Incorporating Design Into Undergraduate Biomedical Engineering Curriculum

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Abstract

With the growth of biomedical engineering undergraduate programs in recent years, more universities are striving to impart comprehensive education in the undergraduate curriculum while satisfying the criteria to gain accreditation through the Accreditation Board of Engineering and Technology (ABET), which is the current gold standard. The capstone senior design project is usually a culmination of the undergraduate experience and clearly brings to bear all the skills imparted to the students in the core curriculum to that point. This makes the senior capstone project a yardstick for accreditation as well. However, there is still much variability between schools and their structure and requirements for senior design courses. The total design curriculum can vary in number of semesters, credit hours, prerequisites, group requirements, funding sources, project options and focus, and mentorship opportunities. There is also a growing emphasis on the translation of some senior design projects into healthcare technology, resulting in the need to incorporate increasing entrepreneurial training into the engineering classrooms. With a healthy number of accredited programs, it is essential to consider the similarities and differences within each design course, highlighting advantages and learning lessons from past results in order to suggest successful approaches for future programs which are seeking accreditation.

Introduction

The U.S. Bureau of Labor Statistics (BLS) lists that Biomedical Engineering (BME) jobs have a projected growth of 27% during the years 2012 to 2022; which is more than double the average 11% job growth rate projected for all occupations [2]. The expected growth is linked to the burgeoning aging population and the potential benefits that BME solutions can provide for them to improve quality of life and healthcare [2]. There has been a sustained increase in BME enrollment and the number of BME programs with the increased demand for biomedical engineers. It is necessary that there be homogeneity or a common minimum skill set amongst the ever increasing undergraduate engineers that the schools are producing. This standardization is driven, in part, by the need for employers to have a general basis for the core knowledge that BME graduates will have compared to graduates from other programs. With biomedical engineering being a relatively new field (the first programs were established in the 1950s and 1960s primarily at the graduate level), there has been a distinct need to establish the unique identity for BME graduates to ensure that industry has a better understanding of the roles they can be hired into [3]. This also gives
prospective students confidence that they are getting a comparable education to not only other BME, but also to other engineering programs.

The main solution to increasing a level of normality among programs in the same field is for those programs to go through an accreditation process. For engineering programs, the leader in the accreditation field is the Accreditation Board for Engineering and Technology (ABET). ABET sets certain standards which must be met and maintained in order to retain the ABET accredited title. Some of these standards are general to all programs while others are specific to particular streams of engineering. Even when the standards given by ABET are met, there is still much variability in how they are achieved between programs. The range of differences can be quite broad. As such, the current study’s focus will be on differences within the senior design courses (and capstone project) because they show the accumulation and depth of the knowledge gained throughout the entire degree program through the development of solutions towards real world problems[4]. These courses allow schools to equip students for the post-graduation workforce life. The designing of such capstone courses requires much forethought and research by the professor because the projects typically require sponsorship, funding and additional training in product design sequences and business management. This final sequence of courses must test, show, and increase each student’s abilities.

It is suggested that standardization of more BME programs through a medium such as ABET will provide a better defined role for the BME graduate seeking employment. However, it is necessary to consider the variability that is seen within such standardization systems. This consideration will allow perspective for schools desiring accreditation as well as insight to future students and employers. As such, the following sections will briefly cover the guidelines provided by ABET for undergraduate Bioengineering and BME programs, highlight the main differences in capstone courses of currently ABET accredited programs, and offer suggestions for BME programs and design courses based on the differences.

Accreditation Board for Engineering and Technology (ABET)

ABET is a globally recognized organization with 34 societies as members [5]. Currently, it accredits over 3,400 programs at nearly 700 schools in 28 countries [5]. There are two phases in ABET accreditation—the assessment process and the 18-month accreditation process. Furthermore, a comprehensive re-evaluation is required at least every six years and non-comprehensive evaluations may be done in-between depending on the need. Extensive information regarding ABET accreditation can be found on their website (abet.org). As such, the following paragraphs are only meant to provide an outlook on BME accreditation and the background ABET eligibility requirements and criteria that have an impact on senior design courses.

Bioengineering and Biomedical Engineering

According to the National Center for Education Statistics (NCES), there are 126 colleges that offer a bachelor’s degree in Bioengineering and BME [6]. Of these 126 colleges, 89 are accredited by ABET [7]. Two more colleges, University of Hartford and University of Maryland College Park, are also accredited by ABET and have bachelor programs for Biomedical Engineering and Bioengineering respectively; however, they did not come up on the NCES search
criteria. This means that roughly 71% (91/128) of bioengineering and BME programs in the United States are ABET accredited. Using the same organizations and process, it was determined that 95% (161/170) of Chemical Engineering, 91% (313/344) of Electrical and Electronics Engineering, 97% (239/247) of Civil Engineering, and over 96% (305/317) of Mechanical Engineering undergraduate programs in the United States are ABET accredited [6, 7]. The difference in percentiles of accredited schools may be mostly due to the fact that BME is a relatively new field compared to the other, more established programs. As can be seen in Fig. 1, the number of ABET accredited Bioengineering and BME programs has continued to increase throughout the last 41 years. However, the percentage of ABET accredited Bioengineering and BME programs is still well below other engineering streams.

![Figure 1: ABET Accredited Schools](chart)

Figure 1: ABET Accredited Schools. This figure shows the increase in number of Bioengineering and BME programs accredited by the ABET’s Engineering Accreditation Commission (EAC) over a 41 year range from 1972 to 2013. Information to make the chart was retrieved from individual school accreditation information provided on the ABET website [7].

Eligibility Requirements

In order for a program to consider applying for ABET accreditation, it must meet the following criteria: (1) the program must fit ABET’s program definition, (2) it must be under a degree-granting institution, (3) it must have at least one graduate, (4) the program name must describe the content of the program and be the same as listed on diplomas, and (5) the program must fit under at least one ABET accreditation commission. The four accreditation commissions are Applied Science Accreditation Commission (ASAC), Computing Accreditation Commission (CAC), Engineering Accreditation Commission (EAC), and Engineering Technology Accreditation Commission (ETAC). This review focuses on Bioengineering and BME undergraduate programs reviewed by the EAC. As such, further discussion of ABET accreditation requirements will be
discussed regarding the EAC requirements and, where applicable, specifically Bioengineering and Biomedical Engineering requirements for program accreditation.

**General Criterion for Accreditation**

In order for schools to gain ABET accreditation, they must meet requirements in the following eight criteria: (i) students, (ii) program education objectives, (iii) student outcomes, (iv) continuous improvement, (v) curriculum, (vi) faculty, (vii) facilities, (viii) institutional support [1]. The student criteria are based on performance and meeting program requirements. The program education objectives must be published and fit properly with the program and its school. The student outcomes these are listed in Table 1 and discussed below. The continuous improvement criteria must have a documented process for improvement in place and carry it out. The curriculum criteria are discussed in more detail in the following paragraphs. The faculty criteria is measured based on a sufficient number and competency level. The facilities must consist of sufficient classrooms, offices, labs, and equipment to support the program. The institutional support must be sufficient to ensure quality and continuity of the program.

Schools may also add their own student outcomes in addition to the ones listed in Table 1. For implementation, it has been suggested that each student outcome is spread throughout multiple courses for both deeper learning and degree completion in fewer credit hours [8]. In order to provide students the most from this suggested strategy, schools can take a weighted effect in how they distribute the student outcomes throughout the courses. One study by Passow emphasizes the perceived differences in weight of different skills [9]. Over the course of 7 years, Passow conducted a survey of engineering graduates aimed at understanding what competencies they found most important in their post-graduation work. He found that competencies corresponding with ABET b2 (data analysis), d, e, and g were rated significantly higher than those corresponding with ABET b1 (ability to design and conduct experiments), h, and j; with the other

<table>
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<th>Table 1: Criteria iii-Student Outcomes</th>
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<td>a) An ability to apply knowledge of mathematics, science, and engineering</td>
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<td>b) An ability to design and conduct experiments, as well as to analyze and interpret data</td>
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<td>c) An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability</td>
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<td>d) An ability to function on multidisciplinary teams</td>
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<td>e) An ability to identify, formulate, and solve engineering problems</td>
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<td>f) An understanding of professional and ethical responsibility</td>
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<td>g) An ability to communicate effectively</td>
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<td>h) The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context</td>
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<td>i) A recognition of the need for, and an ability to engage in life-long learning</td>
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<tr>
<td>j) A knowledge of contemporary issues</td>
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<tr>
<td>k) An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice</td>
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The Student Outcomes (Criteria iii) as listed by ABET [1].
competencies falling in a middle range [9]. Since schools are preparing students for real world jobs, it is important to emphasize the applicable skills while providing the background (core) coursework to enhance those skills.

The general curriculum (criteria v) as defined by ABET is listed in Table 2. This is the one area where ABET also lists Bioengineering and BME specific criteria. Many of these criteria are applicable to the senior design courses directly and indirectly through prerequisite coursework. Though it may be tempting to simply meet the ABET requirements, programs should set goals that exceed the standards in order to produce truly distinguished students [10]. In doing so, the programs will benefit in not only raising the likelihood of accreditation on the first visit but also from actively increasing the program’s success in recurring renewals. These increased standards would also increase the desirability of the school through the increased positive effects that would be seen in their graduates; thus benefiting the school, students, employers, ABET, and other or new programs.

Though some of these criteria may be difficult for young programs to meet initially, it is imperative that schools strive to incorporate some similar processes during the early stages by looking at other programs while incorporating the ABET criteria. Furthermore, it has been suggested that all Bioengineering and BME programs should be accredited and that more defined standards should be in place in order to avoid confusion between students and future employers because of program variation [11].

One potential speed bump in program accreditation may not lie in the ABET considerations but rather in the state rules. It is becoming more prevalent for states to limit the number of credit hours that schools can require for graduation in order to cut costs and increase completion rates [12]. Since bioengineering and BME programs combine multiple disciplines, biology and concepts from various streams of engineering, the credit hour mandate may seem impossible for programs to do. One solution to this could be to focus more on engineering rather than biology heavy degree plans. Voigt indicated that biology heavy degree plans not only hurt the student’s knowledge and development as engineers but also discourages employers from hiring students [11]. Another solution, as mentioned earlier, could be in the creative spreading of student outcomes throughout multiple courses in order to provide more per course and; thus, possibly lower the number of

<table>
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<th>Table 2: Criteria v-Curriculum</th>
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<td><strong>General Criteria</strong></td>
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<tr>
<td>1. One year (32 semester hours) of college level mathematics and basic sciences</td>
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<td>2. One and one-half years (48 semester hours) of engineering topics</td>
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<td>3. General education</td>
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<td><strong>Bioengineering and Biomedical Engineering Specific</strong></td>
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<tr>
<td>1. Applying principles of engineering, biology, human physiology, chemistry, calculus-based physics, mathematics (through differential equations) and statistics</td>
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<tr>
<td>2. Solving bio/biomedical engineering problems, including those associated with the interaction between living and non-living systems</td>
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<tr>
<td>3. Analyzing, modeling, designing, and realizing bio/biomedical engineering devices, systems, components, or processes</td>
</tr>
<tr>
<td>4. Making measurements on and interpreting data from living systems</td>
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The Curriculum Criteria (Criteria v) as listed by ABET [1].
needed courses. This might entail the development of new course curricula specifically tailored to the needs of BME undergraduates rather than simply adapting curricula traditionally in use for similar subject matter in other departments. For example, such new courses could deviate significantly from pedagogy in including transitions between classical mechanics, tissue biology and material modifications to train students in the practice of designing biomaterials. This is especially important in courses such as senior design, where the supporting coursework for biomedical engineering students may not be as rigorous in manufacturing techniques or circuit fabrication as mechanical or electrical engineering students respectively. Thus, it is essential for relevant components to be inculcated into the BME senior design curriculum that allow students to be prepared for the practice of the art.

**Senior Design Courses**

This section specifically surveys the existing senior design (capstone) course prerequisites, requirements, group sizes, and sponsor types. The information provided in this section was gathered from the ABET website and the official school and program websites of Bioengineering and BME accredited schools. The specific data that was collected included listed senior design course prerequisites, design course requirements, design team size, type of sponsors, project type and project competition/showcase. The information provided is strictly based on what was available on these websites.

**Course Prerequisites**

The prerequisites of the senior design courses vary both between universities as well as within universities which have different tracks offered. These tracks typically fall within three main focus areas: biomaterials, imaging/instrumentation, and biomechanics. Despite the differences in tracks and universities, there remain certain common trends in prerequisites. The majority of programs require senior standing in order to enroll in the design courses. However, some schools such as The George Washington University complete a portion of their design courses in the junior year of the curriculum [13]. When the prerequisites are traced back in sequence to the initial departmental courses, it inevitably leads to at least all of the core biomedical courses in most cases. To simplify the required coursework, most program websites have a handbook or diagram detailing the suggested courses for each semester in order for a student to successfully complete the program. This once again underlines the “capstone” aspect of the design exercise being the culmination of the educational curriculum leading to graduation.

**Course Requirements**

The requirements for number of courses, availability of courses, and course hours vary from program to program. For senior design courses, the majority of programs require two courses of two to four credit hours each. Of the 78 schools with available information, 72% required two semesters worth of senior design courses. However, there are programs that lie on either extreme of this standard. For example, the Milwaukee School of Engineering requires a 7 course (16 quarter hours) design sequence that begins in the spring quarter of the student’s sophomore year [14]. On the other hand, the University of Louisville requires only one course totaling 3 credits [15]. When there are only two semesters of coursework, they are often only offered once per year, during the fall and spring semesters of the student’s senior year. Only four of the programs explicitly listed that the design courses are offered multiple semesters in the same school year. The number of credit hours
per design course ranges typically from 2 to 4 semester equivalent hours. Figure 2 displays the total number of credits each school required for the senior design sequence with 39% requiring 6 credits.

![Number of Semester Equivalent Hours vs Number of Schools](image)

**Figure 2: Semester Hours in Capstone Courses.** This figure shows the number of semester equivalent hours required per school for the total sequence of their capstone course. Information for this chart was found by going to the school websites found on ABET [7]. Then, from the individual program websites, semester hours were determined from available information. This was only readily available for 70 of the 91 ABET accredited Bioengineering and Biomedical Engineering programs. For programs that use the quarter system, quarter hours were converted to semester equivalent hours at a 3:2 ratio and rounded to the nearest whole number. About 39% of the schools require 6 semester hours.

Other unique requirements for senior design courses include students having to submit resumes to decide on teams (University of Rochester) and the choice of a senior design project, entrepreneurship, or Master’s research project (University of Miami) [16, 17]. John Hopkins University offers multiple ways for students to complete the design requirements for graduation including an individual senior design project, the BME offered team design courses, and courses from other university departments[18]. One aspect that might confound these observed differences in number of hours within the design sequence is the increasing push by BME departments to include design aspects in multiple courses within their curriculum, which reduces the need for devoted or designated “design” courses.

**Group Size and Composition**

The senior design courses have students form groups ranging from 1 to 6. The groups listed are typically formed completely of biomedical engineering students. However, some universities, such as Lehigh University, have begun to combine business and other engineering (electrical, mechanical, etc) students to provide expertise and insight from other fields [19]. Hotaling et al. suggested that these multidisciplinary engineering capstone design courses produced engineering solutions that were better compared to monodisciplinary courses [20]. This does however increase evaluator burden to ascertain contribution to individual student learning in terms of the core foundational expectations of each of their home departments. When multi-disciplinary teams or
large teams are the norm within a design program, individual student learning objectives can be met by increasing individual assignments and potentially stream specific assignments along the way as a mechanism of assessment and assurance.

**Types of Sponsors**

The sponsors of senior design projects vary by program. The main sponsors include faculty within the BME program, industry partners, grants, medical schools, hospitals and combinations of these. Figure 3 below shows the data collected from the program websites with a large majority of the programs not listing sponsor type. The information may be withheld pending patents and other obligations required by the sponsors.

![Figure 3: Sponsor Types for Capstone Courses](image)

**Design Showcases and Publications**

The rise in undergraduate biomedical engineering research can be seen in conferences such as the annual BioMedical Engineering Society (BMES) meeting. BMES is the primary professional society representing all subspecialties of BME professionals and academics and provides students with an invaluable professional development opportunity [21]. Since 2010, BMES has added an undergraduate research track to the conference agenda with more than 200 participants each year [22]. In addition to such national showcases, more than half of the schools that were investigated have some form of showcase that they encourage or require their senior design students to participate in. In fact, 37% of these schools have a BME only showcase occurring at least once a year in the spring. 43% of these school programs participate in a school showcase which generally included only engineering students but some schools included all undergraduate research areas. Finally, the rest of the schools had students presenting at regional and national showcases. Some other examples of national showcases are the BMES Undergraduate Student Design Competition, the National Council of Examiners for Engineering and Surveying (NCEES) Engineering Award, BMESstart, and BMEidea. BMEidea mandates that entries be health related technology invented by
students and that these products address a real clinical need. The entries are judged on technical, economical and regulatory feasibility, contribution to human health and quality of life, technological innovation as well as potential for commercialization. The categories for product designs may include surgery, therapeutic applications, diagnostic applications, rehabilitative as assistive technologies and home healthcare [23]. BMEStart is an undergraduate student only competition by the National Collegiate Inventors and Innovators Alliance (NCIIA). Submissions must identify a clinical problem to be solved in a novel and practical manner. The team must illustrate a market potential for their proposed solution. Competing teams must demonstrate the development of a device, product, or technology designed to solve the known problem. Additionally, each submission must include a detailed description of potential intellectual property along with steps to protect it [24]. Many of the schools also encourage the undergraduate students to publish their works when applicable. Western New England University states that all of their senior design projects have been published for the past nine years [25]. These avenues serve as both motivation and a sense of accomplishment for students participating in the senior design process while ensuring that the directions of technology developed have a very real chance of solving real world clinical problems. This allows the inventive ideas of new batches of students to be best harnessed to tackle old problems in novel ways.

Summary and Conclusions

Though the majority of Bioengineering and BME undergraduate programs are ABET accredited, the actual percentage, 71%, pales in comparison to other ABET accredited engineering program types. ABET accreditation, the gold standard, is necessary for up and coming BME programs. ABET accreditation provides guidelines that are intended to produce graduates with a standardized knowledge base between different schools providing confidence to employers on what is expected from biomedical engineers. Since BME is a relatively new and upcoming field, programs should strive to go above and beyond the current ABET standards and have a system in place for continued development beyond the average. This could spur the BME field on to higher recognition and encourage stronger students.

Unfortunately, there are still many barriers to accreditation that need to be overcome by new BME programs. Of note, it may be hard for such diverse programs as BME to develop well rounded students with the required depth of knowledge when some states have new mandates limiting the number of hours within a degree. Though this can encourage uniformity amongst degree plans, it may also limit the ability for BME students to get into the full depth of the field. One solution may be to break down BME further into more specializations that schools currently have and then to offer students the ability to specialize in multiple BME areas, as is currently the case at some schools. This will provide employers with a more targeted knowledge of the graduates’ skills as well as provide the students with incentive to take more courses that the state minimum.

As programs move forward in the accreditation process, it is important to recognize the importance of the senior design courses as a display platform for the accumulation of student knowledge throughout the program. Additionally, the senior design courses provide the optimal platform to inculcate applied engineering, technical communication and exposure to regulatory guidelines for BME undergraduates. In designing a capstone design course, we suggest that it be multidisciplinary. This has the potential to increase the effectiveness of projects, the communication
skills of students as they work with colleagues with different scholastic backgrounds, and the knowledge area of students. It is likely that the senior design courses will also meet more ABET criteria and provide graduates with collaborative experience and a wider breadth of knowledge that is essential to success after graduation. On similar lines to the VaNTH project suggestions[26, 27] for the biomedical curriculum, a minimal list of expected student outcomes from the BME Capstone Design course should be developed, particularly addressing the distinctions drawn between the BME graduates and the other engineering programs. This would serve to further establish not only the identity of the BME graduates, but also further define a professional role, above and beyond being communicators who can speak the language of both biologists and engineers[27]. By working with business and other engineering students, students will be directed towards solving real world problems in groups that mimic a real life work environment. Furthermore, this incorporation has potential to increase the long term effects of the capstone projects by providing potential business avenues for the students. Finally, we suggest that students work with clients. If done correctly, this has potential to increase the real world exposure provided by the capstone project, increasing the student’s preparedness for life beyond graduation.

As a higher percentage of BME programs become accredited and strive towards the same standards, it is believed that a clearer role of the BME graduates will emerge – this might include aspects such as knowledge of medical device regulatory pathways, an understanding of how to express physiological interactions in engineering terms or experience with biocompatibility testing and sterility. Despite accreditation from the same governing body (ABET) there will still be variability between programs as shown by this paper’s overview of senior design courses. This allows the ability for students to choose programs based on uniqueness while giving employers confidence in the core knowledge base of biomedical engineers.

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