.00	4.28	6.28	1.44	0.68	226	413	240	54	0.00
10	Princeton	0.18	0.41	4.12	1.59	0.09	0.65	214	184	92	84	0.06
11	Michigan	0.00	0.18	4.62	7.62	1.29	0.59	244	213	136	75	0.29
12	UC Santa Barbara	0.32	0.11	3.84	0.89	0.16	0.50	243	263	206	139	0.58
13	Georgia Tech	0.09	0.06	1.85	4.01	0.30	0.43	n.d.	177	73	24	0.03
13	Purdue	0.00	0.05	2.98	5.31	0.38	0.55	319	315	114	31	0.00
15	Carnegie Mellon	0.16	0.11	4.22	2.22	0.49	0.68	195	183	120	56	0.00
16	Cornell	0.08	0.00	2.88	4.64	0.96	0.64	272	242	132	62	0.00
16	Pennsylvania	0.22	0.22	4.17	3.33	1.50	0.78	193	197	144	71	0.22
18	Northwestern	0.07	0.14	3.07	3.14	0.41	0.66	n.d.	282	144	44	0.00
19	Penn State	0.05	0.05	2.56	7.23	0.41	0.31	163	731	435	37	0.05
20	Texas A&M	0.00	0.06	2.69	6.44	0.78	0.81	657	520	109	21	0.00

[1] *From ASEE data*
[2] *From NSF data*
[3] *For chemical engineering and materials science*

dividing all of the statistics in Table 1 by the number of full-time, tenured/tenure-track faculty (FTF) listed for each department. Table 3 lists these intensive indicators for each department. The data in Table 3 afford an opportunity to determine which departments had the highest values for the different intensive quality and productivity indicators. Table 4 lists the top ten departments (of the twenty considered) in several of the categories.

For each of the five indicators above, at least seven of the ten schools listed are also among the top ten in the *U.S. News* ranking. Illinois is the only top-ten school absent in more than two of the lists above for productivity or quality indicators on a per-FTF basis. CMU, Pennsylvania, Michigan, and UCSB are the only schools ranked in the second ten by *U.S. News* to appear on at least two of the lists above. CMU, Michigan, and UCSB also surfaced as the second-ten departments that most frequently appeared on the top-ten lists in Table 2 for the different extensive productivity or quality indicators. It appears that the chemical engineering graduate programs at CMU, Michigan, Pennsylvania, and UCSB have higher values for their productivity and quality indicators than one might expect based on their *U.S. News* rankings.

The data in Tables 1 and 3 allow identification of the indicators that correlate best with the *U. S. News* ranking. Table 5 presents the results of the correlation analysis in terms of the correlation coefficient (R) for each indicator. This coefficient was calculated as the covariance of the two data sets (the indicator and the ranking) divided by the product of their standard deviations. A negative correlation in Table 5 simply indicates that an increase in that particular quantity was accompanied by an improvement in the ranking.

The quantities in Table 5 with the largest correlations (absolute value) are the annual number of publications, publications per FTF, the number of times cited, the number of NAE members, the number of citations per FTF, and the number of doctorate degrees. This strong correlation between the ranking of a chemical engineering program and its publication output and citation rate was also evident in the results of the 1995 NRC report on graduate program quality. Note that three of the four most strongly correlated quantities are extensive (system-size dependent) variables; that is, they are the absolute numbers of publications, citations, and NAE members. Note too that each of the top four indicators (number of publications, citations, NAE members, and doctorate degrees) correlates better with ranking when considered on an absolute rather than a relative (per FTF) basis.

Table 5 shows that the *U.S. News* rankings do not correlate as strongly with research expenditures as with the other indicators itemized above. The data from the ASEE show the strongest correlation, but keep in mind that this data set is missing entries for three departments. The NSF database included expenditures for all twenty schools, and these data show a poorer correlation with ranking. That there is a modest correlation between total research expenditures and ranking is evident, however, in that eight of the departments in the top ten in expenditures in 2000 (NSF) were in the *U.S. News* top twenty. That the correlation is not strong is evident in that only two of the next ten in total research expenditures were in the *U.S. News* top twenty. The schools with large research expenditures (according to the NSF survey) that were not among the top 20 in the *U.S. News* ranking were NC State (2^{nd} in total expenditures), Case Western (10^{th}), Auburn (11^{th}), Oklahoma (12^{th}), Utah (13^{th}), Johns Hopkins (14^{th}), South Carolina (15^{th}), Florida (18^{th}), New Mexico Institute of Mining & Technology (19^{th}), and New Mexico State (20^{th}).

One must keep in mind that the correlation analysis simply shows where correlations exist. It provides no direct information about causative effects. One might be tempted to conclude, for example, that a department that wants to improve its ranking should work hard at getting more NAE members on its faculty. Such an action might succeed, but the logic leading to that conclusion is faulty in that it is not supported by the mere existence of a correlation. It is possible, for example, that the correlation between a department's ranking and the number of NAE members on its faculty exists because it is easier for faculty at a top-ranked department to become NAE members. That is, the high-ranking of the department (or variables causing that high ranking) could be a partial cause of the high number of NAE members, not the result of it.

Finally, it is worth noting that the correlations found herein to exist between ranking and some indicators of productivity and quality for the twenty departments ranked by *U.S. News*

TABLE 4
Top Ten[1] Departments in Different Intensive Productivity or Quality Indicators

	Publications[1]	*Citations[1]*	*Pubs w/>50 cites[2]*	*NAE Members*	*Doctorate Degrees*
1	Wisconsin	UCSB	UCSB	Caltech	Minnesota
2	Stanford	MIT	Michigan	UCSB	MIT
3	Berkeley	Stanford	MIT	MIT	Wisconsin
4	Michigan	Berkeley	Pennsylvania	Pennsylvania	Delaware
5	Texas	Princeton	Stanford	Minnesota	Texas
6	Minnesota	Michigan	Delaware	Princeton	Texas A&M
7	Illinois	Wisconsin	Minnesota	Berkeley	Pennsylvania
8	CMU	Minnesota	Wisconsin	CMU	Berkeley
9	Delaware	Pennsylvania	Princeton	Texas	Illinois
10	Pennsylvania	Texas	Berkeley	Wisconsin	CMU

[1] Of the 20 ranked by *U.S. News*
[2] Excluding Caltech because of lack of data

likely become weaker as one includes more departments in the analysis. Previous analysis[5] showed that the correlation between reputational rankings and objective indicators is much weaker for departments that are not highly ranked.

CONCLUDING REMARKS

This article provides objective indicators of the productivity and quality for the twenty chemical engineering departments ranked most highly by *U.S. News.* The indicators that correlated most strongly with the rankings were the number of publications, citations, NAE members, and doctorate degrees. For each of these four indicators, the extensive quantity was more strongly correlated with the ranking than was the intensive quantity. This result suggests that departments with more faculty members tend to be more highly ranked than departments with fewer, but equally excellent, faculty members.

TABLE 5
Correlation of *U.S. News* Ranking with Different Indicators

Indicator	*Correlation Coefficient*
Number of Publications[2]	-0.819
Publications per FTF[2]	-0.718
Number of Times Cited[2]	-0.675
NAE Members	-0.602
Citations per FTF[2]	-0.572
Doctorate Degrees	-0.525
Doctorate Degrees per FTF	-0.518
NAE Members per FTF	-0.511
Total Research Expenditures[1]	-0.489
AIChE Institute Awards	-0.402
Federal Research Expenditures[3]	-0.354
Total Research Expenditures per FTF[1]	-0.333
Master Degrees	-0.302
AIChE Institute Awards per FTF	-0.285
Papers with >50 citations[2]	-0.285
Citations per paper[2]	-0.278
Full-Time Tenured/Tenure Track Faculty (FTF)	-0.273
Federal Research Expenditures per FTF[3]	-0.242
Total Research Expenditures[3]	-0.207
Master Degrees per FTF	-0.109
Total Research Expenditures per FTF[3]	-0.077
Bachelor Degrees	0.034
BS Degrees per FTF	0.244

[1] *Excluding schools for which no expenditure data were reported, ASEE*
[2] *Excluding Caltech*
[3] *NSF report*

There have been calls[4,5] for departmental rankings to use objective criteria that indicate excellence rather than relying solely on reputation. Rankings based solely on peer assessment surveys are akin to preseason college football polls that are good at identifying teams that have a history of sustained excellence, but which typically undervalue teams that are on the rise and overvalue teams that are declining. At the end of the season, though, those polled can use statistical data and won/loss records to assess the excellence of the teams. These year-end rankings, whether exclusively from a poll or from a combination of poll results and objective data (*e.g.,* the Bowl-Championship Series, or BCS, formula) provide a reasonable sorting of the different teams by their likely ability to win football games. Likewise, rankings of engineering programs could be improved by including some quantitative measures of objective indicators of productivity or quality. Survey respondents could use these indicators, along with their subjective judgment, to assess different programs (as in a coaches' or writers' poll in college football). Alternatively, these indicators could be used in some formula, along with survey results, to determine rankings (as in the BCS formula). That the ranking systems in college football make better use of objective indicators of excellence than the ranking systems used for chemical engineering graduate programs is revealing.

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