Curricular Efficiency: What Role Does It Play In Student Success?

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Abstract

In this paper we consider how engineering curricula may be "streamlined" in order to address a measure we refer to as *curricular efficiency*. We then demonstrate how curricular efficiency correlates to student academic success—in particular, the effect it has on improved graduation rates, and the number of credit hours accumulated while pursing a degree. In this work, the degree plan for a curriculum is represented as a directed acylic graph. Graph-theoretic metrics related to efficiency are then developed and applied to engineering degree plans obtained from a number of public four-year institutions. In addition, student success data at the class level is adapted to create a weighted directed graph from which a cumulative curricular efficiency metric is obtained. One use for this metric is to provide a tool for evaluating curricular features and the ability to compare these to programs at other universities in order to guide possible curricular changes.

Introduction

Many institutions are working to better understand the highly complex set of factors that contribute to student academic success. Numerous such factors have been studied, with the typical goal of correlating them to the probability of a student graduating.[3,5,7] For the purposes of this paper, we have categorized these factors into two groups: *pre-institutional* and *institutional*. Pre-institutional factors are those that occur prior to a student matriculating in higher education. The Higher Education Research Institute (HERI) has collected a significant amount of pre-institutional data from incoming freshman classes during the past fifteen years, and they periodically publish national norms developed from this data. These norms, which include graduation rates by ethnicity, race, sex, SAT/ACT score, and high school GPA, have been studied at length and their contribution to later academic success is well documented. HERI also conducts a more detailed freshmen survey that investigates additional pre-institutional factors as well as early institutional factors. Using data from 356 four-year public and private non-profit institutions and 210,000 first-time full-time students, HERI has created a calculator that can predict graduation for a single student or an entire incoming class[2]

We have found that the HERI predictions provide rough estimates of the cumulative likelihood for cohort success. Nevertheless, there are institutions that admit very similar student populations, yet they significantly over- or underperform relative to their HERI predictions. The differing results that these institutions obtain therefore must also be partially explained by the institutional factors they apply to their students. The institutional factors that have traditionally received the most focus include the amount and quality of the student support services provided, the tracking of student progress, as well as the quality of advising services.[4,6] Ultimately, however, degree attainment requires the satisfaction of all the requirements associated a given degree program. Thus, the efficiency with which a student may progress through these requirements is what matters most in the end. There are numerous institutional factors that may influence this progression, including those just mentioned, as well as the timing of course offerings, initial mathematics course placement, who teaches particular courses, etc. A factor that is often overlooked, however, are those impediments inherent in the curriculum itself. Specifically, it seems that many institutions build structural impediments to success into their programs by unknowingly creating bottlenecks or exceedingly long prerequisite paths as a part of their curricula. This is particularly common in STEM disciplines where basic science and mathematics skills must be obtained prior to learning discipline-specific topics.

In this paper we consider the role that curriculum plays in student progress. In particular, we develop various metrics related to curricular efficiency that correspond to the ease with which a student may satisfy the degree requirements associated with a given degree. These metrics are intended to measure the role that the structure of a curriculum plays in student academic success. The focus in this paper is on electrical engineering programs at similarly-rated four-year institutions, but the methods we develop may be applied to any curricula. Furthermore, all of the programs we consider are accredited by the Accreditation Board for Engineering and Technology (ABET), and therefore all of them satisfy the same general ABET curricular criteria; yet, the curricular efficiencies of these programs are vastly different. Some might argue that a more efficient curriculum, allowing students to more easily progress, is obtained at the expense of program quality. What we found, however, was quite the opposite, with highly regarded programs often having the most efficient curricula.

Curricula Graphs

The set of requirements associated with the curriculum in a particular degree program, along with the relationships between the individual requirements (e.g., course pre/co-requisites) can be represented as a directed acyclic graph. More specifically, we model a curriculum C consisting of n degree requirements as a directed graph $G_C = (V, E)$, where each vertex $v_1, \ldots, v_n \in V$ represents a requirement in C, and there is a directed edge $(v_i, v_j) \in E$ from requirement v_i to v_j if v_i must be satisfied prior to the satisfaction of v_j. Typically, a degree requirement is satisfied by passing a particular course, and the precedence relationships expressed in G_C correspond to course pre/co-requisites. Thus, we will refer to G_C as a *curriculum graph*, and to each vertex $v \in V$ we assign a weight, denoted $w(v)$, that equals the number of credit hours associated with course v. It is common for departments to list their curricula in the form of curricula graphs, often online. Indeed, we used these online sources of curricula graphs to support the study reported in this paper.

Let us consider some of the important properties associated with a curriculum graph. In curriculum graph $G_C = (V, E)$, the total number of pre/co-requisites for a given course $v \in V$ is given by the in-degree of (i.e., the total number of edges incident on) v, denoted $deg^-(v)$. Similarly, the out-degree of (i.e., the total number of edges incident from) v, denoted $deg^+(v)$, corresponds to the number of courses that require v as a pre/co-requisite. The degree of course $v \in V$ is given by $deg(v) = deg^-(v) + deg^+(v)$, and the maximum degree of the graph is given by

$$\Delta(G_C) = \max_{v \in V} \left(\deg(v)\right),$$

with the maximum in-degree and out-degree of G_C denoted $\Delta^-(G_C)$ and $\Delta^+(G_C)$, respectively.

The set of pre/co-requisites that must be satisfied in order to take course $v_t \in V$ corresponds to a subgraph that we denote $G_{C_{v_t}}$. There may be numerous paths in $G_{C_{v_t}}$ from the vertices in this subgraph to the target vertex v_t. The most important of these is the longest in $G_{C_{v_t}}$, denoted $lp(v_t)$, as it corresponds to the minimum number of courses that must be completed *prior* to taking course v_t. The longest path in the entire curriculum is therefore given by

$$lp(G_C) = \max_{v \in V} \left(lp(v)\right).$$

Note that the prerequisites in $lp(G_C)$ place a lower bound on the amount of time a student must spend in pursing the degree associated with curriculum C.

It is interesting to note that most STEM curricula produce graphs that are highly connected, while many non-STEM curricula produce graphs that are largely disconnected. Given that connectivity implies requirements that must be satisfied, and that each such requirement is a potential stumbling block to student progress, the inherent difficulty of STEM curricula is immediately apparent.

Curricular Efficiency Metrics

Let us now consider a set of metrics that best explain curricular efficiency with respect to student success. For each of the metrics that we introduce, a lower value is considered more efficient.

Degree Hours. The minimum total number of credit hours required in order to obtain the degree associated with curriculum C is given by:

$$\sum_{v \in V} w(v).$$

This is a fairly obvious factor that intuitively should inversely correlate with curricular efficiency, but perhaps positively correlate with program quality (up to a threshold). The number of hours in a curriculum significantly impacts the number of hours a student must take per semester in order to graduate in four years, and this trickles down to the number of hours a student must spend per week on school-related activities. In engineering programs, it is rarely the case that students graduate with the minimum number of required hours.

Maximum In-Degree and Out-Degree. Courses with high in-degree are difficult to reach as every requirement must be satisfied prior to enrolling in the course. Courses with high out-degree are critical in the sense that success in the course enables students to enroll in many other required courses. The courses $\Delta^-(G_C)$ and $\Delta^+(G_C)$ correspond to the largest bottlenecks in the curriculum, and therefore are the most important courses in the curriculum in terms of student success.

Important Courses (Bottlenecks). In addition to the maximum and minimum degree nodes, some curricula have additional "important" courses that we define as follows. An important course (or bottleneck course, bn) is one that has an in-degree or out-degree larger than three, or a combination of the two that is larger than five:

$$bn(G_C) = \sum_{v \in V} I\left[\big(deg^-(v) > 3\big) \vee \big(deg^+(v) > 3\big) \vee \big((deg^-(v) + deg^+(v)) > 5\big)\right]$$

where I is the indicator function, i.e., $I[b] = 1$ if expression b is true, and 0 otherwise. These important courses represent bottlenecks to graduation, where failure can lead to the inability to progress in a timely manner.

Longest Path and number of Long Paths. In a curriculum graph, the longest path represents the longest chain of prerequisites through a curriculum. An example involves a typical engineering mathematics sequence, such as Calculus I, followed by Calculus II, Differential Equations, and then some advanced mathematics class. The path length in this case is three, and if none of these classes is a co-requisite, it would take four semesters to complete. Long paths represent chains of classes that must be taken in order. Failing a class that is part of a long chain often requires summer school to get back on track or falling behind by a semester or year, depending on the availability of the class. The logic is that the more long paths, the more likely a student is to get off track, get frustrated, and drop out of a program. Our definition of a long path is any path length of five or more (five edges and six nodes).

Curriculum Rigidity. As the total number pre/co-requisites increases, a curriculum becomes more rigid in the sense that students have less flexibility in the order that courses must be taken, and any failure to pass a course or take it on time is more likely to lead to a delay in graduation. Thus, a measure of the rigidity of a curriculum is given by the total number of edges in the curriculum graph, G_C, normalized by the total number of courses in the degree program:

$$\frac{\sum_{v \in V} deg^+(v)}{|V|}.$$

Curricular Efficiency Results

Electrical engineering curricula were obtained from websites associated with the programs at four large public universities in the United States: University 1 is an institution located in the southwest, University 2 in the south, University 3 in the west, and University 4 is the electrical engineering program at the University of New Mexico (UNM). These were chosen because of their peer status

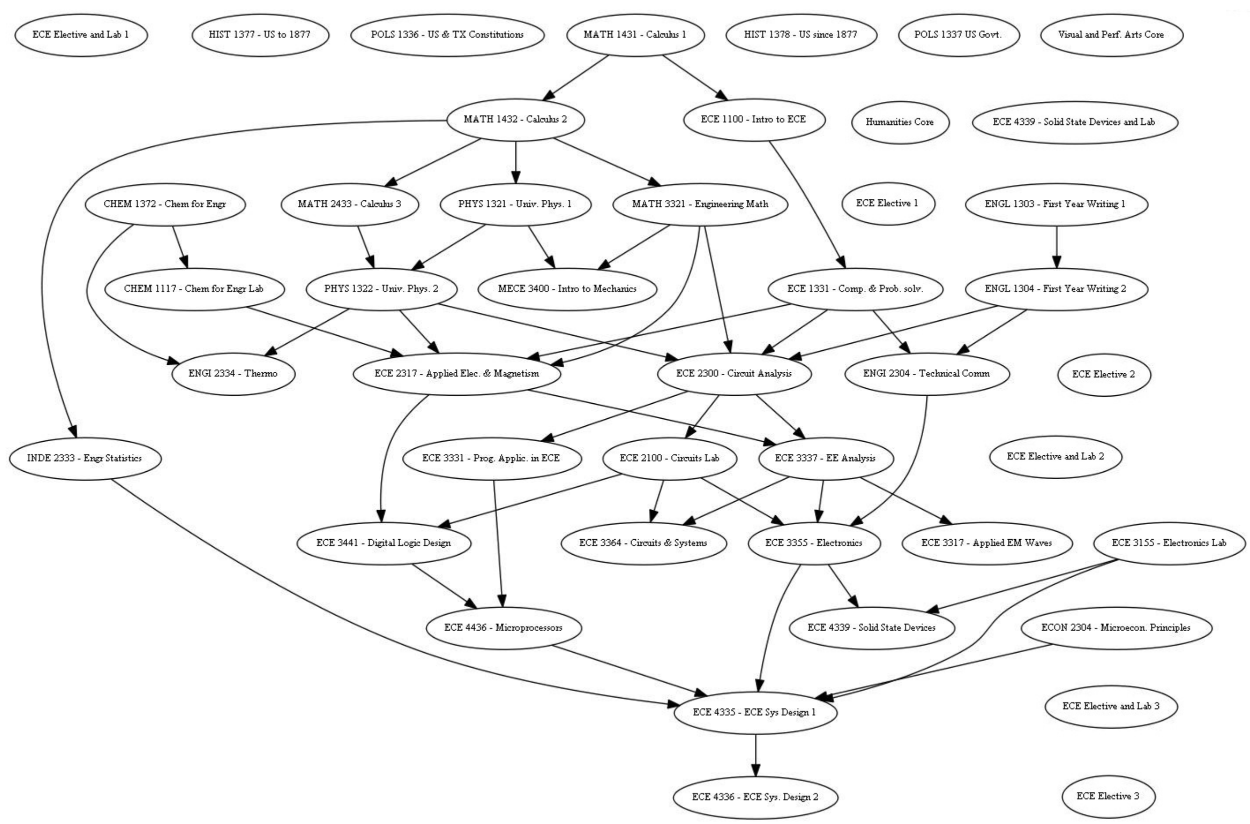

Figure 1: University 1 electrical engineering program in graph form.

as public state universities with similar student acceptance criteria and rates. Also, engineering graduation rates were available for these universities to help test the hypothesis of curriculum affecting these rates. Graphs were created for the electrical engineering curricula using the Ruby Graph Library. (As a note, other qualifications to take a course were not considered in these graphs. E.g., upper class status might be required to take a certain class.) Once a curriculum was encoded, standard graph algorithms we used (e.g., topological sort, depth-first search, longest path, etc.) in order to compute the curricular efficiency metrics.

Figures 1–4 show the curricula graphs created for each degree program, and the computed curricular efficiency metrics can be found in Table 1.

Notice that there are significant differences between these programs in terms of curricular effi-

C = EE Curriculum	$\sum_{v \in V} w(v)$	$\sum_{v \in V} deg^+(v)/\lvert V\rvert$	$\Delta^-(G_C)$	$\Delta^+(G_C)$	$lp(G_C)$	$bn(G_C)$
University 1	133	1.48	7	6	9	8
University 2	128	0.9	2	6	8	2
University 3	120	0.83	3	4	6	2
UNM	128	0.83	4	6	7	2

Table 1: Curriculum efficiency based on the graph metrics for each of the four institutions.

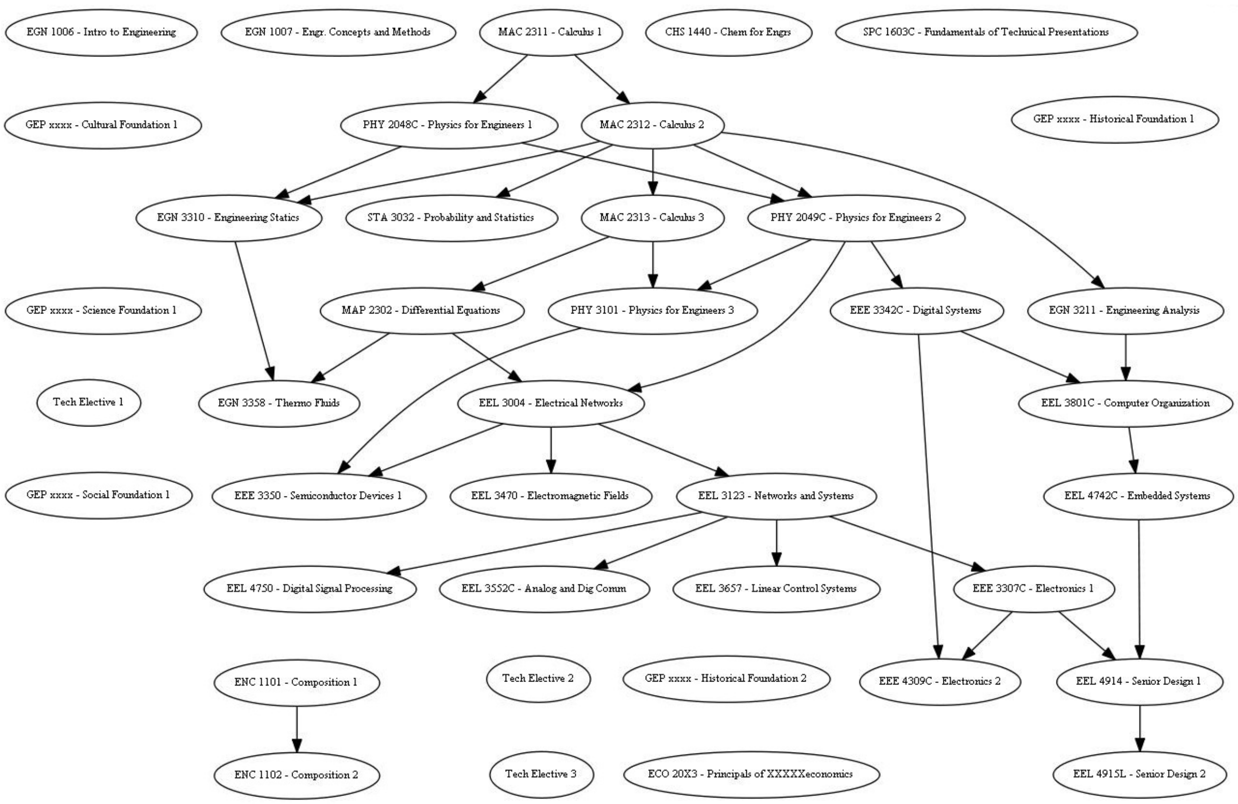

Figure 2: University 2 electrical engineering program in graph form..

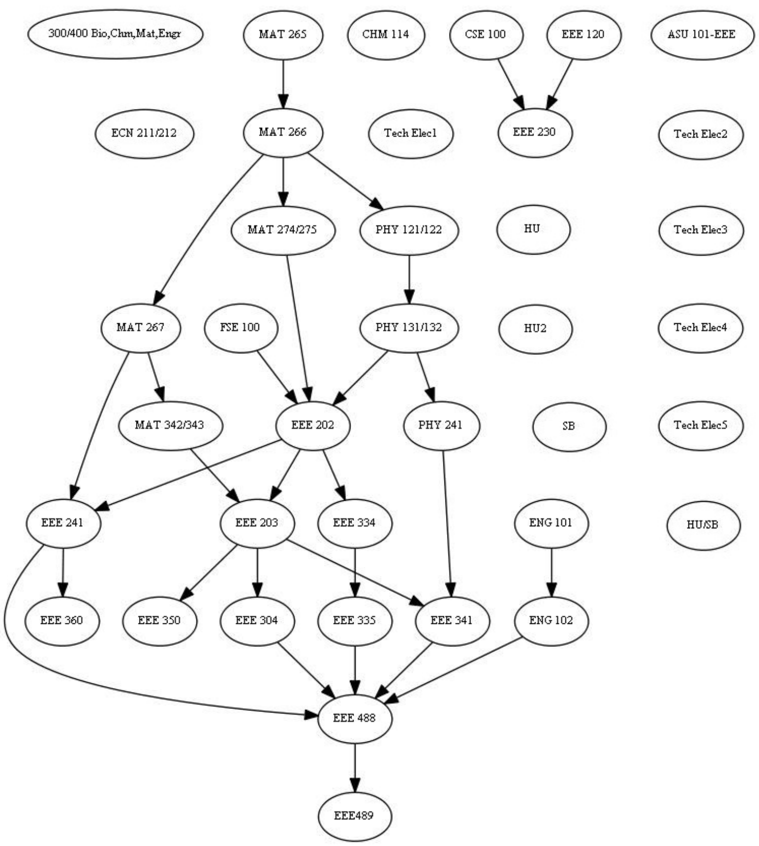

Figure 3: University 3 electrical engineering program in graph form.

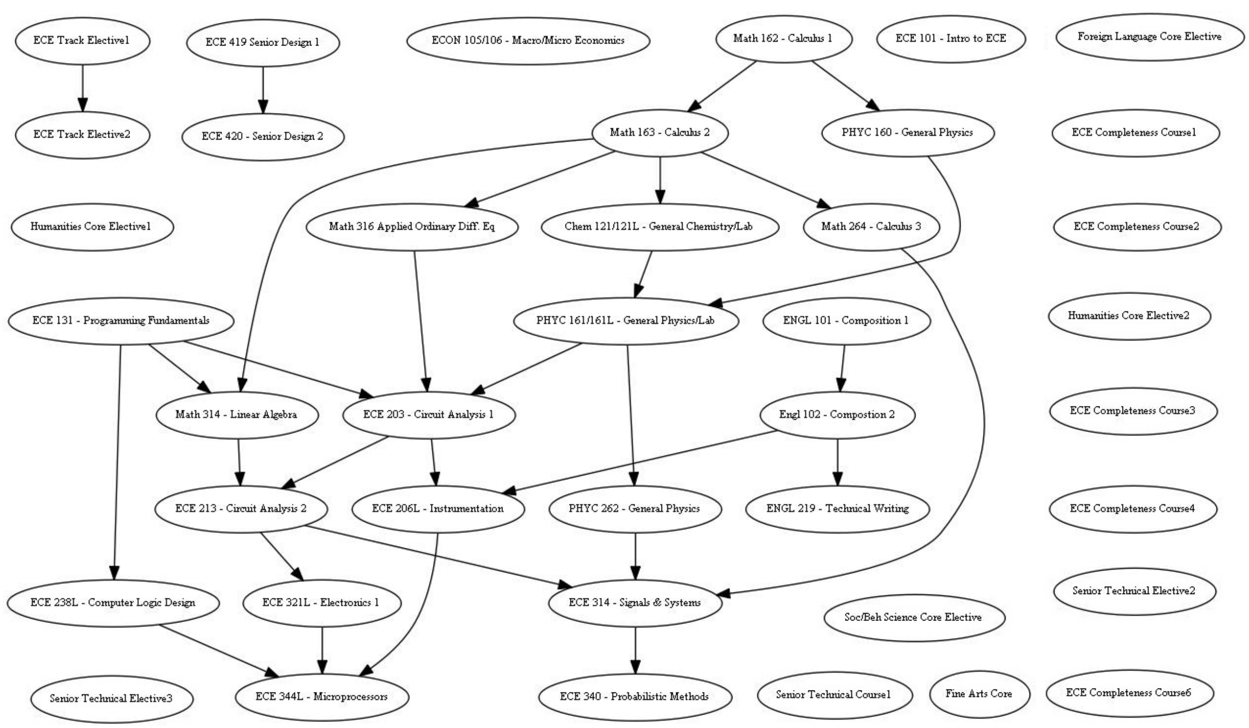

Figure 4: The University of New Mexico electrical engineering program in graph form.

ciency, with University 3 being the most efficient for all metrics, and the University 1 program the most challenging for all metrics. The 131 hours required to obtain an electrical engineering degree at University 1 equates to an average of 16.25 credit hours per semester for a four-year plan. The maximum node in-degree is seven at University 1, for the Circuit Analysis class, and the maximum node out-degree is six for the Calculus II class. These two classes are typical bottlenecks in any electrical engineering program. If someone fails to pass Calculus II, you likely would not want them moving forward in an electrical engineering degree, while passing this class opens the door to the more rigorous engineering classes. Circuit Analysis is also an important class in electrical engineering as it marks the first in a chain of engineering classes based around circuit design/analysis and electronics. However, Figure 1 shows that University 1 has made reaching this class difficult by requiring seven pre/co-requisites. This may slow the advancement of a student through the program, forcing the student to take classes that do not fill a requirement for graduation. A report by UNM's Office of Institutional Analytics shows that students in University 1's engineering departments are taking 138% of the hours that are needed to graduate.[1] For this program, it means students are graduating with approximately 180 hours on average. It is also worth noting the curriculum rigidity of the University 1 program. There are 1.48 edges per node, meaning each class has an average of one-and-a-half prerequisites. The longest path of nine is also significant, as it is longer than the number of semesters in a four year program, i.e., there are ten classes in this pre/co-requisite chain that must be completed in eight semesters. Obviously there are several co-requisites in this chain, meaning that two classes can be taken together, but this length makes a failure very costly in terms of timely graduation and hours-to-graduation. Finally, the longest path for the University 1 program contains four courses that are also bottlenecks and eight total in the entire curriculum.

At the opposite end of the efficiency spectrum is the curriculum graph for University 3, shown in Figure 3, which requires only 120 hours to complete. The highest in-degree is three and the highest out-degree is four. Calculus II is once again the highest out-degree and there are many classes that have an in-degree of three, one of these being their Circuit Analysis class. However, these are the only two classes in the curriculum that would be considered bottlenecks. The longest path is six and the edge to node ratio is 0.82, almost half that of the program at University 1. From the UNM report, engineering students at University 3 take 123% more hours than are needed to graduate. This equates to approximately 148 total hours on average for students at the time of graduation. Compare this with 180 hours students at University 1 are accumulating and we see that the students at University 3 are accumulating what amounts to a year of fewer total credit hours by the time they graduate.

The previous two curricula demonstrate how widely the same degree program can differ at different universities. Figures 2 and 4 show the curricula graphs for the University 2 and UNM programs, respectively, which fall in between the former two in terms of curricular efficiency. An interesting feature of the University 2 graph is that the maximum in-degree is two. This is lower than that of University 3, and any other STEM curriculum graph that we have studied. Since no class has more than two prerequisites, the program has few bottlenecks, in particular only the two mentioned previously, Calculus II and a Networks and Systems course that is equivalent to the Circuit Analysis course described earlier. The maximum out-degree in the University 2 graph is six, the longest path is eight, and the curriculum rigidity 0.9. From the University 2 electrical engineering program website, the administration has highlighted what they believe to be critical path courses in the program. They mention 14 classes that they believe will indicate student success, which is likely based on previous student data and a consensus on what the important topics in the program are. It is probably not a coincidence that five of these courses are also on the longest path. Figure 4 shows the UNM curriculum graph. On average, UNM engineering students accumulate 168 hours by the time they graduate. UNM has curriculum efficiency features that are similar to those of University 2. UNM has a slightly lower curriculum rigidity of 0.83, but a higher maximum in-degree of four. The maximum in-degree is once again Circuit Analysis and the maximum out-degree is Calculus II. We can now look at the pass rates for these classes to determine if they truly are bottlenecks in the curriculum.

Incorporating Course-level Data

By incorporating course-level pass/fail rate data it is possible to arrive at a single curricular efficiency metric that incorporates the previously discussed metrics. This metric is based on a combination of a course's pass/fail rate and the graph metrics discussed earlier, and results in a per node efficiency measure, e_v. These node measures have a cumulative effect and will be used to create a curriculum-wide metric for the curricular efficiency of G_C. Specifically, each node has a pass/fail rate, representing the difficulty of the corresponding course separate from the other structures in G_C. The in-degree of a node and the path length to a vertex represent the complexity of reaching the vertex in a curriculum graph. The in-degree represents the number of immediate prerequisites needed while the path length represents a prerequisite chain needed to reach a certain vertex. The following simple formula determines the efficiency of vertex v:

$$e_v = fr + 0.15\left(\frac{deg^{-}(v)}{\Delta^{-}(G_C)} + \frac{lp}{lp(G_C)}\right)$$

where fr is the fail rate (expressed as a percentage) for the course associated with vertex v. The maximum in-degree and maximum path length are derived from the UNM graph and where used to normalize the feature values between 0 and 1 for UNM. All other schools will be compared to UNM, and thus, will not necessarily be normalized to between 0 and 1. These features are then multiplied by a scaling factor of 0.15 to bring these values in line with typical class failure rates so that this term does not dominate the formula. The theoretical maximum value for a UNM vertex is 1.3, which would occur if the class was the last class in the longest path, had the maximum in-degree, and a 100% fail rate. Isolated vertices will only have the contribution of their fail rate.

The highest e_v value is 0.39 for Calculus II, due mainly to a high fail rate (33.5%). One would expect the numbers to increase as you move deeper in the graph; however, the fail rates for most of the upper-level engineering classes are very low, which compensates for being farther along a path. Summarizing the graph values, early mathematics and general science classes typically have high fail rates (20–35%), while engineering classes have much lower rates (0–12%). One class has a value of 0 (Senior design I), although the sample size for calculating engineering fail rates was much smaller than core, mathematics and sciences classes that are shared among many majors. The total value for the curriculum is 7.68, which averages out to a value of 0.19 per vertex.

Table 2 shows the values calculated for the three other electrical engineering programs. Since class

Institution	Curricular Efficiency
University 1	4.602
University 2	3.491
University 3	2.504
UNM	2.623

Table 2: Curricular efficiency of the electrical engineering programs at each of the four institutions, incorporating course-level pass/fail rate data.

level data was not available for the other schools, the fail rates were dropped from the formula in order to make a fair comparison. This gives a value of 0 to isolated vertices and origin vertices. Without taking into account vertex fail rates, we can see that the UNM curriculum is much closer in difficulty to University 3 than it is to University 2. This is interesting because of University 2's lower maximum in-degree of two. This is apparently offset by the total number of edges in the graph. University 2 has an curriculum rigidity close to 0.1, which is higher than UNM's. When excluding maximum out-degree, University 3 and UNM are much more similar, making differences in graduation rate more likely based on acceptance criteria and the student body make-up.

Discussion

The curricular analysis metrics proposed provide a tool for university faculty and administrators to easily assess the efficiency of their curricula, and may also prove useful to curriculum committees that are considering changes to programs. Due to the nature of this study, however, there are inherent limitations. While universities are required by law to release their graduation rates, they are not required to report down to the major. Without graduation rates from other institutions' electrical engineering departments, it is difficult to show mathematically how the features we are using correlate to graduation rates. Acquiring these from the schools studied and perhaps several additional universities, would allow us to create a regression model that would tell us the amount of variance, if any, these features are explaining. At this time, the only information we have from these schools is the average number of hours engineering students graduate with. From our small sample size, this seems to correlate with the features we are calculating. Another way to determine the effect of these curricular metrics is to perform a longitudinal study on a changing curriculum. The electrical and computer engineering programs at UNM have proposed significant changes to their curricula. The goal is to monitor the results of these changes going forward in order to create a suitable regression model.

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