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Math Assessment: Can it help us in our teaching?

Dr. Shelley Lorimer P.Eng., MacEwan University

Shelley Lorimer is the Chair of the Bachelor of Science in Engineering (BSEN) Transfer Program at MacEwan University. She is an instructor in the introductory engineering courses as well. The BSEN program at MacEwan has grown from forty students since in started almost fifteen years ago, to the current 216 students. The majority of the students in the program transfer to second year engineering at the University of Alberta.

Shelley is a graduate of the University of Alberta in engineering and is a registered professional engineer with APEGA (Association of Professional Engineers, Geologists and Geophysicists of Alberta). Prior to her career at MacEwan, Shelley worked in industry as a research engineer and a consulting engineer for several years. Her current research interests include engineering education, enhanced heavy oil recovery and basic research in diffusion/dispersion mechanisms in porous media.

Dr. Jeffrey A Davis P.Eng., Grant MacEwan University

Dr Davis obtained his PhD at ETH Zurich specializing in multiphase flows and thermal hydraulics in nuclear reactors. With a passion for teaching, Dr. Davis' research focuses on pedagogical topics such as student engagement, active learning, and cognitive development. Projects he is currently working on include "Development of a risk assessment model for the retention of students", "Development of Student Assessment Software", and "Improving Student Engagement through Active Learning".

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Abstract

This paper explores pre-calculus math assessment results from an ongoing longitudinal study of first-year engineering students. The math assessment data was collected for two similar groups prior to entering the first-year program (pre-university) and later at different stages (post and mid-first-year) in the first-year program. Specifically, the goal of this research was to determine if the student scores could elucidate deficiencies in their math skills, and whether or not it might be feasible to use these results to develop interventions to deal with these deficiencies and/or guide instructors in best teaching practices.

The overall pre-university math assessment averages indicate that the students are not ready for first-year engineering, since the averages for both groups are only 50%. The data also shows that these scores are not consistent with students' overall high school averages of 80%. This study suggests that high school averages and first-year GPA have a weak correlation with the math assessment scores for the two samples considered. This was unexpected in light of research published to date that suggests that high school GPA and math placement scores can be used as predictors of success in first-year engineering.

Further examination of correct responses to individual questions on the exam shows that correct student responses decreased with increasing complexity of the math assessment problems, and that the averages on the assessment exams increased as the students progressed through the first-year program. A detailed analysis of the math assessment results for the post/mid-test show some areas of weakness that are not addressed by the first-year curriculum.

According to the classification scheme used by the authors of this paper, areas of serious weakness, not addressed in the first-year curriculum, were low difficulty level algebraic questions. There was some improvement in response rates for geometry and trigonometry questions. Perhaps this could be improved by changes in delivery of the engineering courses as well as the math courses.

Introduction

In recent years there has been an emphasis on reducing attrition rates in engineering programs through the understanding of students' learning needs and through the identification of the underlying deficiencies in their skill sets when they enter university. The literature in this area is extensive. For this research we have focused on a specific area dealing with first-year engineering students and particularly academic predictors associated with pre-engineering math assessment.

There are several articles that have provided valuable insight into the correlation of various parameters associated with engineering success and retention, which in turn have provided the impetus for examining the data for our own first-year engineering students. The focus of the literature review was large scale studies focusing on retention.

Several authors have conducted studies of learning styles and strategies for success of first year engineering students. Anson et al,[1] through their analysis of approximately 1000 first-year engineering students concluded that SAT math scores and high school GPA were predictive of first year GPA, and that students in the cohort studied did not enter university with productive learning strategies. In a later paper, Bernhold et al.[2], using the same set of students concluded that "mathematics is the largest stumbling block causing dropout in the freshman year". Both of these articles confirmed the importance of understanding one's own students and established a link between students' readiness to study engineering and retention in the program.

A more extensive literature review provided by Veenstra et al. [3], highlighted much of the research done prior to 2008. In the review of the literature summarized by Veenstra et al. many of the researchers found that academic success and engineering retention were linked to SAT math scores and other math placement exams as indicated previously. As early as 1988, Levin and Wycoff indicated that high school GPAs and math assessment scores were predictors of first-year GPA. Although the focus of the paper was comparative to non-engineering success, the analysis of the literature and the empirical study conducted by Veenstra et. al provided conclusions that were consistent with the literature: high school grades and SAT math scores were predictive of first-year academic success. Veenstra et al.[4] went even further to construct a model for freshman engineering retention identifying SAT math scores as a significant predictor for academic success, and further illustrated the need to develop models to understand the underlying engineering educational process. The implication of this research was the need for empirical studies to develop these models towards an improved understanding of how to increase first-year engineering retention. The need for further research in these areas was recommended.

All of these research studies have linked success in engineering with a solid understanding of basic mathematics principles, especially in the context of engineering applications. Budny et al.[5], used data spanning a 28 year period for freshman engineering students in the US, and have confirmed the observed trends that success in engineering is correlated to the students' math skills. They have gone even further to suggest that interventions (additional assistance to students with a higher probability of failure) reduce attrition through improving self-efficacy and skill level in mathematics. Moses et al.[6], in an article devoted to math readiness and personality, stress the need to examine math readiness to in order to improve retention of first-year students. This study consisted of participation from 129 freshman engineering majors, and used logistic regression as a means of evaluating the data.

Moreover, research in engineering education has indicated that pre-university assessment of "student readiness" might be used to inform best practices in teaching first-year engineering courses. A substantial portion of the literature considered in this paper was devoted to the evaluation of mathematical and other pre-engineering skills of students entering first-year engineering, particularly as predictors of success and retention in engineering.

It can be seen from this literature that several themes have emerged. However, it is quite clear that one of the more pertinent themes is the deficiency in mathematical problem solving skills that has been observed in engineering programs in North America and the United Kingdom[7,8]. Davis et al.[8] have referred to these observations as the "mathematics problem". It has been suggested that addressing these deficiencies might improve the success rate of students in engineering programs in general. These deficiencies are being explored for our first-year engineering students through results from our math assessment exams. The data has been analyzed in light of the previous studies considered in the literature review, looking for similar relationships among the various academic predictors. In addition, by examining specific details of the math assessment exam, i.e. the frequency of correct/incorrect responses in light of the question type, one may get a sense of common deficiencies in pre-engineering math skills. The rationale for this investigation comes from one of the principal themes of research in engineering education which seeks to improve "best practices" in teaching engineering through the analysis of data.

Background

The first-year engineering program at MacEwan University is involved in an extensive ongoing longitudinal study (2000 – present) of ways to predict and improve first-year engineering success much like what has been ongoing in the US in the last several years, but in the Canadian context.

In particular, there has been a focus at our institution on examining pre-engineering math skills. Analysis of data from our own program has been published in two previous papers.[9,10] These studies indicated that the math assessment exam results were extremely consistent from year to year, and that this consistency might be useful in providing information for our instructors in delivering curricula to enhance student success. These observations provided the impetus to extend the research in this area. A further examination of the engineering education literature in light of the objectives of the longitudinal study indicated that we should pursue a more in depth analysis by collecting data in both a pre-university and a post-first-year fashion[11], specifically for the math assessment exam. For the past two years, data has been collected in this way through a detailed examination of student responses to a twenty question pre-calculus test (math assessment exam) that was administered in our first-year engineering program.

This study focuses on a subset of a current ongoing longitudinal study using two sets of data collected at different points in the students' first year of engineering to monitor their progress. The hypothesis is that these results could be used to make reliable predictions regarding the math deficiencies of students entering first-year engineering, so that interventions could be put in place to address these deficiencies.

Data

The approach taken for this study was to examine math assessment data from the last two years of an ongoing longitudinal study which started in 2000. Up until 2013, the math assessment exams were only administered prior to the start of the program with the intent of providing the students with a formative assessment of their math skills. As the research progressed, the study was extended to collect and analyze more data, as well as delving further into existing data.

It should be noted that the math assessment exam used in this study is not a standardized instrument. SAT scores are not used in admission assessment at our institution, but the students do complete a high school pre-calculus course prior to entering first year, and the math assessment exam is given to students prior to entry into the program. Previous research has indicated that the results from the math assessment test used in our program have been very consistent for the past fifteen years. The Cronbach's alpha for the test ranged from (0.55-0.69) throughout the time period of the overarching longitudinal study.

Two specific cases are considered in this study. The data for Case 1 was collected in 2013/2014 where the pre-university test was administered before the start of the program, and the post-test was administered at the end of the first-year year. The data for Case 2 was collected in 2014/2015 where the pre-university test was administered before the start of the program and the mid-test was administered midway through first-year.

The sample size in both cases was approximately 200 students for the pre-university test, with a slightly reduced group size due to attrition (approximately170) for both the mid and post-test scenarios. A summary of the results for each case is provided in Table 1. The data in Table 1 is collated in terms of question number (Q), question type (Type), percent correct for the sample considered both pre, mid and post-test, the number of students that responded correctly for both cases considered and the normalized gain (NGAIN). The normalized gain, used by Hake[11]and discussed at length in a paper by Colletta and Phillips[12] is defined as the change in score divided the maximum possible increase:

$$\boldsymbol{NGAIN = \frac{postscore\% - prescore\%}{100 - prescore\%}} \tag{1}$$

The question types used in this analysis are based on a classification scheme presented in an earlier paper[10], which consist of three types: A (algebra), T (trigonometry) and G (geometry). The detailed math assessment exam questions were also provided in the same paper. Colletta and Phillips[12] have indicated that normalized gain is a useful objective measure for comparing pre-test and post-test results, but care must be taken in interpreting the data. An attempt to correlate normalized gains with pre-university response correctness was unsuccessful for both cases considered in this study. Colletta and Phillips have also suggested that a lack of correlation between normalized gain and other quantities does not mean that correlations do not exist.

Several cells in Table 1 have been shaded to show post/mid-test performances of less than 50%. These are math assessment problems where less than half the class responds correctly. Q9 is common to both cases. It is a medium difficulty algebra problem with six solution steps. The question itself is the solution of a quadratic equation with unknown coefficients. Previous research showed that typically less than 30% of the students answered this question correctly each year for the last fourteen years. This is clearly a topic of concern that needs to be addressed, since it shows a lack of problem solving skill.

The trends in the data in Table 1 for both cases are very similar. The overall post/mid-test average increases in both cases. The overall post-test average for Case 2 is lower than Case 1. The post-test average for individual questions are higher than the pre-test averages in all cases but one (Q10). This happens in Case 2 only, where test was administered mid-term. The questions that have overall correct responses lower than 50% are shaded in the post/mid- term scenarios. This was done to illustrate deficiencies that have not been "corrected" as students progressed through their first-year program.

Table 1: Math Assessment Results Comparison – Summary

		Case 1 (2013/14)					Case 2 (2014/15)				
		Pre	**Post**	**Pre**	**Post**	**NGAIN**	**Pre**	**Mid**	**Pre**	**Mid**	**NGAIN**
Q	**Type**	**% correct**	**% correct**	**#**	**#**		**% correct**	**% correct**	**#**	**#**	
1	A	57	90	116	150	0.77	61	75	123	129	0.34
2	A	81	97	164	161	0.84	82	94	165	162	0.64
3	A	94	95	190	158	0.19	94	95	188	165	0.29
4	A	30	87	60	145	0.82	34	68	69	117	0.51
5	A	51	72	103	120	0.43	58	73	117	126	0.35
6	A	41	72	83	119	0.52	44	60	88	104	0.29
7	A	72	94	145	156	0.79	74	94	148	162	0.76
8	A	57	78	115	129	0.48	59	73	118	126	0.34
9	A	26	41	52	68	0.20	26	37	53	64	0.14
10	A	63	85	127	141	0.59	74	72	148	125	-0.05
11	A	43	60	86	99	0.30	34	49	68	84	0.22
12	G	45	53	90	88	0.15	47	47	94	82	0.01
13	G	36	51	72	85	0.24	34	48	69	83	0.21
14	G & T	36	54	72	90	0.29	31	52	63	90	0.30
15	G	40	56	81	93	0.27	41	56	83	97	0.25
16	A	93	96	188	159	0.39	90	97	181	167	0.65
17	G	46	67	92	111	0.39	48	73	97	127	0.49
18	T	26	62	53	103	0.49	33	55	67	95	0.32
19	T	27	64	54	106	0.51	32	64	64	111	0.47
20	T	26	57	53	95	0.42	23	36	46	63	0.18

Table 2 shows a subset of the data shown in Table 1, with the normalized gain (NGAIN) sorted in descending order based on Case 1, and with an additional question description column. This table more clearly illustrates the connection between question type and normalized gain between pre and post/mid-test results. An examination of the relationship between the two normalized gains gave a correlation coefficient of r = 0.56, which suggests a moderate correlation between the two data sets.

Table 2: Math Assessment Results – Normalized Gain Assessment

Q	Type	Case 1 (2013/14) NGAIN	Case 2 (2014/15) NGAIN	Question Description
2	A	0.84	0.64	simplify a quotient with numerator addition
4	A	0.82	0.51	sqrt function of addition of squares
7	A	0.79	0.76	simply exponents and evaluate
1	A	0.77	0.34	simplify a quotient with denominator addition
10	A	0.59	-0.05	solve a simple algebraic expression
6	A	0.52	0.29	equivalent expressions with square roots
19	T	0.51	0.47	simplify trigonometric expression
18	T	0.49	0.32	tan of an angle - knowledge of unit circle
8	A	0.48	0.34	factor a cubic polynomial
5	A	0.43	0.35	rationalize a denominator with square root
20	T	0.42	0.18	solve a trigonometric function
17	G	0.39	0.49	verbal problem with geometry
16	A	0.39	0.65	evaluate a function of a function
11	A	0.30	0.22	solve a verbal question two equations two unknowns
14	G & T	0.29	0.30	identify a graphical equation
15	G	0.27	0.25	find the vertex of a parabola
13	G	0.24	0.21	find points on a line of given slope
9	A	0.20	0.14	solve a quadratic with an unknown coefficient
3	A	0.19	0.29	add polynomials together - 3rd order highest
12	G	0.15	0.01	find slope of a line perpendicular to another one

The analysis continued with a more detailed treatment of the math assessment questions by classifying them in terms of difficulty and number of solution steps. This new classification scheme is presented in Table 3. Three difficulty classifications were used. Class 1 numerically classifies questions in order of difficulty from 1-20, with 1 being the easiest. Class 2 assigns categories of difficulty to each question: E (easy), M (medium) and H (hard). The third classification, Class 3 estimates the steps required to solve the problem. It should be noted that all three classification schemes are subjective, and were determined by the researchers.

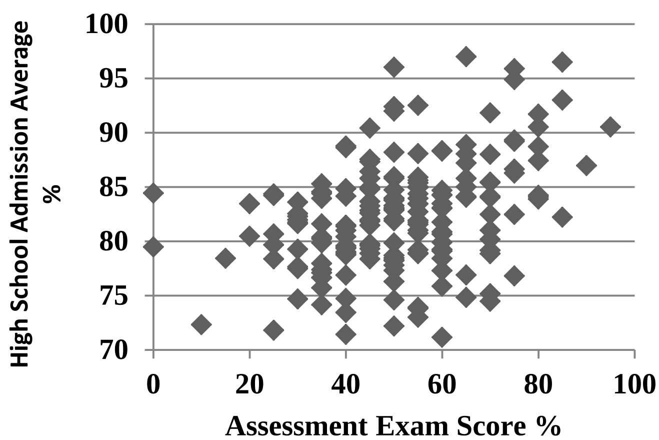
The next part of the analysis involved exploring relationships that might exist amongst various academic predictors on an individual per student basis. Individual student data was collated for students that participated in the math assessment exams and these results were correlated with high school achievement and first-year GPA. It should be noted that the data set was reduced to 144 students in this analysis, since some of the students had participated in only one testing scenario, and hence the normal gain was not relevant where two exam scores were not available.

In all cases, high school averages were calculated using five courses (MATH 30 (algebra), MATH 31 (calculus), PHYSICS 30, CHEM 30 and ENGL 30). Pearson correlation coefficients were calculated using excel. An example of the type of scatter seen in the data is presented in Figure 1 for high school averages as a function of the math assessment score in percent. The results presented in Figure 1 have a Pearson correlation $r = 0.4$. For this research the following interpretation was followed for the Pearson correlation coefficient: little or no correlation (0 – 0.3), weak correlation (0.3 – 0.5), moderate correlation (0.5 – 0.7), and high correlation (0.7 – 1.0) [13].

Table 3: Math Assessment Results Difficulty Categorization

Q	Class 1	Class 2	Class 3	Question Type
7	1	E	6	simply exponents and evaluate
2	2	E	6	simplify a quotient with numerator addition
11	3	E	8	solve a verbal question two equations two unknowns
3	4	E	4	add polynomials together - 3rd order highest
12	5	E	5	find slope of a line perpendicular to another lone
16	6	E	3	evaluate a function of a function
10	7	M	6	solve a simple algebraic expression
19	8	M	7	simplify trigonometric expression
6	9	M	7	equivalent expressions with square roots
4	10	M	7	sqrt function of addition of squares
8	11	M	10	factor a cubic polynomial
9	12	M	7	solve a quadratic with an unknown coefficient
13	13	M	8	find points on a line of given slope
20	14	M	11	solve a trigonometric function
18	15	H	6	tan of an angle - knowledge of unit circle
5	16	H	9	rationalize a denominator with square root
1	17	H	5	simplify a quotient with denominator addition
17	18	H	9	verbal problem with geometry
14	19	H	9	identify a graphical equation - circles, ellipses, parabolas, hyperbolas
15	20	H	9	find the vertex of a parabola

Figure 1: High School Admission average and Math Assessment Exam Score Mid-Test ($r = 0.40$, $p < 0.00001$) – Case 2



A summary of these results are presented in Table 4 for various correlation coefficients between the various quantities of interest. The math scores, designated A were correlated with the academic indicators, designated B. For the data analyzed, there were no strong correlations amongst the data. It should be further noted that cumulative GPA for first year was not available in Case 2 – N/A. The data was not analyzed for correlations between the individual high school course marks and the assessment data.

Table 4: Pearson correlation coefficients for various parameters in the study – Math Scores versus Academic Indicators

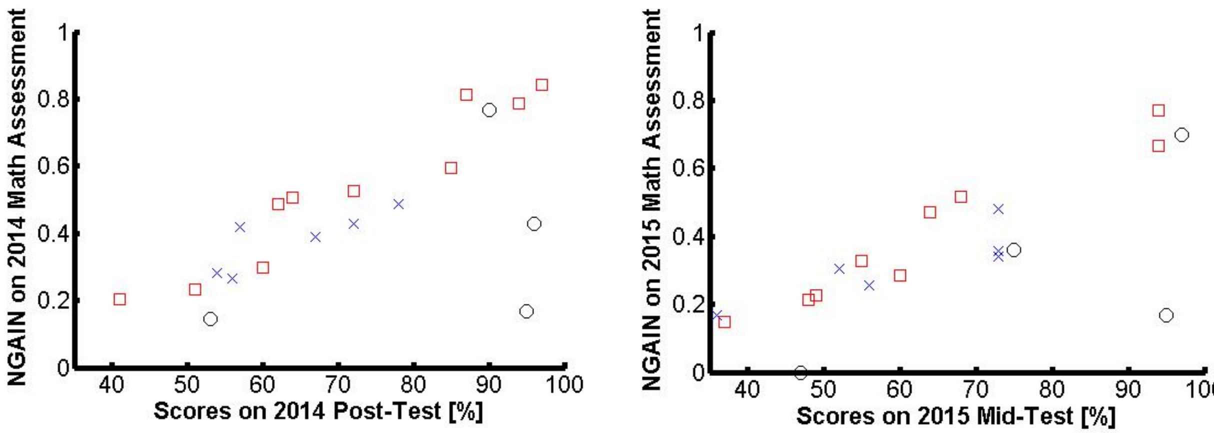
Academic Indicators B.	**A. Math Assessment Score**					
	Case 2 (2014/15)			**Case 1 (2013/14)**		
	Pre	**Mid**	**NGAIN**	**Pre**	**Post**	**NGAIN**
High School Admission Average	0.38 $p < 0.00001$	0.40 $p < 0.00001$	0.09 $p > 0.05$ Not significant	0.43 $p < 0.00001$	0.27 $p < 0.05$	-0.13 $p > 0.05$ Not Significant
1st Year TERMGPA	0.19 $p < 0.05$	0.36 $p < 0.00001$	0.20 $p < 0.05$	0.29 $p < 0.001$	0.48 $p < 0.00001$	0.20 $p < 0.05$
1st Year CUMGPA	N/A	N/A	N/A	0.30 $p < 0.05$	0.48 $p < 0.00001$	0.19 $p < 0.05$

To explore the connection between math assessment problem difficulty and the normalized gain achieved during the term, scatter plots were made for normalized gain versus scores for both the mid and post-test results. Three categories were chosen for the number of steps: i) 3-5, ii) 6-8, and iii) 9-11. These results are presented in Figure 2.

Discussion

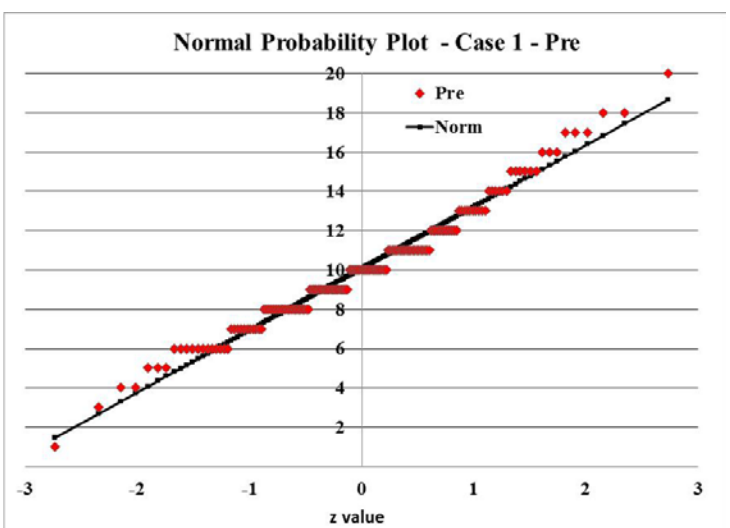
The overall averages on the assessment exam increased from 49% to 72% for Case 1 and from 50% to 66% for Case 2: statistically significant in both cases. First, the data for both cases was analyzed using a normal distribution probability plot to determine whether or not the data followed a normal distribution curve. Figure 3 shows the normal probability plot for Case 1 Pre-test, showing that the except for some tails at either end of the spectrum, the assumption that the data satisfies a normal distribution is reasonable. The other three scenarios including Case 1 – post-test, and Case 2 pre-test and mid-test were very similar to that shown in Figure 3. The means for the test cases were then examined using a two sample t-test with different variances and an ANOVA test. The conclusion reached was that in both cases, the post-test and mid-test means were significantly different than the pre-test values.

Figure 2: Scatter plots showing percentage scores vs. NGAIN with 3-5 steps (○), 6-8 steps(□) and 9-11 steps (x) – a) 2014 Post-test (Case1) b) 2015 Mid-test (Case 2)



a) b)

Figure 3: Normal Probability Plot for Data – Case 1 – Pre-Test



In an earlier paper, it was shown that the average achievement on the math assessment exam was not consistent with overall high school averages[10]. This was confirmed in the results shown here. The overall high school average for all of the students considered in this study was 80%. In both cases, the pre-university test average was approximately 50%, which is 30% lower.

The average on the post-test (Case 1 – 72%) was higher than the average on the mid-test (Case 2 – 66%) as expected. The overall performance on the math assessment exam was better in the post-test scenario compared to the mid-test scenario. This suggests that post/mid-test performance on the math assessment exam was influenced by the courses taken by the students during first-year either for the full year (post) or for one term (mid).

The correct response rate for individual questions was compared for each of the pre and post/mid exam results to determine subject areas where deficiencies continued to exist even after completing first-year math courses. Based on the classification scheme adopted in this analysis, deficiencies were most apparent in problem solving questions and trigonometry and geometry in all of the cases considered. Basic algebra skills improved substantially in both cases, although the degree of improvement was better in Case 1 than Case 2. From these results we would recommend that the first-year curriculum should increase the focus on problem solving strategies, not only in the math courses, but in the other first-year courses as well.

The normalized gain for Case 1 was correlated to the normalized gain for Case 2. There was a strong correlation between these two cases ($r = 0.74$). Typically, the gains for Case 2 were less than Case 1, but there were four questions where this was not the case: Q3, Q14, Q16, and Q17. Q3 and Q16 were easy questions, and Q14 and Q17 were hard questions. The gain in Q16 is a very large gain compared to the other three. Since this question is strongly algebraic and quite easy, the material was likely covered quite well in the math course given in the first term. The difference in gains for Q14 is likely not significant. Q14 is definitely problematic as the response rate on this question is consistently low (< 40%) from year to year.

The scatter plots shown in Figure 2 can be used to draw some qualitative conclusions. Problems with a low number of steps tend to see less improvement during the first term. Problems with mid and large number of steps tend to see the most improvement. There is little differentiation of problem difficulty and problem score. This was not expected since it was anticipated that there would be a strong correlation between problem difficulty and problem score. It is possible that the subjectivity in the classification scheme for problem difficulty and complexity have influenced the results obtained.

We were not able to find a correlation amongst high school averages, our math assessment scores and first-year GPAs. It is plausible that the math advisory exam may not be a reliable predictor of math readiness of our students, or that the high school grades are not consistent with the students' skills in the various subject areas. Students that enter our first-year program are able to upgrade their high school marks, and these upgraded marks may not necessarily reflect their achievement when compared to those students who do not upgrade.

Summary

We hypothesized that our math assessment exam might have the potential to be a predictor of first-year GPA, much like SAT-math scores in the US are predictors of first-year engineering success. This was not the case. As well, the authors were unable to find a strong correlation between high school marks and first-year GPA. This was unexpected, since high school marks have been noted as predictors of academic success in several US studies of first-year engineering students.

A positive outcome of the study is the statistically significant improvement in the math scores of the first-year engineering students considered in this study; between pre-university and post/mid-first-year. Interestingly, the post-test average is still less than the overall high school average of the students entering first year. Further research is needed to test the validity of our math assessment tool[14]. It might be useful to use a larger sample size in the analysis of the relationships between academic indicators and assessment results. Pre-university test data is available for a period spanning fourteen years.

Recommendations

The results from this study should be shared with mathematics articulation committees that deal with curriculum for the K-12 in schools in our region. Feedback might be useful in addressing the deficiencies seen in the pre-university math testing. The deficiencies in the math post-first-year testing might be addressed through increased concentration of curriculum particularly in geometry and trigonometry. The information regarding the types of questions that students typically have difficulty with could be shared with other instructors, especially those that each mathematics to the engineering students. Since the test is administered at the very beginning of first-year, this tool can provide feedback to both students and instructors in an attempt to address the weaknesses that the students have prior to studying first-year engineering.

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