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Understanding the cumulative effects of learning on the quality of engineering programs

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Abstract

The quality of engineers is an important issue in industrialised countries. This quality is commonly assured by the accreditation of engineering programs and the certification, licensure, and registration of graduates. A high-quality engineering program should be concerned with the quality of education of its graduates. This paper presents an analytical method for understanding the cumulative effects of competence acquisition in courses on the quality of engineering programs, thus allowing quality enhancement from a global perspective of the program. The proposed method was developed from a model established through the theory of Markov chains, considering the cumulative effects of acquisition of competencies over the semesters on the quality of engineering graduates. In the proposed model, the quality of engineering graduates is represented by discrete levels, numbered from 1 to 5, representing the worst to the best quality, respectively. This paper does not answer the question of how to achieve the desired quality or what learning methods could be used; however, the method can predict the quality of engineering education in a program and provide information to allow the faculty an opportunity to adjust their teaching during the program. The model explains how the heterogeneity of learning affects the average quality of engineering graduates. Understanding this process is critical to proactive quality management in engineering undergraduate programs.

Keywords

Engineering education, quality assurance, self assessment

Introduction

The quality of higher education is defined in Sparkes[1] as "a matter of specifying worthwhile learning goals and enabling students to achieve them". The quality of

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engineering education is an important issue, and neglecting it could lead a country or region to become less economically attractive and more dependent on other technology development centers. According to Shi-Mei et al.,[2] the quality assurance of engineer formation can be divided into three parts. The first part is professional accreditation of the engineering program. The second is professional certification, which certifies the competence of the candidate; however, certification is not a legal requirement for practicing a profession. The third is registration/licensure of the certificated engineers.

Commonly, countries use independent agencies for engineering programs accreditation such as the Accreditation Board for Engineering and Technology (ABET) in the United States and the European Federation of National Engineering Associations in Europe, e.g., ABET defines a set of student learning outcomes by which to measure U.S. engineering programs[3] and establishes the criteria for accreditation.[4]

Regulation/licensure is the process through which an engineer becomes authorised to provide professional services to the public. After completing an accredited university program in engineering, requirements for moving towards licensure vary considerably. In some countries the applicant takes a written examination to attest his/her knowledge and skills in a chosen engineering discipline. Other jurisdictions require a process akin to apprenticeship or the creation of a portfolio of engineering achievements. The model for the engineering program accreditation and regulation/licensure varies among countries.

According to Williams,[5] engineering program accreditation in the United States has shifted emphasis away from the simple counting of required courses to the documentation of student learning outcomes. Nevertheless, besides program accreditation, the administrators of engineering programs could use feedback on the performance of their former students in the licensure process as a control loop for adjusting their teaching strategies. The feedback for the engineering program coordinator, however, allows actions to be taken with very large time delays, typically over the length of the program.

Student outcomes describe what students are expected to know and are able to do at a given stage in the program. These relate to the skills, knowledge, and behaviours that students acquire as they progress through the program. A method of assessment for higher education was proposed by Astin,[6] in which the author suggested the ‘‘repeated assessment of the same qualities on the same students done at different points in time’’. According to Finelli and Wicks[7] the results of such assessment provide information that will allow the faculty an opportunity to adjust their teaching during the course, a baseline for assessing how much the students actually learn, and long-term feed-back on the overall effectiveness of the courses.

Extending the concept of assessment proposed in Astin[6] to the whole undergraduate program, the faculty could use a method to relate the student outcomes in the courses with the quality of technical formation of students at the end of the program, without having to wait for the student to complete the program.

Understanding how the degree of learning measured in each semester affects the final average quality of engineering graduates is critical to decision-making. This paper presents a methodology to address this issue. The proposed methodology can be used to establish goals for the minimal assessment of learning achievement in the courses to get the required quality of engineering graduates. A Markovian model was developed to predict the quality of graduates based on the end-of-course grades. The results show that even small variations in the academic performance index (API), calculated by an independent examination, have a huge impact on the final expected average quality at the end of the engineering program. The model uses an independent examination of students instead of grades in courses because assigning grades depends on toughness or leniency of instructors in grading and/or difficulty of their tests. However, in some cases, the grades in selected courses can still be used.

The rest of this paper is structured as follows: the next section describes the proposed model for predicting the cumulative effects of learning on the quality of graduates. Next, how the model can be parameterised is shown. The results and model validation are described next and finally the conclusions are presented.

A model to predict the quality of graduates

Typically, the curriculum of engineering programs consists of a number of courses offered at specific stages of the curriculum[8]; for example, the 2004 IEEE/ACM Curriculum Guidelines for Undergraduate Degree Programs in Computer Engineering[9] recommends three phases: introductory, intermediate, and advanced. The courses are commonly offered on semester basis, and there are typically a required number of core hours, according to the specific program objectives, and a prerequisite structure. Therefore, the engineer formation could be considered as a *cumulative process of acquisition of competences*. This is the basic hypothesis for the proposed model.

Suppose that the skills of a student at each semester of an engineering program can be evaluated using a quality of education index (QEI), represented by the numbers 1 to 5, with their corresponding meanings shown in Table 1. A QEI = 5 indicates that the student has developed all the competences expected at his/her

Table 1. Meaning of QEI.

API	Technical skill
5	Excellent
4	Good
3	Fair
2	Poor
1	Bad

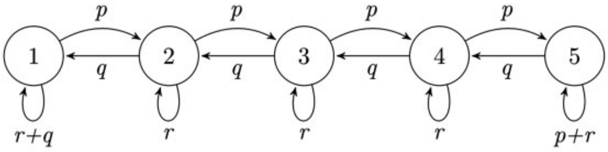

Figure 1. QEI over the semesters.

stage in the program, whereas a QEI = 1 indicates that the expected competences were not developed.

The proposed model supposes that the QEI varies over the semesters as result of the learning activities in the courses. At the end of each semester, there is a transition in the state diagram shown in Figure 1, e.g., in an engineering program of 10 semesters, there are at least 10 transitions. The initial QEI is given by the student's previous skills. The quality of engineering graduates is given by the final state after the required number of transitions has been completed.

Figure 1 also illustrates the probabilities of increase, decrease, or stabilization of the QEI, respectively given by *p, q*, and *r*. For the sake of simplicity, these probabilities are considered constant over the length of the program. The model could be easily rewritten to represent different transition probabilities for QEI, but the resulting equations would be significantly more complex. Nevertheless, with the assumption of constant probabilities, the overall behavior can yet be established. Thus, one can write

$$p + q + r = 1 \tag{1}$$

In contrast, changes in the QEI are dependent only on the current state. Thus, it is possible to write a Markov chain, according to the state transition diagram shown in Figure 1, which results in the probability transition matrix *P* given by the following equation

$$P = \begin{array}{c} \text{QEI} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{c} \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\ \begin{pmatrix} (r+q) & p & 0 & 0 & 0 \\ q & r & p & 0 & 0 \\ 0 & q & r & p & 0 \\ 0 & 0 & q & r & p \\ 0 & 0 & 0 & q & (p+r) \end{pmatrix} \end{array} \tag{2}$$

The resulting Markov chain is ergodic and regular; thus, it is possible to evaluate the steady-state distribution, given by the vector $W = [w_1\ w_2\ w_3\ w_4\ w_5]$ with $w_1 + w_2 + w_3 + w_4 + w_5 = 1$. Steady-state probabilities are used to describe the long-run behavior of a Markov chain and, in this case, indicate the probability to get a given QEI after a large enough number of transitions. The typical length of an engineering course is 8 to 10 semesters, which leads to a sufficient number of transitions for this assumption. If the program can be completed in 6 semesters or less, the Markov chain can still be used but by evaluating P^n, where n is the number of semesters.

The basic limit theorem of Markov chains indicates that the vector W can be obtained by solving $W \cdot P = W$.[10] Applying $r = 1 - (p+q)$ and solving the system of equations with the help of the algebraic manipulation software Maxima,[11] the steady-state vector can be written as

$$\begin{aligned} &w_1 = \frac{q^4}{A}, \quad w_2 = \frac{p \cdot q^3}{A}, \quad w_3 = \frac{p^2 \cdot q^2}{A}, \quad w_4 = \frac{p^3 \cdot q}{A}, \quad w_5 = \frac{p^4}{A}, \\ &A = q^4 + p \cdot q^3 + p^2 \cdot q^2 + p^3 \cdot q + q^4, \end{aligned} \tag{3}$$

where w_1, w_2, w_3, w_4, and w_5 are the steady state probabilities and A is an auxiliary term used to simplify the expressions.

The steady-state probabilities w_1, w_2, w_3, w_4, and w_5, represent the probability of the QEI being equal to 1, 2, 3, 4 and 5, respectively, after a sufficiently large number of semesters. The expected value of the QEI at the end of the program, denoted by μ, can be obtained by $\mu = w_1 + 2w_2 + 3w_3 + 4w_4 + 5w_5$. Used with equation (3), this expression may be given as

$$\mu = \frac{q^4 + 2 \cdot p \cdot q^3 + 3 \cdot p^2 \cdot q^2 + 4 \cdot p^3 \cdot q + 5 \cdot q^4}{q^4 + p \cdot q^3 + p^2 \cdot q^2 + p^3 \cdot q + q^4} \tag{4}$$

The probabilities p and q represent the efficiency of learning in the semesters. The variable μ can be used in two ways: for performance prediction, and for establish outcome assessment objectives for courses.

Planning goals and efficiency of teaching

To use the proposed model, the value of probabilities p, q, and r should be known. One possible way to get these values is through the academic performance index (API). The API is a metric calculated based on an independent evaluation of students, held each semester, as proposed by Finelli and Wicks.[7] Given a large enough group of students, the central limit theorem states that grades in this examination should converge to normal probability distribution.[12] Thus, the average API could be used to obtain the p, q, and r probabilities and vice-versa. The average API is represented by $\overline{API}$.

To obtain the values of p, q, and r, the following heuristics can be used:

1. A threshold should be established for whether or not learning is assumed to occur, T_2 and T_1, respectively. In the examples used in this article, these limits were set to $T_1 = 0.4$ and $T_2 = 0.6$.

2. The values p, r, and q can be obtained from the normal probability distribution, solving $P(X \leq T_1) = q$, $P(T_1 < X \leq T_2) = r$, and $P(X > T_2) = p$.

Figure 2(a) presents a case where $\overline{API} = 0.3$, with a standard deviation of 0.15. Figure 2(b) illustrates a case in which $\overline{API} = 0.5$, and Figure 2(c) shows $\overline{API} = 0.7$. Table 2 shows the values of p, q, and r for these examples.

Based on the values of p, q, and r, and using equation (4), one can find the value of μ. The average percentage of students expected to get a final grade of 1, 2, 3, 4, and 5 can also be obtained. Table 3 shows the results for the examples illustrated in Figure 2.

One can observe that small changes in the $\overline{API}$ over the semesters strongly affect the value of μ. Figure 3 shows that for the $\overline{API} = 0.5$, the final average quality of graduates is $\mu = 3$. For the other cases, $\overline{API} = 0.3$, and $\overline{API} = 0.7$, the average scores are approximately $\mu = 1$ and $\mu = 5$, respectively.

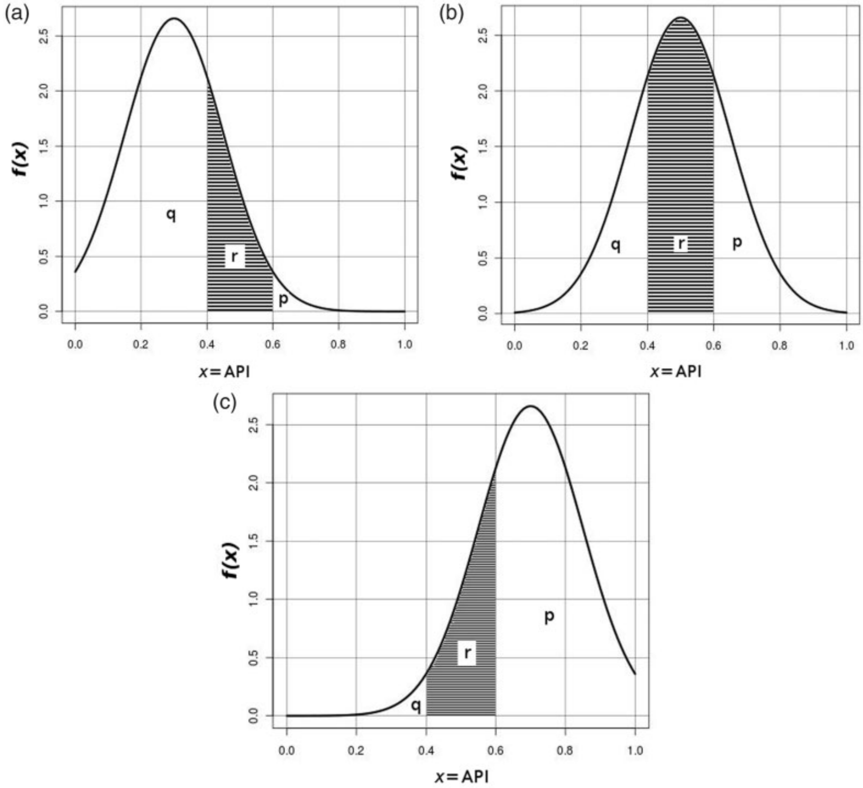

Figure 2. Example of the evaluation of *p, r,* and *q*: the horizontal axis represents the $\overline{API}$ and $f(x)$ represents the normal probability distribution function for $\overline{API} = 0.3$ (a), $\overline{API} = 0.5$ (b), and $\overline{API} = 0.7$ (c), all with a standard deviation of 0.15.

Figure 3 illustrates μ as a function of the variation in the $\overline{API}$ for the three situations previously stated. It can be seen that small variations in the $\overline{API}$ can lead to large variations in μ. In the curve illustrating the API standard deviation of 0.15, the $\overline{API} = 0.5$ results in $\mu = 3$. If the value of the $\overline{API}$ increases by 10% to 0.55, the average final expected quality will be approximately $\mu = 4.3$ (an increase of 43%), i.e. a small increase in the $\overline{API}$ over the semesters leads to a significant increase in the average quality of graduates.

Figure 3 also shows the effects of the standard deviation of the API. The results indicate that if the learning in courses is not homogeneous, i.e. there are significant differences in the end-of-course grades and a higher API standard deviation, it will be harder to increase μ with the increase in the $\overline{API}$. For instance, using the graph in Figure 3, to get $\mu = 4.75$, the $\overline{API}$ should be 0.55 for a standard deviation of 0.10. In order to get the same quality with a standard deviation of 0.25, the $\overline{API}$ should be 0.70. Thus, the ideal situation is to decrease the standard deviation of the API as much as possible. Practical observations show that the standard deviation of a normalised API is typically between 0.10 and 0.25.

In many cases, the courses evaluation system may not represent the actual acquisition of competence of students. The reasons for this are varied, and the analysis of the factors involved is beyond the scope of this article. It is important to note, however, that this could actually happen in many real situations.

Table 2. Values of *p, q*, and *r*, for the three examples in Figure 2.

	Case (a)	Case (b)	Case (c)
q	0.75	0.25	0.02
r	0.23	0.50	0.23
p	0.02	0.25	0.75

Table 3. Values of w_1, w_2, w_3, w_4, and w_5 for the cases in Figure 2.

	Case (a)	Case (b)	Case (c)
w_1	96.96%	20.00%	0.00%
w_2	2.95%	20.00%	0.00%
w_3	0.09	20.00%	0.09%
w_4	0.00%	20.00%	2.95%
w_5	0.00%	20.00%	96.96%
μ	1.03	3.00	4.97%

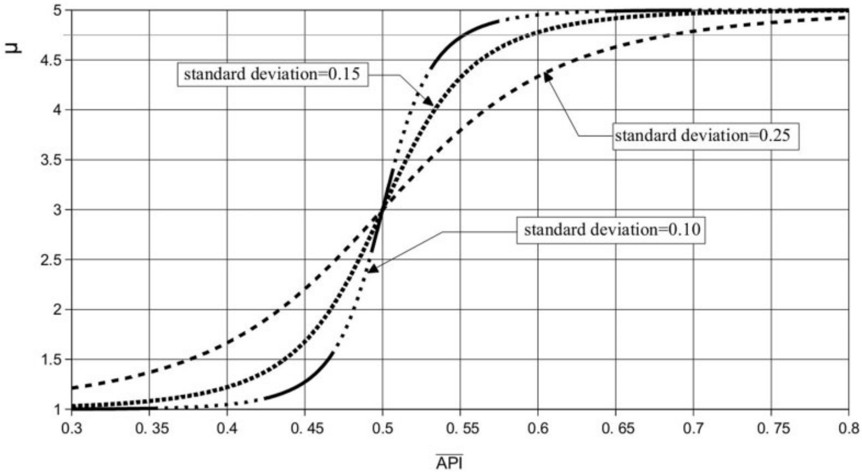

Figure 3. Variation of $\overline{API}$ and the correspondent consequences in the quality of graduates μ.

The independent examination applied to students at the end of each semester can provide a better estimate of the probability of learning. However, if is not possible accomplish such an examination, the use of grades of courses carefully chosen can still be used for approximating the result of and allow the analysis.

The systematic evaluation of the effectiveness of learning can be used for decision making by program coordinators. The faculty could achieve the desired final quality of graduates using the following procedure:

1. If the standard deviation of the API is higher than S_{max}, then the efficiency of learning is heterogeneous, and the program should consider offering recovery activities for weaker students. Such heterogeneity should be avoided because the effects of the increase in the $\overline{API}$ does not produce significant increases in μ for higher values of the API standard deviation. Ideally, the S_{max} value should be lower than 0.15 (see Figure 3).
2. If the goal of the program is to deliver a pre-established value of μ, then the minimal average grades, $\overline{API}$, over the semesters can be evaluated using equations (4) and (3) and through the inverse of normal probability distribution.

Results and discussion

In Brazil, the Ministry of Education evaluates undergraduate programs through a mandatory examination for all students completing the programs, held every three years for each area of knowledge. The students completing engineering programs in Brazil were given the examination in 2011, 2008, and 2005. All graduates must take the examination, which contains objective and subjective questions about their particular field of engineering. The exam consists of three sections: fundamentals of engineering, fundamentals of a particular discipline, and advanced topics. The result is estimative of μ and is used to validate the proposed model. The Ministry of Education also evaluates academic and support staff, as well as the educational facilities, but only the written examination of graduates is considered here.

The Pontifical Catholic University of Parana (Pontificia Universidade Catolica do Parana, PUCPR) is the second largest university by enrollment in Parana State, Brazil, with around 30,000 enrollees. PUCPR has engineering programs in the following main disciplines: Civil, Computer, Electrical, Mechanical, Chemical, Production, and Environmental Engineering. All these engineering programs have duration of 5 years, divided into 10 academic semesters, and the first two years are dedicated to basic disciplines, such as Calculus and Physics. The student is required to complete 6 to 8 courses each semester. At the end of each course, the student is given a grade, ranging from 0 to 100. The minimal grade for approval is 50.

The first estimate of program quality using the proposed model was made in 2004, using the normalised final grade of students in the discipline of Differential and Integral Calculus I to estimate the $\overline{API}$ and its standard deviation. This discipline is mandatory for students in the first semester of engineering programs. Based on the final grades in this discipline, the values of $p, r, q, w_1, w_2, w_3, w_4, w_5$, and μ were calculated. For this test, the parameters T_1 and T_2 were set to 40 and 60, respectively. The value of μ was then compared with the average grade of graduates in the examination given by the Ministry of Education. The purpose of the test was to compare the model output with the actual assessment for engineering programs in following disciplines: Civil, Computing, Environmental, Mechanical, Chemical and Production Engineering, with a total of 594 students. In this case, the examination results in 2008 were used.

Although is not recommended to use the grades of a specific course to estimate $\overline{API}$, when the procedure was first tested in 2004 there were no more reliable alternative. In subsequent years the engineering programs of PUCPR began to perform an annual *independent examination* to estimate $\overline{API}$ and its standard deviation. The purpose of the examination is to provide a reliable estimate of the $\overline{API}$. The examination is mandatory for all students, and is not prepared by the teachers responsible for courses; although evaluation of each discipline remains the responsibility of each teacher. Five different tests are elaborated every year. Each student must take the test compatible with their progress in the program. From the results of these evaluations, corrective actions were taken. Corrective actions were implemented over a period of seven years. These learning assessments have become an official part of the engineering programs of PUCPR. The costs for preparation of the examination are high, but the results have proven to be worth the investment. The analysis was not static, because we were actually interfering in the system, i.e., trying to reduce the standard deviation of the efficiency of learning. The actions involved thousands of students and many teachers in a dynamic process of

Table 4. Model results and actual examination results of graduates of several engineering disciplines in PUCPR.

	Civil	Computer	Environmental	Production	Electrical	Chemical	Mechanical
$\overline{API}$	0.588	0.464	0.622	0.305	0.369	0.584	0.411
$\overline{API}$ std.dev.	0.214	0.216	0.270	0.272	0.119	0.281	0.190
Students	101	66	37	106	73	111	100
q	0.189	0.384	0.205	0.636	0.602	0.257	0.477
r	0.590	0.396	0.574	0.143	0.177	0.522	0.302
p	0.221	0.221	0.221	0.221	0.221	0.221	0.221
w_1	14.35%	45.27%	17.16%	65.62%	63.74%	26.43%	54.91%
w_2	16.74%	26.08%	18.48%	22.78%	23.38%	22.73%	25.40%
w_3	19.53%	15.02%	19.89%	7.91%	8.58%	19.55%	11.75%
w_4	22.79%	8.65%	21.42%	2.74%	3.15%	16.82%	5.43%
w_5	26.59%	4.98%	23.06%	0.95%	1.15%	14.47%	2.51%
μ	3.31	2.02	3.15	1.51	1.55	2.70	1.75
Actual	3	2	3	2	4	3	3

medium/long term. The results shown in this paper are focused on evaluation points that coincide with the independent evaluation of the Brazilian Ministry of Education, but the adjustment process was dynamic over the years.

Table 4 provides a summary of the results for all programs under consideration. It also shows the $\overline{API}$ and its standard deviation, as well as the number of students in each engineering discipline, and the model results. For better visualization, Figure 4 illustrates the value of μ according the proposed model and the result of the examination by the Brazilian Ministry of Education of 2008. The grades for each engineering discipline were grouped with an ellipse. One can see that the model predicted with high accuracy, based on the $\overline{API}$, the quality of engineers for the engineering disciplines of Chemical, Civil, Computer, Mechanical, and Production.

The director of faculty of Electrical Engineering was, at that time in the year of 2004, concerned about student performance and started a recovery program in basic physics and math for freshmen. Over the coming years, the learning was evaluated by independent examination and recovery activities were offered to the courses which were identified heterogeneity of learning. As can be seen in Figure 4, the results were greatly positive. The model predicted $\mu = 1.55$, but in 2008 the same students concluding the program get an average grade of 4 in examination of Ministry of Education. The objective of recovery program was to increase the basic skills and reduce the heterogeneity of students' competences. In following years, the Electrical Engineering continue with same procedure and, in the examination of Ministry in 2011, the graduates were evaluated with grade 5.

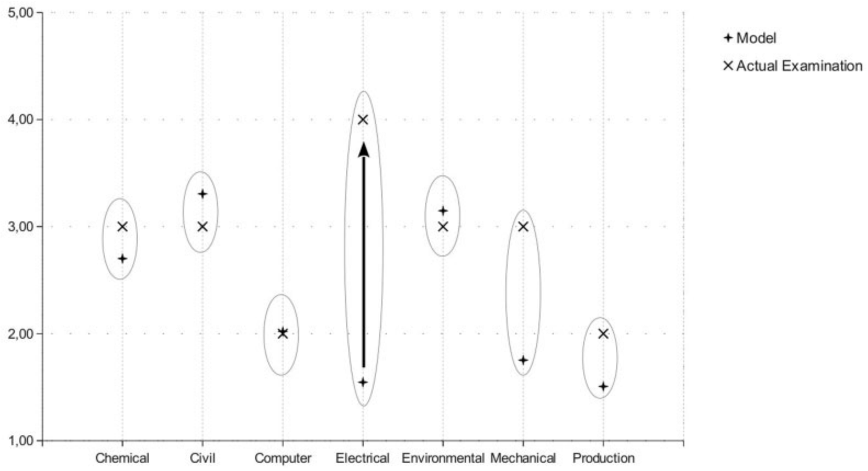

Figure 4. Model results and actual examination results of graduates.

Conclusions

The model presented in this paper may be used as a prediction and decision-making tool by engineering program coordinators. The results indicate that heterogeneity of learning in courses may strongly affect the final quality of graduates. The major contribution of the proposed model is that of providing a method that enables the systematic study of this phenomenon, allowing performance predictions and adjustments of strategies. The proposed model can be used to establish the goals, in terms of course outcomes assessment, required to achieve the desired quality of engineering graduates. Additionally, the model provides an explanation about the benefits and importance of maintaining the heterogeneity of learning between students.

The proposed model can also be used by institutions that receive students with major shortcomings in basic skills. The faculty could identify the fundamental skills potentially relevant to a particular program and evaluate the student's initial QEI. Supported with this information, the offer of recovery activities can reduce the heterogeneity of learning and increase the graduates' quality. The system of equations can be easily rewritten to determine the minimum $\overline{API}$ required to result in a desired quality by the time these students graduate. The faculty may also be interested in the effects of the admission of students with level 1 and 2 in the final quality of education if corrective actions are not taken. Another possible application of the proposed model is in the optimization of quality education and retention. These themes will be explored in a future work.

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