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Benchmarking the integration of complex systems study in mechanical engineering programs in the southeastern United States

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Abstract Complex systems study, defined as an understanding of interrelationships between engineered, technical, and non-technical (e.g., social or environmental) systems, has been identified as a critical component of undergraduate engineering education. This paper assesses the extent to which complex systems study has been integrated into undergraduate mechanical engineering programs in the southeastern United States. Engineering administrators and faculty were surveyed and university websites associated with engineering education were examined. The results suggest engineering administrators and faculty believe that undergraduate engineering education remains focused on traditional engineering topics. However, the review of university websites indicates a significant level of activity in complex systems study integration at the university level, although less so at college and department levels.

Keywords complex systems; educational development; undergraduate engineering students

Introduction

The immediate past president of the National Academy of Engineering in the US, William Wulf, has observed that engineers are increasingly required to solve problems that involve complex physical, biological, and social systems. He lamented, however, that 'Many of the students who make it to graduation enter the workforce ill-equipped for the complex interactions, across many disciplines, of real-world engineered systems' [1]. In response to concerns such as those expressed by Wulf, this paper examines the extent to which today's undergraduate engineering programs are preparing tomorrow's engineers to successfully encounter, engage with, and interrelate complex systems in their professional lives.

In the context of this paper, complex systems study is defined as an awareness and understanding of the interrelationships of engineered systems with technical and non-technical (i.e., economic, social/cultural, environmental, ethical and global) systems, even when these systems cannot be broken down into solvable, simple equations. Thus, complex systems study is the study of a holistic system and its interactions with other systems [2], and it is laying the foundation for all sciences to move beyond reductionism into holism [3]. In the realm of engineering, complex systems study requires the engineer to consider not only the technical aspects of a system, but also the social, environmental, economic, ethical, and global aspects. Characteristics that embody a complex systems thinker include the ability to see the larger picture, the ability to synthesize (as well as analyze), a strong macro-ethic (defined as an overarching ethical framework for understanding the intersection between human engineered systems and earth systems [4]), creativity and flexibility in thought, a strong business sense (at a local and global scale), the ability to empathize with other people, good communication skills (formal and informal), good meta-cognitive skills (the ability to self-assess) and an aptitude for lifelong learning. Although the term 'complex systems study' is not typically used in the realm of engineering education, it encompasses many of the concerns that have been discussed throughout the history of engineering schools.

During most of the twentieth century, stakeholders from the engineering community have noted a disjuncture between engineering education and engineering practice. The knowledge, skills and abilities students learned in their undergraduate engineering curricula aligned poorly with those needed by practicing engineers. For example, as early as 1918, the Carnegie Foundation reported industry's concern regarding the state of engineering education [5]: 'The professional criticisms of the [engineering] schools indicate that this field offers the greatest opportunity for effective changes in current practice, because lack of good English, of business sense, and of understanding of men, are most frequently mentioned by practicing engineers as points of weakness in the graduates of the schools'. The 'points of weakness' identified in the Carnegie Foundation report closely align with the characteristics of a complex systems thinker.

Engineering education has changed during the last century to match evolving technologies and priorities. For example, after World War II, the focus of engineering education in the United States rapidly moved from developing practical skills, such as drafting and surveying, to developing the analytical skills underlying the study of the engineering sciences, such as statics, dynamics, circuits, calculus, and physical sciences [6]. While this shift was widely endorsed, some expressed caution; for example, the 1956 Grinter report warned: 'Engineering educators must never lose sight of the broad issues with which large engineering problems are always associated' [7].

By the late twentieth century, Evans and his colleagues' survey of engineering employers and engineering alumni [8] found 'both the industry group and the alumni rated communication skills, professionalism and ethics, and a responsible and open mind, above both depth and breadth of technical skills, and math and science skills. This is indicative of the mounting evidence that employers, especially those that are joining or that have joined the quality revolution, are desperate for people who do not have to learn on the job how to fit into a team-centered culture where communication, interpersonal skills, and professionalism, are as important as technical skills.' After almost three-quarters of a century, concerns raised by the Carnegie Foundation study are mirrored in these survey results, pointing to the continued need to integrate complex systems study into the educational development of engineers.

As noted above and echoing the same concerns, the immediate past president of the National Academy of Engineering, William Wulf, recently stated: ‘Today’s student engineers not only need to acquire the skills of their predecessors but many more, and in broader areas. As the world becomes more complex, engineers must appreciate more than ever the human dimensions of technology, have a grasp of the panoply of global issues, be sensitive to cultural diversity, and know how to communicate effectively. In short, they must be far more versatile than the traditional stereotype of the asocial geek’ [1].

In response to these ongoing concerns, the National Academy of Engineering established the Engineer of 2020 Project [9, 10], an effort that encourages collaborative, multidisciplinary teams of experts to address the increasing complexity and scale of systems-based engineering problems. Team members must have the following attributes: ‘Excellence in communication (with technical and public audiences), an ability to communicate using technology, and an understanding of the complexities associated with a global market and social context’ [10], all attributes of a complex systems thinker.

Meanwhile, leaders from the American Society of Mechanical Engineers, the American Society of Civil Engineers, the American Institute of Chemical Engineers, and the Institute of Electrical and Electronic Engineers have also addressed the need for engineers to solve problems involving complex physical, biological, and social systems [11–14]. For example, the American Society of Mechanical Engineers now promotes a ‘shared vision of the future of mechanical engineering education in the context of new and rapidly emerging technologies and disciplines, national and global trends, societal challenges for the twenty-first century, and associated opportunities for the profession’ [11].

In 2001, the US Accreditation Board for Engineering and Technology (ABET) began holding engineering schools accountable for more than just teaching the required subjects; engineering schools are also now accountable for what students are learning [15]. ABET requires that graduates meet a specific set of outcomes (knowledge, skills, and attitudes) in addition to outcomes that address the individual program’s educational objectives. ABET Engineering Criteria require [12, 15] that graduates of accredited programs possess:

(1) an ability to apply knowledge of mathematics, science, and engineering;
(2) an ability to design and conduct experiments, as well as to analyze and interpret data;
(3) an ability to design a system, component, or process to meet desired needs;
(4) an ability to function on multidisciplinary teams;
(5) an ability to identify, formulate, and solve engineering problems;
(6) an understanding of the broad education necessary to understand the impact of engineering solutions in a global/societal context;
(7) a recognition of the need for and an ability to engage in lifelong learning;

(8) a knowledge of contemporary issues;
(9) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

These accountability-based outcomes align with the characteristics described in the 1918 Carnegie Foundation report [5], those in the Engineer of 2020 project [9], and those of a complex systems thinker.

Thus, engineering experts appear to agree that engineering students should be prepared to analyze problems, design under varying non-technical constraints (e.g., social or environmental), communicate with people outside of their specific discipline, and remain lifelong learners in a rapidly changing world. In other words, engineering experts appear to concur that engineering students need to be educated as complex systems thinkers. To what extent are undergraduate engineering programs engaging their students in the study of complex systems?

The present paper addresses the extent to which undergraduate engineering education engages students in the study of complex systems by investigating two sources: survey reports from engineering administrators; and institutions' electronic presentations of engineering education. The two research questions are therefore as follows:

(1) According to engineering administrators, to what extent do undergraduate engineering programs engage their students in the study of complex systems?
(2) According to electronic representations of engineering education, to what extent do undergraduate engineering programs engage their students in the study of complex systems?

Research design

Engineering deans and department chairs of targeted universities were asked to respond to an online survey to assess the extent to which they reported their students were engaged in the study of complex systems. Websites of targeted universities were next examined and systematically reviewed on both a basic and an advanced level. On a basic level, websites were systematically reviewed for pre-identified terms and phrases marking the presence of complex systems thinking. On an advanced level, websites were qualitatively assessed at four instructional levels for evidence marking the presence of complex systems thinking.

Sample

The research sample included all colleges and universities in the southeast region of the American Society for Engineering Education (ASEE) that: responded to the ASEE 2002 Engineering and Engineering Technology College Profiles in the southeastern region; and offer an ABET-accredited bachelor's degree in mechanical engineering. Forty-three institutions in the southeastern United States met these criteria.

Survey

The authors developed an online survey to determine the extent to which engineering administrators – those at the level of dean of an engineering college or chair of a mechanical engineering department – believed that complex systems study was being incorporated into their undergraduate mechanical engineering curriculum. The initial e-mail to the deans and chairs, which included a link to the online survey, yielded 29 responses. A second e-mail sent three weeks later yielded 11 additional responses. The authors received 14 responses from engineering deans, 20 from mechanical engineering chairs, and 6 from mechanical engineering faculty (a total of 40 respondents). Survey respondents represented universities distributed throughout the southeastern United States. One survey question asked 'Which college do you represent?' Of the 40 respondents, 23 answered by giving the name of their university, while the other 17 answered 'Engineering' or 'College of Engineering'. Nineteen of these respondents were from different universities.

Website analysis

All 43 institutions (see above) had websites that could be examined in the manner described below.

Methods

Survey

The authors developed an online survey to determine the extent to which engineering administrators (as defined above) believed that complex systems study was being incorporated into their undergraduate mechanical engineering programs. Survey questions were developed cooperatively by the authors. Survey questions collected data to determine respondents' demographic attributes, the extent to which they believed graduates should have an awareness and understanding of complex systems, and the extent to which they believed that complex systems study was incorporated into their undergraduate engineering curricula. This survey collected quantitative data using Likert scale questions with the following response options: strongly disagree (1), disagree (2), agree (3), and strongly agree (4).

To administer the online survey, the first author e-mailed each targeted engineering dean and mechanical engineering department chair an introductory letter containing a link to the survey. Recipients were given the option either to complete the survey or to have someone complete the survey on their behalf. After completing the survey, the engineering chairs were instructed to forward the survey to faculty and students as they deemed appropriate. After three weeks, the first author e-mailed the survey sample to thank respondents for participating, and to ask for non-respondents' participation.

Survey data were analyzed by calculating the mean of each question for all of the respondents and for each subset of respondents (dean, chair, faculty, and students). Question means at or above a 3 on the Likert scale or at or below a 2 on the Likert scale were considered significant.

Website analysis

To collect institutional website data, authors mimicked the information-gathering technique most familiar to today's high school students (who are also potential future undergraduate engineering students): they surfed institutional websites. The hypothetical potential engineering student envisioned by the authors for this study is a high school senior residing in the southeastern United States in search of a mechanical engineering program stressing the study of complex systems. All website-based information used for this study was collected in November and December 2003.

The extent of incorporation of complex systems study in southeastern mechanical undergraduate engineering programs was systematically assessed using website searches at both a basic and at an advanced level. At a basic level, authors attempted to capture a broad overview of each institution's educational culture. For each institution in the sample, website search engines were used to identify the occurrence and frequency of three fundamental terms thought to most closely represent complex systems study: 'complexity', 'complex systems', and 'emergent properties'. The university's website search engine, the engineering college search engine, the mechanical engineering department search engine, and the mechanical engineering undergraduate curriculum were each examined. The occurrence and frequency of the three fundamental terms were tallied and recorded for each search engine.

At an advanced level, the authors conducted a systematic analysis to provide a more thorough assessment of the extent to which the university, college, department, and curricula included the concepts of complexity. Each of these four instructional levels on the institution's website was reviewed according to the procedures detailed below. For clarification, an example of the incorporation of complex systems study at each level is provided.

- Access university website and review, when available, the vision or mission statement and president's welcome message. Search for terms and phrases indicating that the concepts of complexity are being integrated into the educational experience. *Example:* 'Undergraduate education is designed to promote the growth of the individual to think critically and analytically, to communicate effectively, to acquire information and apply it to problem-solving, and to understand the context of global complexity and diversity in which knowledge is applied' (from a university mission statement).
- Access college of engineering website and review, when available, the vision or mission statement and dean's welcome message. Search for terms and phrases indicating that the concepts of complexity are being integrated into the educational experience. *Example:* 'To aid students to develop an understanding and a sensitivity for social, political, economic, and environmental implications of technological systems in the real world' (from a college goal statement).
- Access department of mechanical engineering website and review, when available, department's educational objectives, educational outcomes, and chair's welcome message. Search for terms and phrases that indicate that the concepts of complexity are being woven into the educational experience. *Example:* 'Furthermore, to be a responsible member of the engineering profession, each grad-

uate must be aware of social, ethical, environmental and economic factors and constraints on engineering activity, and must understand the importance of these matters in a global context' (from a department chair's statement).

- Access mechanical engineering curricula and descriptions of courses. Search for courses with complexity content, that is, courses addressing the intersection of technical and non-technical issues including, but not limited to, environmental, political, economic, social, regulatory, and corporate factors. *Example:* 'The Complexity in the Socio-Technological Problems' (title of a mechanical undergraduate engineering course).

Results

(1) According to engineering administrators, to what extent do undergraduate engineering programs engage their students in the study of complex systems?

Survey response frequency distributions were reviewed to answer this question. The response distribution on the survey question stem 'Our students receive a fundamental grounding in . . .' indicated respondents believe there is a strong emphasis on traditional engineering topics, such as engineering sciences, humanities, social sciences, mathematics, and physical sciences (Fig. 1). Response patterns further indicated that students do not receive a fundamental grounding in the life sciences, which are considered to be a broader engineering topic.

The response distribution on the survey question stem 'Our students have an awareness of the interrelationship of engineering with . . .' indicated respondents

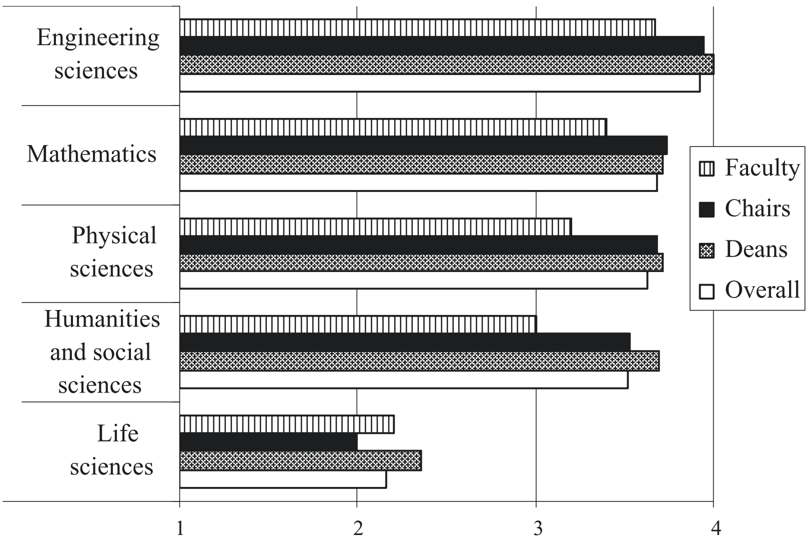

Fig. 1 *Survey results of the question stem 'Our students receive a fundamental grounding in:' . . . 1, strongly disagree; 2, disagree; 3, agree; 4, strongly agree.*

believe students have an awareness of the interrelationship of engineering with the economy, the environment, and ethics, but lack an awareness of the interrelationship of engineering with societal areas, such as esthetics, culture, law, politics, and social norms (Fig. 2).

The response distribution on the survey question stem 'Curriculum presents a focus on "emerging" or "evolving" disciplines such as . . .' indicated respondents believe the curriculum maintains a focus limited to traditional engineering topics, to the exclusion of broader topics (Fig. 3). Traditional engineering topics include advanced manufacturing, engineering ethics, and information technology, while broader topics include advanced/ intelligent materials, bioelectrics, bioengineering, critical infrastructure, earth systems engineering, financial systems, hazard engineering, health systems, micro-electro-mechanical systems (MEMS), nanotechnology, and transportation systems.

The response distribution on the survey question stem 'It is important that our students have the ability to . . .' indicated respondents believe it is important that undergraduate students have the ability to analyze and synthesize complex systems, apply knowledge, communicate effectively, engage in lifelong learning, solve complex and open-ended problems, think critically, tolerate uncertainty, and work

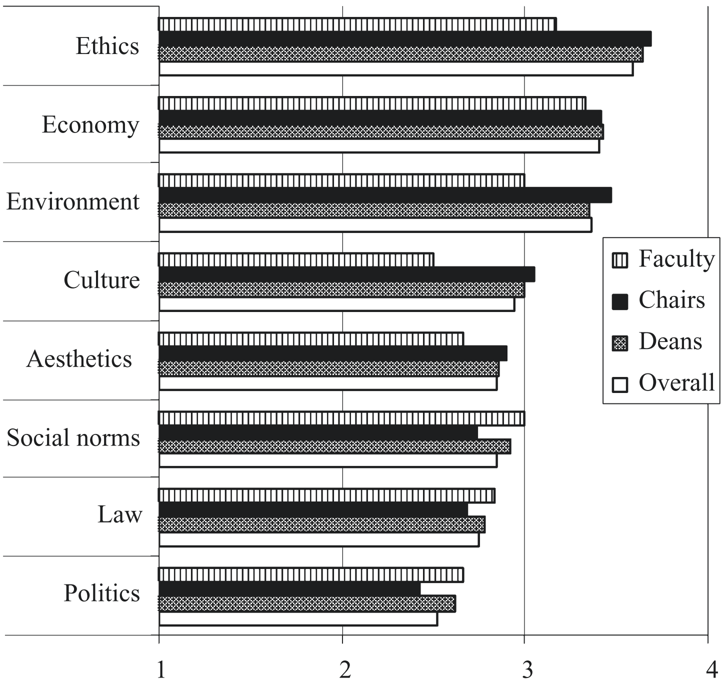

Fig. 2 *Survey results of the question stem 'Our students have an awareness of the interrelationship of engineering with:' . . . 1, strongly disagree; 2, disagree; 3, agree; 4, strongly agree.*

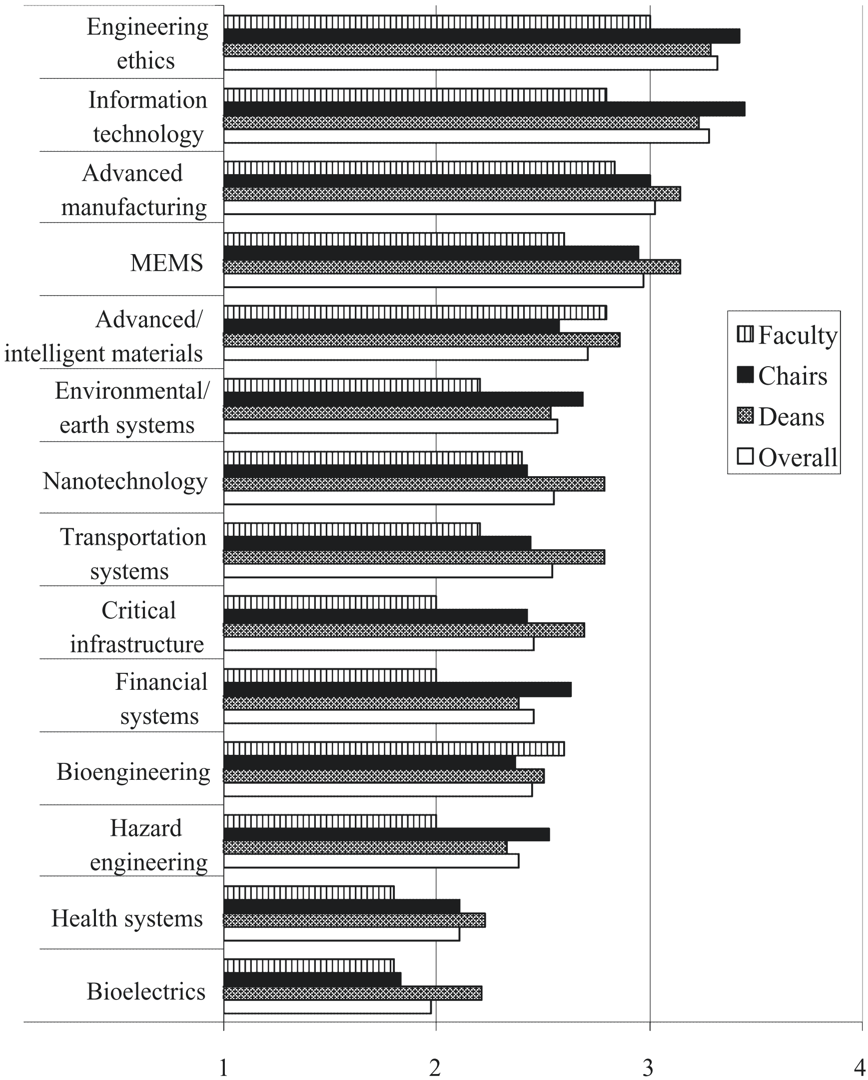

Fig. 3 *Survey results of question stem 'Curriculum presents a focus on "emerging" or "evolving" lines such as:' . . . 1, strongly disagree; 2, disagree; 3, agree; 4, strongly agree.*

in multicultural and multidisciplinary teams (Fig. 4). This suggests that the deans and chairs believe it is important to incorporate complex systems into the undergraduate's engineering curriculum.

Responses to the survey question series 'In your capstone/comprehensive design experience, are the students exposed to: critical thinking, experiential thinking, "real world" experience, and teaming' indicated that the chairs and deans believe that the capstone engineering experience provides students with an understanding of complex

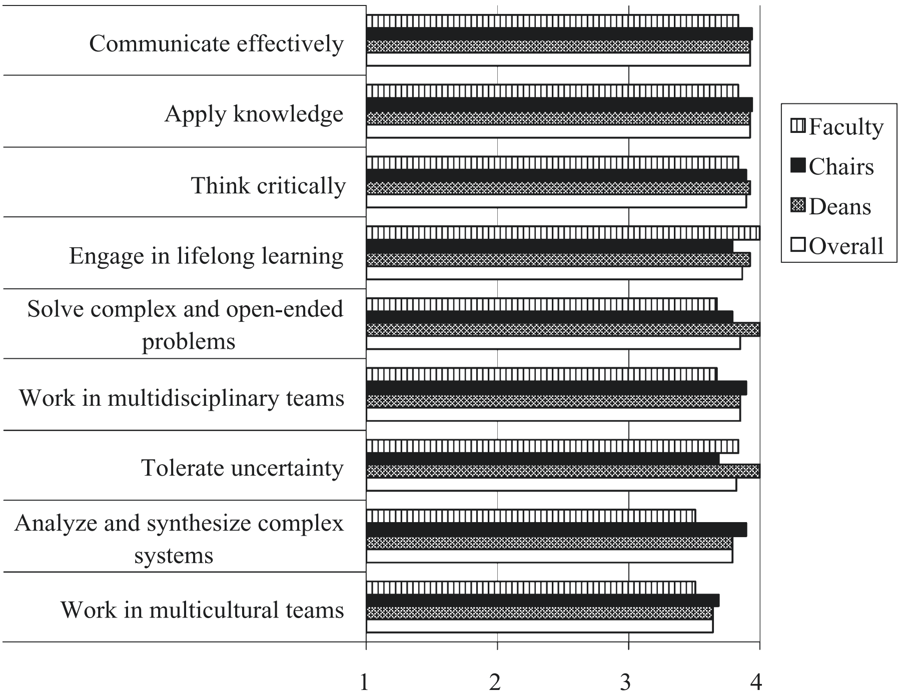

Fig. 4 *Survey results of question stem 'It is important that our students have the ability to:' . . . 1, strongly disagree; 2, disagree; 3, agree; 4, strongly agree.*

systems. An overwhelming majority (94.4%) of the responses were 'yes' for the four questions in this section.

(2) According to electronic representations of engineering education, to what extent do undergraduate engineering programs engage their students in the study of complex systems?

At the basic level, the searches for the words or phrases 'complexity', 'complex systems', and 'emergent properties' were conducted using the university search engines and, where applicable, using the college- and department-level search engines. The right-hand side of Fig. 5 presents a graph of the frequency of these terms for each institution's search engine queried. In this graph, combined frequencies of the terms 'complexity', 'complex systems', and 'emergent properties' at the university, college, and department levels are represented by bars and grouped by institution using the institution's identification number (1–43). Note that frequencies are displayed using a log scale. If a bar is absent, it was not possible to conduct a search at that level, or the search results yielded a zero or one. Three universities returned search results of zero or one for the college-level search. These universities, numbers 16, 28, and 36, have asterisks placed in lieu of bars due to the limitations

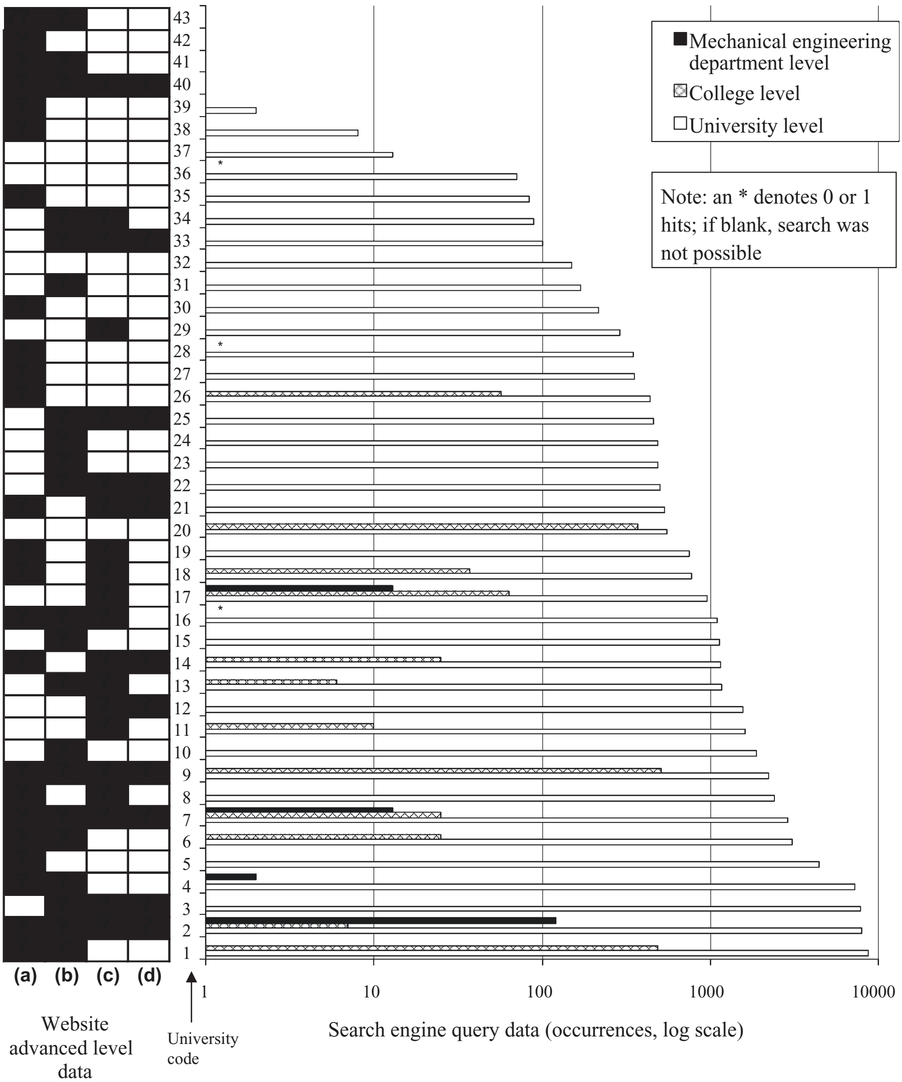

Fig. 5 *Internet query results. Left – Advanced-level data collected from systematic review of websites: shaded rectangle denotes that concepts of complexity are addressed; columns denote (a) university search, (b) college level, (c) department level, (d) curriculum level. Right – Basic-level data collected from systematic review of websites: combined frequencies of the terms 'complexity', 'complex systems', and 'emergent properties' at the university, college, and department levels.*

of presenting the data using a log scale. It was not possible to conduct a search for the remaining universities that have no bar and no asterisk in Fig. 5.

At the advanced level, a systematic review of the websites of the selected southeastern universities was conducted to collect a more thorough set of data. These results are presented on the left side of Fig. 5. At each targeted institution, the university website, the college of engineering website, the department of mechanical engineering website, and descriptions of department of mechanical engineering curricula were examined for terms and concepts representative of the concepts of complexity. In Fig. 5, a black shaded box denotes that concepts of complexity were addressed. An unshaded box denotes that there was no mention of complexity.

A university was identified as supporting the integration of complex systems if the concepts of complexity were present in the university's vision statement, mission statement, and/or president's welcome message. At the university level, 24 of 43 universities (56%) were identified as supporting the integration of complex systems study. A college was identified as supporting the integration of complex systems study into undergraduate engineering education if the concepts of complexity were present in its vision statement, mission statement, or dean's welcome message. At the college of engineering level, 21 of 43 engineering colleges (49%) were identified as supporting the integration of complex systems study. A mechanical engineering department was identified as supporting the integration of complex systems study if the concepts of complexity were present in the department's educational objectives, educational outcomes, or chair's welcome message. At the department level, 20 of 43 departments (47%) displayed online material indicating they supported the integration of complex systems study into undergraduate engineering education. The authors believe, however, that the most accurate measure of the extent to which engineering educators are integrating complex systems study into undergraduate engineering education is in its inclusion in course curricula. In this study, of the 43 institutional websites reviewed, only 11 (26%) displayed curricula and course descriptions incorporating complexity.

Discussion

This study examined the extent to which today's undergraduate engineering programs are preparing tomorrow's engineers to successfully encounter, engage, and interrelate complex systems in their professional lives. The results of this study suggest that, from an engineering administrator and faculty perspective, the focus of undergraduate engineering education remains tied to traditional engineering topics. Only a modest amount of complex systems study is integrated into mechanical undergraduate engineering educational programs, and this is limited to areas where engineering education overlaps with non-technical areas, such as the economy, the environment, and ethics. Typically excluded from engineering education is an understanding of how engineering interacts with areas such as esthetics, culture, law, politics, and social norms.

From a review of electronic representations of engineering education, there has been significant integration of complex systems study at the university level, but less activity is evident at the college and department levels. A concurrent view of search engine and website review data indicates that interest in complexity integration at the university level does not guarantee interest at the college and department levels. It should be noted, however, that the absence of search engine capabilities for college and department levels may lessen the reliability of these indicators of the actual implementation of complexity as found from website review.

A possible explanation for the study findings is that departmental and course structures discourage students from understanding interrelationships between engineering and other disciplines. Although accounting for the separation between engineering and other disciplines is beyond the scope of this study, an anecdotal observation from a mechanical engineering department chair may offer insight. When asked why engineering students fail to make connections between their liberal arts and engineering courses, this chairperson responded: 'That doesn't surprise me, because as engineers we [engineering educators] make them [students] think in a different way, and they end up thinking that way, because we are more numbers-based people . . . sometimes we'll show numbers that don't make sense, but we are happy to see the numbers, which again is a deficiency for us' [15].

Implications for engineering education

These research results have implications for the southeastern region of the United States and beyond. Study findings suggest that while the integration of complex systems study into undergraduate engineering students' education is important to leaders in the engineering field, it is only being partially incorporated into current engineering students' education. This has several important implications:

(1) the continued production of engineers who are not fully qualified to meet the demands of a more globally involved workplace,
(2) which in turn implies that current problems requiring an understanding of how engineering intersects other disciplines will not be addressed,
(3) which further implies that more problems will arise, problems that future engineers may not be able to address.

These results suggest that traditional engineering methods (departmental structures, course structures, course content, and teaching methods) are not currently preparing engineers to address the interconnections between technical and non-technical (i.e., global, environmental, and social) domains [16]. The question then becomes one of how engineering education programs could or should transform themselves so their graduates have both technical expertise and an understanding of how that expertise can be best used in a complex systems world.

Conclusion

The authors would like to suggest that a true measure of the extent to which engineering educators have embraced complex systems study is its inclusion in curricula and courses. Although few mechanical engineering programs currently meet this measure, the widespread interest in complexity demonstrated in the sample supports the creation of synergistic partnerships to embrace and implement complex systems study into the curriculum.

A recommendation to prospective students who have an interest in exploring complexity would be to use all means available to gather information about educational opportunities available in various departments, colleges, and universities. For example, website searches and website reviews should be augmented by personal contact by both telephone and campus visits.

Progress toward achieving the educational development of engineering graduates with a holistic understanding of engineering, and how engineering influences and is influenced by the world around it, not only may attract people to the engineering profession, but may also help retain the students who are already interested in engineering. The attributes of an engineer who embraces the concepts of complex systems are described in the closing paragraph of the *Engineer of 2020: Visions of Engineering in the New Century* [9]. 'What attributes will the engineer of 2020 have? He or she will aspire to have the ingenuity of Lillian Gilbreth, the problem-solving capabilities of Gordon Moore, the scientific insight of Albert Einstein, the creativity of Pablo Picasso, the determination of the Wright brothers, the leadership abilities of Bill Gates, the conscience of Eleanor Roosevelt, the vision of Martin Luther King, and the curiosity and wonder of our grandchildren.'

Acknowledgments

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