Using Benchmarking Methods to Inform Curriculum Changes in Mechanical Engineering Programs

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Abstract

Engineering curriculum development often occurs in a single course or a series of courses, for instance where new material or tools are implemented (e.g., the inclusion of CAD/CAE tools throughout design courses). However, the entire curriculum for a degree should be periodically reviewed to investigate holistic characteristics and inform broader curriculum changes. This paper seeks to use benchmarking of other institutions as an initial step to inform whole curriculum development for a Mechanical Engineering degree. This benchmarking will be used as an initial tool to investigate changes in the Mechanical Engineering curricula at The University of Pittsburgh (Pitt) and Carnegie Mellon University (CMU).

Ten institutions, including Pitt and CMU, were selected for this study, with a goal of including both public and private institutions as well as a range of department sizes. The most recent Mechanical Engineering degree requirements were compared course-by-course to quantify broad trends in numbers of credits required in various areas and also find specific differences in particular requirements. The required courses were separated into three broad areas: Math & Science, Engineering, and Other; and the number of credits in each area were tallied and compared. Engineering was further subdivided into Mechanical and non-Mechanical courses for a more detailed comparison. Finally, Engineering courses were organized into subject areas (e.g., Mechanics / Dynamics, Thermo-Fluids, Dynamic Systems & Controls, etc.) and the requirements in each area were compared to understand differences in emphases between institutions.

The broad benchmarking results show that all institutions have similar numbers of Math & Science credit requirements (30 – 36) as well as a similar number of total required credits (128 – 129). The number of Engineering credits ranges from 51 to 79, with an average of 65.4 credits. The number of specifically Mechanical Engineering credits required ranges from 45 – 67, with an average of 51.4. The remainder of the credits in Other ranged from 19 – 45, with an average of 29.6.

Outcomes from this study show that Pitt's program requires approximately 10 more Engineering credits than the average with a corresponding low number of General Education credits, and is thus a comparatively inflexible program. Additionally, Pitt requires more specific mechanical engineering courses, such as a second Thermodynamics and a second Fluid Mechanics course. CMU's curriculum falls within the middle of the range for comparable institutions in requirements and flexibility. These findings will be used by the faculty of these departments as an initial step in deciding future curriculum changes. For example, Pitt may decide to make some required courses technical electives, in line with ASME Vision 2030's suggestion for increased curricular flexibility. Likewise, CMU may decide to increase the flexibility of its curriculum even further noting that other curricula (e.g., the MIT 2A curriculum) have substantially greater flexibility. This method is transparent and adaptable by other universities as a first-step in analyzing their own curricula.

Challenges and limitations of this approach include the somewhat arbitrary separation of engineering courses into Mechanical or non-Mechanical and the difficulty of categorizing courses based on course descriptions alone. Furthermore, the selection of only a small number of institutions for benchmarking may not be representative of broader trends, and it is impossible to discern trends over time by only looking at current degree requirements.

Introduction

The curriculum in any engineering department undergoes periodic changes. Most frequently, these are incremental changes, such as adding a course or changing a course requirement. Over time, these incremental changes can build to cause unintended consequences, e.g. overly-restrictive requirements or over- or under-emphasis in specific subject areas. Thus, most curricula also undergo less frequent, wide-ranging changes, such as revamping entire course sequences, adjusting pre-requisites, and re-balancing required and elective courses. The evaluation of wide-ranging curriculum changes also provides a good opportunity to consider current and future trends, both in technical content as well as the various needs of stakeholders (students, faculty, industry). In their early history, engineering schools focused on practical technical skills for industry but later shifting the emphasis to engineering science [1]. More recently, trends have focused on increasing hands-on learning, design/build/test, and increased flexibility in curricula.

This paper focuses on using curriculum benchmarking of other engineering programs as an initial step in a larger curriculum review process, as applied to the Mechanical Engineering programs at the University of Pittsburgh (Pitt) and Carnegie Mellon University (CMU). By evaluating the number and types of courses required by other universities, as well as the amount of flexibility offered, a particular department can identify where their current curriculum may be an outlier and use this information as an initial step in considering changes to their program.

The past three decades have seen many universities re-evaluate their curricula in the face of changing student bodies and workforce needs. Some broad studies have given overall guidance on curriculum structure based on evidence gleaned from surveys of industry, academic, and student stakeholders [2-4]. Others have considered general approaches for redesigning a curriculum, including what specific triggers drive a curriculum review [5]. These curriculum redesign efforts can be top-down, wherein an entire college transforms simultaneously, or bottom up, in which change is driven by faculty within a specific department. Many literature descriptions of curricular change have reported a process that focuses on stakeholders such as students, alumni, and employers along with the above-referenced guidance documents, but does not contain a substantial benchmarking effort [1, 6-11]. Less common in the literature is the approach of benchmarking curriculum changes against a set of "competitors". One approach is shown in [12], in which other curricula are compared based on how they integrate experimental training into the program. This approach is consistent with the typical engineering design process, in that a wide range of competitive solutions are considered in developing new curriculum concepts. This paper's primary contribution is to provide a snapshot of the mechanical engineering curriculum landscape at 10 institutions as of early 2020, with the goal of providing guidance to institutions evaluating their programs. While this, of course, does not replace the need for robust stakeholder input, the authors believe the information is useful when evaluating curriculum changes, particularly in the early phases of a curriculum review process.

Methods

A total of ten schools were compared, including Pitt and CMU. The other schools were selected because they are considered competitive with Pitt and CMU. That is, they are R1 universities with highly-ranked, ABET-accredited Mechanical Engineering departments. Of the ten, seven are ranked in the Top 10 rankings for Mechanical Engineering Undergraduate programs and two within the top 50 [13]. The study included a mix of 1/3 private and 2/3 public universities. Lastly, benchmarked universities have readily-available public information on their specific degree requirements. The other eight schools in the study were Cornell University, Georgia Institute of Technology, University of Illinois at Urbana-Champaign, University of Iowa, University of Michigan, Pennsylvania State University, Purdue University, and Stanford University.

For each program, the Fall 2019 requirements for a mechanical engineering degree were found on each university's website. The required courses were first separated into three large categories that roughly follow the ABET curriculum criterion groupings [14]: Engineering courses (including Mechanical Engineering), Math & Science courses, and Other courses. Engineering courses were defined as any course offered within an engineering department, including any engineering elective course requirements. Math & Science courses were defined as chemistry, physics, and any "pure math" course that was not offered by an engineering department (e.g., calculus, differential equations, linear algebra), including any math or science electives. The Other category accounted for any other requirements: Humanities/Social Science electives, required writing courses, required economics courses, and any free electives allowed within a program. The Engineering category was further subdivided to separate specific Mechanical Engineering courses. However, some programs may offer a course (such as the first Statics/Solid Mechanics course) as a mechanical engineering course, whereas other programs offer it as a general engineering course. In those mixed cases, the course was generally placed into the Mechanical Engineering category for all programs.

The total number of credits in each category were summed and compared. This allowed a high-level comparison of which programs required more focused, technical content versus more broad content in their mechanical engineering degree. This broad comparison allowed for a comparison of program flexibility in two ways: technical-course flexibility and overall flexibility. Technical-course flexibility is identified by the proportion of total Engineering credits that are dedicated to Mechanical Engineering, where a lower proportion relates to a more flexible program. Overall flexibility is identified by the proportion of credits in the Other category compared to the total number of credits required.

Two universities used a different accounting of credits compared to the other universities, so a scaling factor was applied in order to compare the total number of credits appropriately. CMU's courses are assigned a number of units, where 3 units are approximately equivalent to 1 credit, so each course's units were divided by 3 before comparison. Stanford University operates on a trimester system, with a total number of ~180 credits required for graduation. This compared to an average of 128 credits required to graduate from the other universities. So, the course credits at Stanford were divided by 1.4 before comparison; given the tight clustering of other universities around the mean (1σ = 0.6 credits) this simple multiplicative factor seemed sufficient.

Once the courses were divided into large categories, each course was tabulated in a spreadsheet and matched against similar required courses at Pitt and CMU. This process required deeper investigation of course descriptions within each program in order to best match the courses at different universities. Some courses are common and match well across universities (e.g., Thermodynamics 1) while other courses are more difficult to match. In these cases, course descriptions were analyzed and then categorized based on the expertise and judgment of a professor of Mechanical Engineering. Ideally, syllabi with detailed course contents would be used, but these are not consistently available for access across the benchmarked universities. An example course comparison is shown in Figure 1 below, comparing a subset of the Mechanical Engineering courses at Pitt, CMU, and the University of Michigan. Horizontal rows match the comparable courses in each program.

U. of Pittsburgh		Carnegie Mellon Univ.		U. of Michigan	
Course Title	**Credits**	**Course Title**	**Credits**	**Course Title**	**Credits**
Statics & Mechanics 1	3	Statics	3.3	Solid Mechanics	4
Statics & Mechanics. 2	3	Stress Analysis / FEA	4.0		
Intro. to ME Design	3	Design 1	4.0	Design Mfg 1 / CAD	4
Materials & Manufacturing	3			Behavior of Materials	4
Intro. to Thermodynamics	3	Thermodynamics 1	3.3	Thermodynamics 1	3
Intro. to Fluid Mechanics	3	Fluid Mechanics	3.3	Fluid Mechanics 1	3
Dynamic Systems	3	Dynamic Sys. and Controls	4.0	Dynamic Sys. and Controls	4
Rigid-Body Dynamics	3	Dynamics	3.3	Dynamics and Vibrations	4
Mech. Design 1	3				
Mech.Design 2	3			Design Mfg 2 / Mach. Des.	4
Mech. Measurements 1	3	Thermal-Fluids Exper.	4.0	Laboratory 1	4
Mech. Measurements 2	3	Mechanical Systems Exper.	3.0	Laboratory 2	4
Senior Design Project	3	Capstone Design Elective	4.0	Capstone Design	4
Applied Thermodynamics	3				
Heat and Mass Transfer	3	Heat Transfer	3.3	Heat Transfer	3
Applied Fluid Mechanics	3				
Departmental Seminar	0	MechE Seminar Elective	0.7		
ME Technical Elective 1	3	MechE Tech Elective	4.0	ME Tech Elective	3
ME Technical Elective 2	3			ME Tech Elective	3
ME Technical Elective 3	3			ME Tech Elective	3
Dynamic Systems Elective	3				
		Numerical Methods	4.0		

Figure 1 – Example of course comparisons for Mechanical Engineering between three universities in the study. Note: this data set is available for use by contacting the authors.

Finally, the Engineering courses were organized into sub-disciplines (subject areas): Mechanics/Dynamics, Materials & Manufacturing, Thermo-Fluids, Dynamic Systems &

Controls, Design (including capstone courses), Experimentation, Technical Skills (such as CAD), Electronics, and Engineering Computation. This provided information on the balance of the requirements in each subject area and the balance in all areas. Also, some programs offer, say, three three-credit courses in a particular sub-discipline (e.g., Mechanics) that are comparable to two four-credit courses at another university. In these cases, analyzing the total number of credits in each subject area provides a better comparison than simply looking at a one-to-one comparison of each required course.

Results

The highest level of comparison is shown in Table 1, comparing the overall number of required credits in each program separated into the broad categories of Engineering (including Mechanical Engineering), Mechanical Engineering (a subset of total Engineering), Math & Science, and Other.

Table 1 – Summary of credits required in broad categories at each university

University	Public/ Private	Total Credits	Engineering Credits	Mech. Eng Credits	Science & Math Credits	Other Credits
U. of Pittsburgh	Pub	128.0	75.0	60.0	32.0	21.0
Carnegie Mellon	Prv	127.3	59.0	47.7	30.0	36.0
U. of Iowa	Pub	129.0	79.0	67.0	31.0	19.0
Purdue	Pub	129.0	70.0	47.0	32.0	27.0
U. of Michigan	Pub	128.0	69.0	54.0	34.0	25.0
Penn State	Pub	128.0	66.0	42.0	32.0	29.0
Cornell	Prv	128.0	65.0	53.0	35.0	27.0
U. of Illinois	Pub	128.0	64.0	51.0	36.0	28.0
Georgia Tech	Pub	129.0	56.0	47.0	31.0	39.0
Stanford	Prv	128.6	51.4	45.0	31.4	45.0
AVERAGE		128.5	65.4	51.4	32.4	29.6

This data set is somewhat biased towards large public institutions, with only three of the ten entries coming from private universities. Nonetheless, we can begin to answer questions about whether there are differences between public and private universities in terms of flexibility. Given that the total credit counts are similar, the size of the "Other Credits" category seems to be a natural metric for overall program flexibility (note that this does not measure flexibility *within* a single broad credit category).

Looking at engineering courses specifically, the number of course credits dedicated to each sub-discipline is shown in Table 2. In this case, courses were categorized by the main focus of each course. This means, for example, though all programs will include CAD, many of them will have it as a component of a broader course, e.g. a design course. In these cases, the "Tech Skills/CAD" category may read zero. This was done as it is difficult to separate the number of credits in a single course that are devoted to particular topics. Similarly, technical elective courses were not included unless they are allocated to a specific sub-discipline. For this reason, the total number of credits for each school in this table will not equal the number of engineering credits from Table 1 above.

Table 2 – Summary of credits required in engineering sub-disciplines*

	Pitt	CMU	Iowa	Purdue	Mich.	Penn State	Cornell	Illinois	GA Tech	Stanford	AVG
Mechanics / Dynamics	12.0	10.7	12.0	9.0	8.0	9.0	7.0	11.0	8.0	7.1	9.4
Materials / Manufacturing	6.0	0.0	6.0	3.0	4.0	3.0	4.0	4.0	6.0	2.1	3.8
Thermal-Fluids	15.0	10.0	10.0	11.0	9.0	9.0	10.0	11.0	9.0	7.1	10.1
Dynamic Sys. and Controls	6.0	4.0	3.0	0.0	4.0	3.0	8.0	5.3	3.0	0.0	3.6
Design (incl. capstone)	9.0	8.0	12.0	14.0	12.0	12.0	7.0	9.0	9.0	15.7	10.8
Experimentation	6.0	7.0	6.0	6.0	8.0	6.0	6.0	1.8	6.0	0.0	5.3
Tech. Skills (e.g. CAD)	0.0	1.0	0.0	5.0	0.0	0.0	0.0	3.0	3.0	0.0	1.2
Electronics	3.0	0.0	3.0	4.0	4.0	3.0	0.0	4.0	3.0	0.0	2.4
Engineering Computation	3.0	4.3	3.0	2.0	4.0	3.0	4.0	3.0	6.0	3.6	3.6

**Data compiled by looking at whole courses devoted to a topic. Entries of zero may indicate that a topic is integrated into another course*

Discussion

At the highest level, looking at the broad categories in Table 1, most programs require approximately the same number of total credits to graduate, with an average of 128.5 and a narrow range of 127.3 – 129.0. Similarly, the number of Math & Science credits are comparable between all schools, with an average of 32.4 credits and a range of 30.0 – 36.0. The number of Engineering credits varies more widely, with an average of 65.4 credits and a range of 51.4 – 79.0. Similarly, the number of Mechanical Engineering credits varies widely, with an average of 51.4 credits and a range of 42.0 – 67.0. These differences in Engineering credits are made up for in the Other category (Humanities, Social Science, writing, free elective, etc.), where the average number of credits is 29.6 with a range of 19.0 – 45.0.

The story is more complex when it comes to distribution of credits within engineering subject areas. The average number of credits in each category shows that the curricula are dominated by Design (10.8 credits), Thermal-Fluids (10.1 credits), and Mechanics/Dynamics (9.4 credits). This is perhaps not surprising given the importance of design education and the predominance of topics in Thermal-Fluids and Mechanics in the conventional mechanical engineering curriculum. What is more surprising is the relative dearth of credits dedicated to Dynamic Systems and Controls (3.6 credits), historically a major component of many degree programs. However, some of this education might have moved into experimentation or electronics courses (in the form of mechatronics). As discussed below, this overlap of concepts between courses makes it difficult to make definitive conclusions from the data in Table 2, but the sparsity of the matrix may still be instructive. For instance, while Georgia Tech has at least one dedicated class in each subject area, Stanford has four subject areas without an associated course. This may indicate that the Stanford program's heavy emphasis on design courses teaches these same concepts in an integrated fashion.

Looking first at the University of Pittsburgh compared to the other schools in the study, Pitt has the second-highest number of Engineering credits required at 75, which is 9.6 credits higher than the mean (equivalent to three full courses) and 30 credits higher than the minimum set by ABET Criterion 5 for engineering programs [14]. Similarly, the number of Mechanical Engineering credits required is 8.6 higher than the mean. While the total number of Engineering credits is high, the proportion of credits specific to Mechanical Engineering is comparable to other programs.

Pitt's overall program flexibility can be compared by looking at Other credits, where it requires only 21, which is 8.6 credits lower than the mean. Overall, Pitt has lower flexibility in its curriculum compared to the other programs in this study. Given the ASME Vision 2030 recommendation to increase flexibility [3], Pitt could consider modifying its MechE curriculum to increase flexibility.

Areas of specific change can be examined using the sub-discipline summary in Table 2. Pitt's program has at least three more credit hours than the average devoted to Mechanics/Dynamics and Thermal-Fluids courses. When looking at the course comparison, Pitt has a three-class sequence in solid mechanics and failure analysis, for a total of 9 credit hours, whereas most other schools devote ~6 credit hours for these topics. Thus, Pitt could examine the content of these courses and consider reducing them to two courses by reducing course topic overlap, or trimming the total amount of material covered, thus freeing up 3 credits. In the Thermal-Fluids area, the course comparison shows that Pitt is the only program that requires two thermodynamics and two fluid mechanics courses. These additional courses could be made technical electives instead of required courses, freeing up an additional 6 credits. These 9 credits could become MechE technical electives, broader Engineering electives, or free electives.

Adding a limited number of free elective credits was identified as an area Pitt could modify its program. For example, a student who was interested in entrepreneurship and wished to take a business course could not count those credits toward any of the current graduation requirements. Another area to increase Pitt's program flexibility that was identified: the program allows for some courses from other engineering departments to substitute for a MechE technical elective, but there was not a list of pre-approved courses available to students. This inhibition to flexibility is currently being addressed by creating and publishing such a list. While this is a subtle change, it could significantly improve a student's ability to tailor their mechanical engineering degree to fit the breadth of careers available to mechanical engineering graduates.

In contrast, Carnegie Mellon University appears to be near the middle-of-the-pack in terms of credit counts in each area. In overall engineering credits, its 59 credits are over 6 credits (approximately two courses) below the mean and the third lowest of the ten institutions. However, this is still over 7 credits above the university with the lowest number (Stanford). When looking specifically at MechE credits, CMU is much closer to the average (47.7 vs. 51.4). Thus the program is on the high end in terms of overall curriculum flexibility, with only Georgia Tech and Stanford requiring fewer credits in the "Other" category. The need for students to develop broad professional skills to complement their technical excellence has been highlighted in all major curriculum guidance documents [2-4] and based on this limited study CMU's curriculum appears to be competitive in developing these skills.

When it comes to the topical breakdown in Table 2, CMU's program is notable in its lack of training in Materials / Manufacturing (it is alone here) and electronics (two other schools also show a zero in this row). Students may use the program's flexibility to take electives in these areas, and many do take courses in mechatronics and material selection. Unlike at Pitt, there is no area that CMU is notably above the mean from which credits can be taken to bolster these skills. One possibility may be to consolidate the technical skills training into other courses as occurs in six of the ten schools analyzed. However, the Stanford model shows that there may be opportunities to provide substantial compression of credits in various areas that may be used to provide required training in one or both areas.

One challenge of this approach is the separation of engineering courses into Mechanical or Non-Mechanical. Thus, it was decided to include Mechanical Engineering courses into the broader "Engineering" category. At the course level, it can be difficult to determine course content solely from brief course descriptions, which can lead to mis-categorization. Similarly, content can be re-combined in different ways, particular for computing skills such as CAD. Combining a benchmarking study with a structural analysis, such as the one conducted in [12], could help address this issue. Specific structures of interest might be the extent to which experimentation is integrated into courses, the existence of depth tracks, or progression of topics such as design skills throughout the four years. Additionally, if syllabi were available for all courses at all universities with in-depth descriptions of course contents, then statistical methods could be used to automatically categorize courses.

Furthermore, the selection of only a small number of institutions for benchmarking may not be representative of all mechanical engineering programs. As previously mentioned, only three of the ten universities in this study were private, and there may be different characteristics in programs at public vs. private universities. This is an area for further research.

Another limitation is that it is impossible to discern trends over time by only looking at current degree requirements: a more in-depth study would look at curricular changes over time at these institutions. This is time consuming and would not glean the underlying *reasons* for curricular changes without discussions with people in those other departments.

Of course, any curricular changes need to be carefully considered and will be specific to an institution, its goals, and its constraints (faculty availability for course offerings, ABET accreditation, particular university or college-level requirements, perceived unique strengths to be preserved).

Conclusions

When departments periodically review their curricula a variety of data sources are used to inform the decision making. This paper has presented a benchmarking study comparing required courses and credits for a mechanical engineering degree at multiple universities and has shown it to be a helpful, first-level tool for considering curricular changes. A comparison of credit requirements in broad areas is helpful to understand the overall flexibility of a given program. A deeper look into the specific credit requirements in engineering sub-disciplines identified the areas where credits could be freed up to increase flexibility, if desired. While limited in scope, the authors hope that this data in this study will at least provide a starting point for determining *how* a curriculum can be compared against competing institutions. Because the data set takes much time and expertise to develop, it is available upon request for others to use for benchmarking their own programs.

Future work will explore curriculum structural differences between universities within mechanical engineering credits. By focusing on a more limited set of metrics (e.g. whether the program requires students to select a concentration) data can be collected more broadly and compared more readily. In addition, the authors would like to explore methods for determining the directions in which curricula are changing. These data may help universities become more confident in taking the difficult first steps in curriculum change.

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