Gateway Course Performance as Predictors of Success in Engineering Education

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Abstract

To maintain global competitiveness, STEM education has received significant interest in the United States in the last decade. One result of that interest has been an increase in applications to college and university STEM related programs. In some engineering programs the increase in the number of students has caused a strain on the education infrastructure because programs have grown beyond their ability to deliver a high-quality education. A secondary effect has been a higher turnover of students who either do not complete a higher education program or switch to a non-STEM program after a year or two. Current admission criteria focus heavily on high school GPA and SAT scores; however, there are significant differences in how different schools calculate GPA and some schools have moved away completely from SAT scores.

Although more students are applying to engineering in some programs, the students are not necessarily prepared for a rigorous engineering curriculum. Many programs require students to pass one or more gateway courses with a "C" or better in order to proceed in the program. This paper considers the performance in a number of gateway courses at the Virginia Military Institute (VMI) that all students have to complete in the Civil and Mechanical Engineering programs during their first and second years. These gateway courses are evaluated as predictors of success in the students' engineering education. Specifically, the performance in Calculus 1 and 2, Statics, and Solid Mechanics was analyzed for two cohorts of students: the classes of 2020 and 2021. Success was defined as graduating from the program with a GPA greater than 2.5. The correlations between performance in Calculus and Statics, Solid Mechanics, and ultimately successfully completing the engineering program was investigated. The analysis showed that performance in pre-calculus did not directly play a role in later performance; however, performance in Statics, Solid Mechanics and Calculus II was directly correlated to and could reasonably predict performance in the engineering curriculum.

Keywords

Success, performance predictors, mathematics, engineering mechanics

Background

Pre-college performance in terms of GPA, class rank, and standardized test scores have been proven to have a positive correlation to engineering student success [1, 2, 3]. At the college level, higher performance in mathematics during the first term of college is positively correlated to student success and retention in engineering [4]. Wilkens et al. studied the relationship between a first-year engineering student's success in engineering and their performance in mathematics during their first term of college. Although Calculus is in many cases the first mathematics course in engineering curricula, a total of ten courses were recorded by students during their first year for this study. These courses ranged in levels, from pre-college algebra to linear algebra and advanced math. With each mathematics course, a higher recorded grade for the course increased the probability of a student to graduate in engineering within 6 years of matriculation. While higher graduation rates in engineering were recorded for those students taking more advanced mathematics courses during their first term, significant student success and retention were also shown to exist among students passing lower-level mathematics with a grade of A or B [4].

While performance in mathematics has been shown to correlate to general student success and retention in engineering, less is known about any direct correlation between mathematics performance and student success in specific engineering courses. Statics and Solid Mechanics (i.e., Mechanics of Materials) are often coined as the first "real engineering courses" students take at the college level. They earn this title because they challenge students to apply concepts beyond memorization. Also considered "gateway courses," the authors have identified these courses as another significant barrier for engineering students. In civil and mechanical engineering, these courses are foundational to multiple subdisciplines. As such, a minimum grade of "C" is often required in both courses for students to advance in these engineering programs. Therefore, it is critical to understand what affects student performance in these foundational engineering courses. It is also critical to understand how performance in these gateway courses affect the overall success of a student to graduate with an engineering degree.

Method

The following study investigated predictor courses for success in the civil and mechanical engineering programs at VMI. Success was defined as graduating with an engineering degree within 6 years of matriculation. The transcripts from a total of 194 students in the class of 2020 and 2021 were gathered and analyzed. The database was anonymized and there was no gender or race information. Grades from the students' performance in mathematics, statics, and solid mechanics were gathered. In addition, overall GPA and SAT math scores were ascertained and used as additional predictor variables. Other studies have considered and incorporated both cognitive and non-cognitive factors in predicting "success." However, this study was limited to cognitive factors only.

The following questions guided the analysis:

1. Combining all factors in an analysis matrix, are there any strong correlations? Are there strong correlations, not only between the GPA and the other classes or scores, but also between the performance in the individual classes?

2. Which regression technique best models the student performance: simple linear or multivariable?

3. Which class or classes may be used to model overall performance in the engineering program?

4. Can SAT scores and performance in Mathematics courses be used to predict performance in Statics and Solid Mechanics?

Three primary statistical modeling methods were used to assess student success: simple linear regression, multiple linear regression, and correlational analysis. The dependent variable was the student academic performance as measured by the recorded GPA and the independent variables were the end-of-semester grades in Calculus I, Calculus II, Statics, and Solid Mechanics. We also incorporated the available SAT scores (verbal, math and combined) as well as whether the students had to take pre-calculus at the time of matriculation. Additionally, we investigated whether the students repeated any of the courses and the effect that had on their success. VMI does not assign grades with plus and minuses, therefore the grades available for analysis were A, B, C, D, and F coded as 4, 3, 2, 1, and 0, respectively. Precalculus is a pass/fail only class and therefore coded as 1 or 0.

Results

Descriptive statistics

A summary of descriptive statistics is presented in Table 1. This includes 79 graduates for the class of 2020 and 115 for the class of 2021, for a total n = 194. The data set was analyzed as one group; the students were not separated by matriculation year. The average mathematics SAT score is 606, which places the average student in the 80th percentile nationally, while the average verbal SAT score is 567, which places the average student in the 70th percentile nationally.

The average GPA for both Statics and Solid Mechanics was 2.266, which would place the average student in the C grade range. Nine students did not pass Statics on their first attempt, while 10 students did not pass Solid Mechanics on their first attempt. That translates to 11.25% and 12.5%, respectively. An additional 8 students had to repeat Statics because they failed to earn the "minimum grade of C" required to progress to Solid Mechanics, while an additional 5 students had to repeat Solid Mechanics because they failed to earn the "minimum grade of C" required to progress to higher level courses which require Solid Mechanics as a pre-requisite. This institution, much like other similar institutions, mandates a minimum grade of C to pass certain key general engineering courses such as Statics and Solid Mechanics.

The Calculus I and II overall performance as reflected in the average scores was 2.177 and 2.165, respectively. Of the students studied, 22.5% who registered for Calculus I and 16.3% of those who registered for Calculus II failed to pass during their first attempt.

Table 1. Summary of descriptive statistics

Variable	Average	Standard Deviation	Maximum	Minimum
Overall GPA	2.789	0.584	3.912	1.161
SAT – Math score	605.9	58.3	770	440
SAT – Verbal score	566.3	73.2	750	390
SAT – Combined score	1172.1	103.8	1400	870
Calculus I	2.177	1.439	4.000	0.000
Calculus II	2.165	1.295	4.000	0.000
Statics	2.266	1.268	4.000	0.000
Solid Mechanics	2.266	1.206	4.000	0.000

Correlation matrix

While the correlation matrix was far too large to be presented here in its entirety, the results can be summarized as follows:

GPA correlated with the first attempts of Calculus II, Statics and Solid mechanics with R-Square values of 0.605, 0.697 and 0.697, respectively. The third attempt at Calculus I also correlated strongly with the GPA with an R-Square value of 0.836. Interestingly however, the correlation dropped with subsequent attempts at Statics and Calculus II. The authors believe the reason for these correlations to be as follows: Students who have the necessary study skills and ability to perform well during their first attempt at Calculus II, Statics and Solid Mechanics will continue to perform well for the duration of their education. The students without the necessary skills who are given the opportunity to develop those skills in Calculus I, show an overall improvement in their academic performance. However, multiple attempts at the subsequent courses in the academic sequence, Calculus II and Statics, no longer show the same improvement as multiple attempts in Calculus I. This effect may be due to the volume of new information an engineering student is expected to absorb. A student who did not develop necessary skills during Calculus I will be challenged to develop those skills while simultaneously learning brand new and, often, very difficult concepts. These values are presented in Table 2.

Table 2. GPA correlation values

	Calculus II	Statics	Solid mechanics	Calculus I (third attempt)
GPA	0.605	0.697	0.697	0.836

The first attempt at Statics correlated strongly with the second and third attempts at Calculus I with R-Square values of 0.760 and 0.756, respectively. Solid mechanics showed the same trend, with strong correlations with the second and third attempts at Calculus I. The R-Square values were 0.795 and 1.000, respectively. It is important to note that the third attempt at Statics correlated negatively with all variables, but it showed surprisingly strong negative correlations with the third attempt at Calculus I and the second attempt at Calculus II with R-Square values of -0.945 and -0.853, respectively. Table 3 summarizes these correlations.

Table 3. Statics and Solid Mechanics correlations

	Calculus I (second attempt)	Calculus I (third attempt)
Statics	0.760	0.756
Solid Mechanics	0.795	1.000

Linear regression analysis

Using the first attempts at Pre-Calculus, Calculus I, Calculus II, Statics, and Solid Mechanics as the independent variables and the GPA as the dependent variable, a multiple linear regression (MLR) analysis was performed. The goal of the analysis is to model the relationship between the independent variables and the dependent variable in an attempt at creating a predicting model. In MLR the model takes the form:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_n x_{in} + \varepsilon \qquad \text{Equation 1}$$

Where: y_i= dependent variable
β_0= y-intercept constant
β_n= slope coefficient of each independent variable
x_{in}= independent variable
ε = the independent error term

Our model regression line, therefore, took the form:

$$y_i = 1.7488 + 0.1541x_{i1} + 0.1743x_{i2} + 0.0143x_{i3} + 0.0106x_{i4} + 0.1240x_{i5} \qquad \text{Equation 2}$$

Where: y_i= GPA
x_{i1}= Statics
x_{i2}= Solid mechanics
x_{i3}= Pre-Calculus
x_{i4}= Calculus I
x_{i5}= Calculus II

The model shows that Statics, Solid Mechanics and Calculus II affect the GPA in relatively equal and statistically significant measures, whereas Pre-Calculus and Calculus I do not. The adjusted R-square value for the model was 0.613 indicating a relatively good fit. We elected to use the first attempts at each class primarily because there were insufficient data for regression analysis. Removing Pre-Calculus and Calculus I from the model yields the following best fit equation which now has an R-squared value of 0.622:

$$y_i = 1.7730 + 0.1559x_{i1} + 0.1718x_{i2} + 0.1264x_{i5} \qquad \text{Equation 3}$$

Interestingly, performance in Pre-Calculus did not appear to predict the performance in any later courses, such as Calculus I, Calculus II, Statics, or Solid Mechanics. Similarly, the performance in Calculus I and II also did not appear to predict performance in Statics and Solid Mechanics. Less surprisingly, the performance in Statics was a reasonable predictor for successful performance in Solid Mechanics. The linear regression model with Solid Mechanics as the dependent variable and Statics as the independent variable took the form as shown by Equation 4 with an R-square value of 0.4546.

$$y_i = 0.8130 + 0.6412x_{i1} \qquad \text{Equation 4}$$

Conclusions

The analysis shows that the performance in Pre-Calculus does not appear to predict the performance in subsequent courses or the overall GPA. This may be because it is a pass/fail class and therefore there is insufficient resolution in the data to allow for deeper analysis.

Secondly, multiple attempts at Calculus I appear to bear some fruit in the performance of subsequent courses; however, multiple attempts in more advanced courses such as Calculus II and Statics did not appear to show the same benefit.

The third conclusion drawn from the regression analysis is that performance in Statics, Solid Mechanics, and Calculus II can similarly determine the overall performance in the engineering program.

Lastly, the performance in Statics may be used to predict successful performance in Solid Mechanics, albeit this relationship was not as strong as expected.

Based on these conclusions, we believe that having a minimum required grade of C to progress in certain key courses is warranted.

Recommendations

Further analysis of additional data is necessary to determine the effect of repeating foundational mathematics and engineering mechanics courses as related to performance in the engineering program.

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