An Analytical Control System Model of Undergraduate Engineering Education

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Introduction

Engineering programs over the last two decades have been re-engineered in a vain attempt to increase enrollment but the failure has been dismal. From 1986 to 1996 the total number of university B.S. degrees increased by 18%, while engineering B.S. degree quantity decreased by about 19% [1]. We as engineering educators observed this decline and proposed innovative methods for stemming the trend. We suggested that engineering required too much abstract mathematics, too many hours to graduate, was too structured in format, had too little "design", and required more "real engineering" in the early semesters. Our presidents and academic vice presidents looked at engineering retention figures and suggested that if only our programs were modified to improve retention, all would be well. The problem is that we did those things without noticeable effects. Engineering students may have become "more fulfilled" as some would say and hopefully the quality and ability to work in the environment of the 21st century was improved. But the quantity of B.S. degrees did not go up; it went down.

Since our efforts have not produced the desired increase in B.S. quantity, some have asked if perhaps the problem lies within the K-12 school system. International test scores (TIMMS) show that U.S. students are at levels in Math and Science below all other industrialized countries [2]. Students are not being challenged nor taught critical thinking skills. Some would say high school teachers are not sufficiently trained or are assigned courses out of their competency [3]. Perhaps the solution to our problem lies in improving the K-12 system.

Our real weakness, however, is that we have never stopped to analyze the problem. We teach our students that the first step in engineering problem solving is to "define the problem"; yet we have not done that ourselves. We have gathered all manner of data and performed a variety of "longitudinal" studies. We have proposed a variety of approaches, but by and large have solved the wrong problems and missed addressing the actual one. Our efforts have been basically futile because we do not understand in detail how the educational system works.

The purpose of this paper is to present the development of an analytical system model that describes the fundamental operation of the B.S. educational system. Once such a model is identified it is then possible to set about analyzing its operation and revealing the relationships that govern the process of producing B.S. graduates. Only then can we define the problem in concrete terms and propose program activities that truly address the need.

The Engineering Pathway Model

The engineering education process must be clearly understood before realistic efforts can be made to design a program that will significantly and cost-effectively increase the number of B.S. degrees earned in engineering. To aid in that preemptive task, we have developed a control system model of the education process as shown in Figure 1.

There are two system inputs: the number of middle school students, N_i, entering the eighth and ninth grades and the number of engineers, N_{req}, needed by U.S. companies and government. The output, N_o, is the number of B.S. degrees earned from U.S. institutions granting engineering degrees. System elements consist of an eighth-ninth grade block, a high school block, and the university engineering program block. There is also a recruitment block which models the effects of industry and other institutions recruiting B.S. graduates to satisfy the annually changing needs for trained engineers. The model is a discrete time system. Blocks are defined in terms of a transfer coefficient and a delay. The transfer coefficients have values between 0 and 1 and represent the fraction of input students, on the engineering education pathway, who show up at the block output still on the B.S. pathway. The delay term of each block is simply the time duration in years required for students to pass through the block. For example, one can observe from Figure 1 that the delay for the high school block (grades 10 through 12) is, as one would expect, three years.

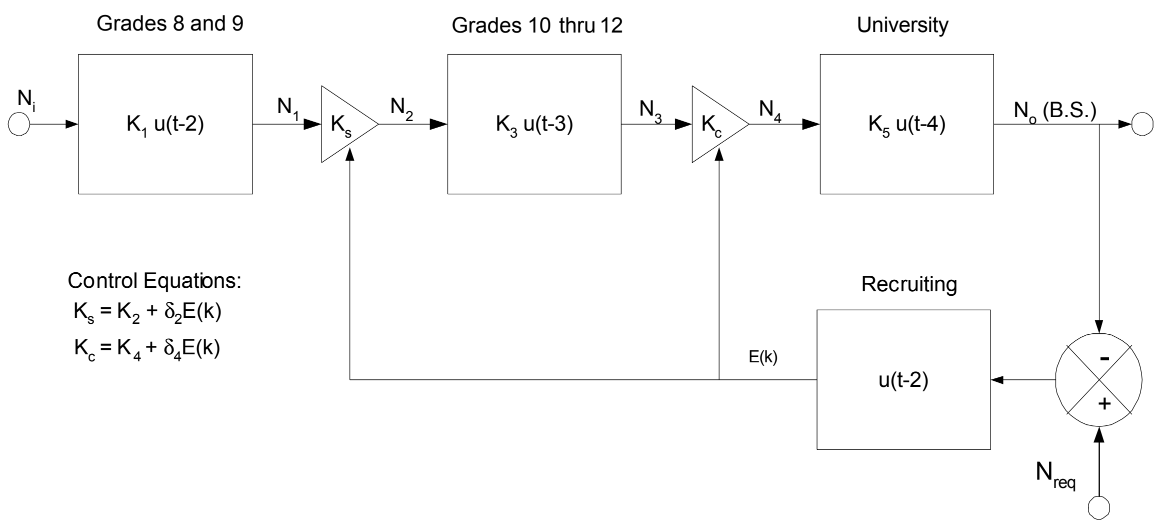

Figure 1: Control System Model of the Engineering B.S. Degree Process

An interesting aspect of the model is that coefficients K_s and K_c are not constant but rather are functionally related to the difference signal created when the actual output and the required number of B.S. degrees are not equal. This difference signal, called E(k), modulates the values of K_s and K_c and hence, the total quantity of students progressing through the system. Justification for this feedback is supplied in the literature [4]. If the output of bachelor degrees is less than the value of N_{req}, a positive difference signal is formed and feeds back into the system in such a way as to increase the fraction of students that remain on the engineering pathway. K_s stands for "School system input coefficient" and K_c stands for "College system input coefficient". Each of these coefficients is the sum of two terms. The functional relationship for K_s is

$$K_s = K_2 + \delta_2 E[t-2] \quad (1)$$

Thus, if the difference signal, two years prior to the present time, is zero then $K_s = K_2$. The term δ_2 is the slope of the control relationship and determines the change in K_s caused by a difference magnitude E(k) delayed by two years. The model assumes that it takes approximately two years for the industrial recruiting system to recognize the need for modification of recruiting effort. The upper value of δ_2 is bounded by stability considerations. In a practical situation, the value of K_s is dominated by the value of K_2 and differs from K_2 by only a few percent. The parameter K_c operates similarly and is controlled by parameters K_4 and δ_4.

The system difference equations are easily derived from the interconnections defined in Figure 1, as stated below. The system node values, N_1 through N_4, represent the number of students still on the engineering pathway:

$$N_1 = K_1 N_i[t-1] \quad (2)$$

$$N_2 = (K_2 + \delta_2 E[t-2]) N_1 \quad (3)$$

$$N_3 = K_3 N_2[t-3] \quad (4)$$

$$N_4 = (K_4 + \delta_4 E[t-2]) N_3 \quad (5)$$

$$N_o = K_5 N_4[t-4] \quad (6)$$

Realistically valid values of system parameters are derived from NSF pipeline numbers [5], population statistics [6], and data from the American Association of Engineering Societies [7]. The parameter meanings and magnitudes are stated in Table 1 and detailed magnitude derivations are given in Appendix 1. (In Table 1, MPC stands for Math-Physics-Chemistry courses.) The values of δ_2 and δ_4 are chosen to be 0.0015 and 0.0025 respectively. These are based on an upper bound associated with system stability and a lower bound associated with realistic control action due to recruiting activities. Operating the system with these parameter values results in a steady state output of about 60,000 B.S. degrees per year. This value is consistent with the actual present production rate of undergraduate engineers reported to be 62,000 [8].

Even though the model can be run with the input N_i chosen to match any past or future demographic data, we report here only results obtained by holding N_i constant at 3,500,000 students. This is the number of eighth grade students reported by the National Council for Education Statistics (NCES) for 1998 [6].

Table 1: Control System Model Parameters

Name	Function	Value
K_1	Fraction of middle school graduates prepared to take high school MPC courses	0.18
K_2	Main component of K_s, the fraction of middle school students prepared to take high school MPC courses who actually enroll in those courses	0.75
K_3	Fraction of high school students who actually complete the MPC courses (high school pathway retention)	0.81
K_4	Main component of K_c, the fraction of high school students having taken all MPC courses who actually enroll in engineering	0.22
K_5	Fraction of engineering enrollees who actually complete the educational program requirements (engineering retention)	0.61

System Operation

Figure 2 shows the system response assuming all inputs and parameter values remain constant.

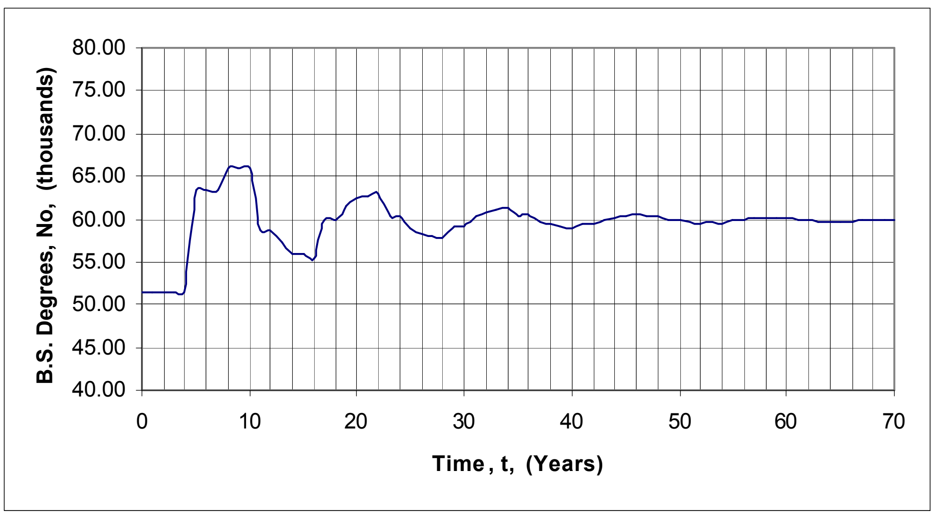

Figure 2: Nominal System Response Using K Values from Table 1
Inputs are N_i = 3,500,000 students and N_{req} = 72,000 B.S. degrees

The initial system output, at about 50,000 B.S. degrees, is artificial because of the initialization process involving the required system delays. The value for the first four time increments has no physical meaning. However, note the long delay of about 30 years to achieve a stable output. In actual runs with a progressively changing value of N_i this is not nearly so obvious. Nevertheless, there is a characteristically long stabilization time inherent in the educational system. Changes require a long time to propagate through the system given the long natural delays. We must recognize this when instituting programs for change.

An inherent long-term periodicity of slightly over 12 years is also observed. This is caused by the feedback path values of the δ's and the inherent delays associated with system blocks. Most whom have been educators for over 30 years have recognized the existence of this periodic action. However, the inherent system periodicity is not always obvious because of superimposed perturbations associated with business cycles.

Even though the required value of B.S. degrees, N_{req}, is assumed constant at 72,000, the system stabilizes approximately at $N_o = 60{,}000$. The importance of this observation must be understood. Given the system parameter values and an input of $N_i = 3{,}500{,}000$ students, an output of only 60,000 B.S. degrees is possible. In times past this was not an obvious output limitation because the number of incoming students kept rising. However, if the input quantity is constrained, we see the present set of system parameters inherently limits the number of output B.S. degrees. The meaning of this reality is not very startling, but is nonetheless important to recognize. To change the output we must change at least one or more system coefficients. As we set about to "define the problem" we must recognize what it is we are required to do, i.e. change the values of the K's.

The system is easily programmed using a simple Excel spreadsheet. The first spreadsheet column tracks time, with each row representing one year. The second column represents annual values of the input N_i and the third the values of N_{req}. Succeeding columns represent system node values of students on the engineering pathway in thousands. They are successively N_1, N_2, N_3, N_4, N_o, and (N_{req}-N_o). The cells are each programmed with an equation as given by Equations (2-6).

Figure 2 depicts system operation when the input is held constant. Holding N_i constant reveals the functional characteristics of the system. Additionally, demographic data predicts that this value in the real world educational system is expected to change very little. The NCES [6] projects that the eighth grade population will peak at about 3,700,000 in 2003 and then decrease slowly for the foreseeable future. This trend is confirmed by data published by the Western Interstate Commission for Higher Education [9]. This means that we cannot depend on an increased input value to create the additionally needed number of engineering B.S. degrees. Considering only civil, mechanical, and electrical engineers, the U.S. Bureau of Labor Statistics Occupational Employment data projects a need of 20,000 additional jobs by 2010 [10]. The same source indicates we might need a similar or even larger increment for computer software and applications engineers. These increments are impossible to attain with the present set of system parameters. That problem is evidenced by the number of available H-1B visas in amounts of nearly 200,000, as indicated in Congressional Bill S.2045 (1988) and presently amended upward [11].

It is instructive to run the model under conditions that produce verifiable operation. For example, Figure 3 shows the system operation if the feedback terms δ_2 and δ_4 are set equal to zero.

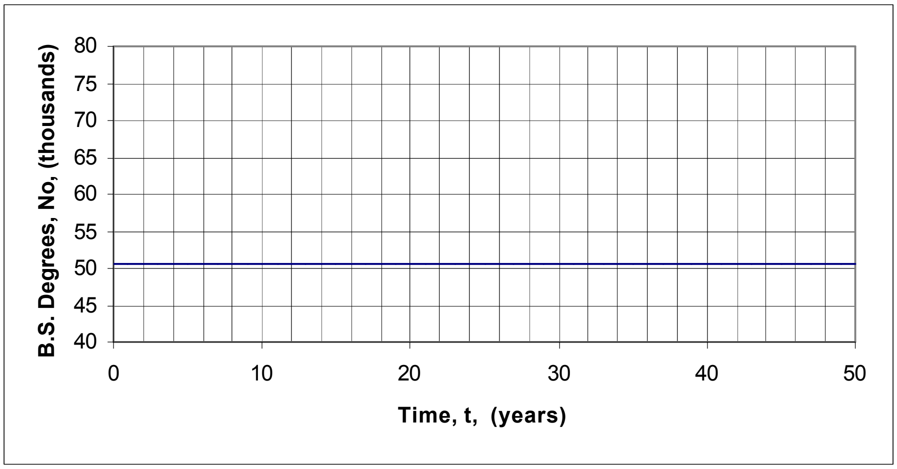

Figure 3: System Response with Zero Feedback
δ_2 and δ_4 both equal zero

Note in this case the oscillatory response no longer exists. In addition, the response is constant at a little over N_o = 50,000 B.S. degrees. Based on the block diagram, this magnitude should be equal to the input value of 3,500,00 multiplied by the open loop gain. This gain is the product of the transfer coefficients, $(K_1)(K_2)(K_3)(K_4)(K_5)$. This theoretical value computes to N_o = 50,500, completely in agreement with the observed response.

A second test run performed observes the system response to a step function change in the required number of B.S. degrees. Assume that we introduce a step increment in N_{req} from 72,000 to 82,000, i.e. an increment of 10,000 bachelor degrees or almost 15%. That amount is about 50% of what might be realistically expected over the next decade [10]. Based on the fact that the system could not reach the specified 72,000 B.S. degrees of Figure 2, we would expect the output to stabilize at some level significantly short of the 82,000 input value. Figure 4 shows the result.

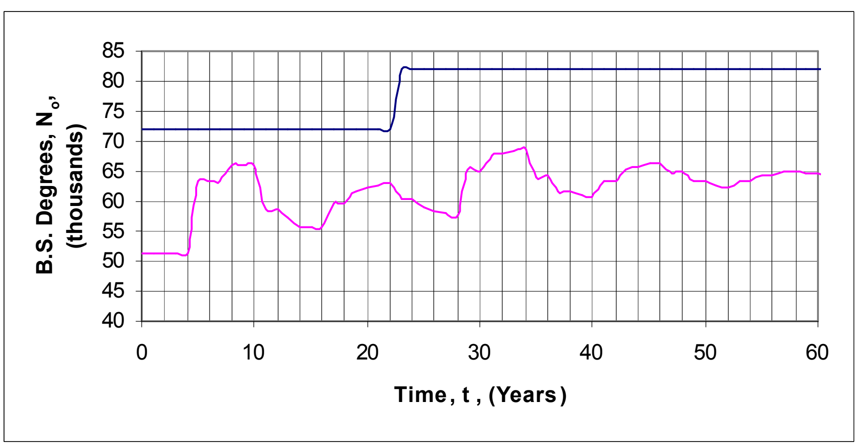

Figure 4: System Response with Step Input on N_{req} at t = 22 years

Note that the step change takes place at year 22, when the system is about to stabilize at an output of 60,000 B.S. degrees. The input change in required degrees from 72,000 to 82,000 begins a process, albeit delayed by about six years, where the output increases towards its new stable level. From Figure 4 it is obvious that the new output value will be somewhat less than 64,000 B.S. degrees. This value is dramatically lower than the value of N_{req}. Prior to the input step, the system shortfall was about 12,000 B. S. degrees, (72,000 – 60,000). After the step, the shortfall is about 18,000 B.S. degrees (82,000 – 64,000). N_o increases but not nearly enough.

It is data of the type shown in Figure 4 that begins to illuminate the fundamental limitation of the present engineering B.S. level educational system. The present system will simply not produce the required number of degrees. The higher the number of degrees required, the greater becomes the disparity between the actual number of degrees produced and the number needed. The key question now is: "Which system parameters should be changed in order to generate the required number of degrees?"

Using the Model

Of course it is possible to compute "what-if" results. One can simply assume a new value for a system coefficient, for example K_3, and then run the model with an input N_i to find out what will happen. We propose a more sophisticated approach towards the goal of predicting what must be done to effectively produce more engineering graduates.

First, the model helps us think about the problem. It is clear that what we must do is make changes to the system transfer coefficients. It would be helpful if each system block had a "crank" on the side so that we could simply adjust each coefficient at will. Alas, such is not the case. But if we first develop an understanding of the influence that each coefficient has on the output, it will at least be possible to identify which coefficients are the most responsive in producing a change in the output. Once that has been identified we might propose new goals for the values of these coefficients and then use the model to verify that they do in fact project the desired output change. Finally, by understanding the physical meaning of each coefficient one is able to then propose an "action" in the real world that should in turn cause the desired increment in the appropriate coefficient. We therefore suggest the following problem definition:

> The problem is to find the coefficients that most easily cause a change in N_o, and then develop an external action plan which carries out specified tasks directed to changing the appropriate coefficients. As that plan is executed, use the model to verify that the desired changes are being affected in the educational system and, if required, make adjustments to the plan. Incorporate the model into the "evaluation" phase of the plan to accurately quantify results.

In order to evaluate the relative steady state sensitivity of the output to changes in system coefficients, a simple "what-if" analysis is performed. Holding inputs constant, and varying only one system coefficient at a time, the observed steady state value of N_o was recorded. In each case the increment was a constant value of $\Delta K_i = 0.01$, where *i* is an integer between 1 and 5. For example, when K_1 was changed, it was incremented from its nominal value of $K_1 = 0.18$ to $K_1 = 0.19$. From the resultant system runs it is possible to determine the change in output in thousands of B.S. degrees per increment ΔK_i, as depicted in Table 2.

Table 2: Increment in B.S. Degrees per Unit Basis Increment in K_i

Parameter Changed	K_1	K_2	K_3	K_4	K_5
$\Delta N_o / \Delta K_i$	194	45	43	136	58

Note from these results that the output is significantly more sensitive to a change in K_1 than a change in any other system parameter. In fact, a change in K_1 will produce almost three times the increment in B.S. degrees as the same change in K_5. Recall that K_5 represents the retention rate in the university B.S. program. Already, we can see that the historically "obvious" action of attempting to increase the university retention rate is an activity encumbered with a parameter of low sensitivity. Of course improving this university retention value of K_5 will increase output, but for a given amount of "effort", considerably greater effect will be likely if we work on improving K_1 or K_4.

The term $\Delta N_o / \Delta K_i$ is only part of the practical problem in changing N_o. We know from experience that as the value of K_i approaches 1, it becomes more difficult to affect a change in magnitude. Thus, if the engineering program retention rate is 20% ($K_5 = 0.20$), it is not too difficult to raise it to 30%. However, if retention is already 70%, it becomes much more difficult to raise it to 80%. The functional relationship between "required effort" and K_i magnitude is not clearly known. However, to the first order we can arrive at the correct conceptual effect by assuming a simple linear relationship. Thus, we propose that the actual "control" of the output depends both on the term $\Delta N_o / \Delta K_i$ of Table 2 as well as the nearness of the actual K_i value to a magnitude of 1. The analysis follows.

We assume that the effect of executing a certain educational program will be to create a "force", F, which will change the value of a particular system coefficient K_i. The change of coefficient K_i will in turn create a change in the system output N_o. Assume also that the effects of multiple engineering program components will modify each model coefficient according to superposition. The result of instituting the program could then be expressed as:

$$\Delta N_o = \frac{\partial N_o}{\partial K_1} dK_1 + \frac{\partial N_o}{\partial K_2} dK_2 + \Lambda + \frac{\partial N_o}{\partial K_n} dK_n \tag{7}$$

To the first order, assume the change in the nth coefficient "dK_n" is related both to the value of the force F_n created by the program as well as the fact that as the coefficient magnitude approaches a value of 1, the effect of F_n on the value of K_n approaches zero. In the simplest linear assumption these approximations then yield:

$$\Delta N_o = \frac{\partial N_o}{\partial K_1}\frac{\partial K_1}{\partial F_1} F_1(1-K_1) + \frac{\partial N_o}{\partial K_2}\frac{\partial K_2}{\partial F_2} F_2(1-K_2) + \Lambda + \frac{\partial N_o}{\partial K_n}\frac{\partial K_n}{\partial F_n} F_n(1-K_n) \tag{8}$$

The values of F_n and the slopes $\partial K / \partial F$ are not explicitly known. However, the values of the K's are approximately known and are given in Table 1. The values of $\partial No / \partial Ki$ can be approximated by the numbers in Table 2. Incorporating these numbers into Equation 8 gives:

$$\Delta N_o = (194)(1-0.18)\frac{\partial K_1}{\partial F_1}F_1 + (45)(1-0.75)\frac{\partial K_2}{\partial F_2}F_2 + \Lambda + (58)(1-0.61)\frac{\partial K_5}{\partial F_5}F_5 \qquad (9)$$

The forcing function terms are dependent on program design. However, it is reasonable to assume that with careful program design, these terms could all be structured to be approximately equal. Given that characteristic, the relative effect of each term is represented by the magnitude of the numeric coefficient. Table 3 presents these effectiveness magnitudes.

Table 3: Measures of Effectiveness Associated with Each System Parameter

Related K_i	Effectiveness Magnitude	Educational System Parameter
K_1	159.1	Fraction of middle school graduates prepared to take high school MPC courses
K_2	11.3	Fraction of prepared middle school graduates who actually enroll in high school MPC courses
K_3	8.2	High school retention fraction
K_4	106.1	Fraction of high school graduates prepared with MPC courses who actually enroll in engineering programs
K_5	22.6	Engineering program retention fraction

From Table 3, we deduce that the goal of increasing engineering B.S. degrees should be attacked by increasing the value of K_1. Expressed in terms of the educational system, the most significant effort to increase engineering B.S. degrees should be expended in motivating more middle school students to prepare themselves to take the Math-Physics-Chemistry (MPC) courses. Middle school consultants confirm that there are numerous middle school students who possess the requisite intellectual capacity to succeed in the MPC courses but who are not presently motivated to prepare for that track.

The second most effective parameter to increase is K_4. That is, we must structure program components that increase the fraction of MPC prepared high school students who actually enroll in engineering programs. This effort is purely motivational and informational in nature. These students have the requisite preparatory courses. In obtaining them they have demonstrated they possess the required intellectual attributes. Pipeline data [5] indicates that at present only about 22% of those prepared students actually enroll in engineering programs. Rather, they often choose non math-and-science university tracks. It should be noted that most high school students select their university track and institution during their senior school year. Any program geared to increasing the value of K_4 must function prior to the September-June time frame of the senior year.

Conclusion

Increasing the number of undergraduate B.S. engineering degrees is a task of national importance. Numerous ideas have been generated and implemented in order to solve the current shortfall. But without a system model that accurately mirrors actual B.S. degree processing, these ideas have no support or justification that they will have the desired effect. After all, the first step in an engineering design problem is problem identification. In this paper, we have provided an analytical model that properly identifies the problem. A simple adaptive system has been developed and sensitivity factors calculated for all involved system parameters. Using actual engineering pathway data reported by several sources, the system's performance has been verified. Additionally, simple scenarios have been posed to demonstrate the model's usefulness for predicting the effect of changing a model parameter or system input.

With the development of the model described in this paper, we have shown that there are places in the education pathway that are more critical and responsive to change than others. In particular, the parameter representing the fraction of middle school graduates prepared to take high school math, physics, and chemistry courses has a sensitivity factor of almost three times that of other parameters. By a factor of two, the next most sensitive parameter is the fraction of high school graduates prepared with math, physics, and chemistry courses who actually enroll in engineering programs. Our analysis concludes that the alternatives (focusing on both high school and undergraduate retention rates) will not significantly affect the number of engineering degrees produced annually.

The model provides a necessary fundamental understanding of how the educational system works and the responsiveness of each system coefficient. This helps define which coefficient should be modified and what real-world actions might be performed to modify the specific system coefficient. Thus, the College of Engineering at Ohio Northern University has focused on modifying the choices in course selection made by middle school students and in maintaining their long-term motivation. After consulting with local high school educators, our college has initiated a unique set of programs whereby engineering faculty and undergraduate students interact with middle school and high school students. The initial response has been positive, and it is hoped that data gleamed from this outreach will further confirm the model's operation and enable engineering educators to properly design solutions to the posed problem of producing enough B.S. engineering degrees to meet society's needs.

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Appendix 1

The model parameters are identified from a variety of data, including the following table from the National Science Foundation. Here, NS&E refers to Natural Science and Engineering.

Table 4: The Pipeline
Persistence of Natural Science and Engineering Interest from High School through Ph.D. Degree

Date	Group Definition	Model Node	Number of Students
1977	All High School Sophomores		4,000,000
	High School Sophomores with NS&E Interest		730,000
1979	High School Seniors with NS&E Interest	N_3	590,000
1980	College Freshmen with NS&E Intentions	N_4	340,000
1984	B.S. Graduates in NS&E	N_o	208,000
	Graduate Students in NS&E Programs	--	61,000
1986	Masters Degrees in NS&E	--	46,000
1992	Ph.D. Degrees in NS&E	--	9,700

Estimate of K_1:
K_1 is the percentage of students leaving middle school with NS&E qualifications and interest, and is the ratio of two terms: the sum of 8th grade and 9th grade students passing algebra versus the total number of 8th grade and 9th grade students.

However, the Pipeline information does not include middle school data. We assume this ratio is reasonably close to the ratio obtained from the Pipeline data of high school sophomores with NS&E interest versus all high school sophomores. From Table 4,

$$K_1 = (730{,}000) / (4{,}000{,}000) = 0.18 .$$

Estimate of K_2:
The percentage of students interested in NS&E at graduation from middle school who enroll in NS&E courses at the beginning of high school.

K_2 numerator = number of 10th grade students committed to NS&E sequence delayed by 1 year.
K_2 denominator = number of 8th grade plus 9th grade students passing algebra

This information is not available from the Pipeline data given above. At present the required data has not been located from any source, though we feel it likely exists. Instead, we have identified all other system parameters, established verifiable input and output data pairs, and determined this one unknown value using an elementary system identification method. K_2 has been found to be 0.75.

Estimate of K_3:
The parameter K_3 is the percentage of students who entered high school on the engineering pathway and actually completed all the pathway courses (the high school pathway retention).

> K_3 numerator = number of seniors having taken all college recommended courses, including physics
> K_3 denominator = number of sophomores enrolling in NS&E courses.
>
> K_3 numerator = 590,000 (from the Pipeline data)
> K_3 denominator = 730,000 (from the Pipeline data)

Thus,

> K_3 = 590,000 / 730,000 = 0.81 .

Estimate of K_4:
The parameter K_4 is the percentage of students qualified with the high school prerequisites necessary for engineering who actually enroll in an engineering program the following year.

> K_4 numerator = number of university freshmen in 1980 enrolled in engineering
> K_4 denominator = number of high school seniors having taken all college recommended courses including physics
>
> K_4 numerator = 95,000; from *Engineers,* April, 1997, Figure on page 12
>
> K_4 Denominator: Compute the number of senior students graduating with all engineering entrance requirements. These are estimated as those courses recommended by the National Commission on Excellence in Education for college bound students. In 1990, 18.3% of the graduating seniors satisfied this criterion [7].

The number of graduating seniors is 2,392,000 students, as stated in http://nces.ed.gov/pubs2001/proj01/tables/table03.asp. Note this reference gives the number of senior students not the number of graduates; thus the denominator is likely a little smaller than the value used here. As a result, the actual value of K_4 will be a little larger than calculated using this method.

Thus, K_4 = 95,000 / ((0.183)(2,392,000)) = 0.22

Estimate of K_5:
The parameter K_5 physically represents the university engineering retention percentage.

> K_5 numerator = number of graduating B.S. degrees at time t+4
> K_5 denominator = number of freshmen enrolled at time t

Both numerator and denominator are given by the Pipeline table above.

$$K_5 = 208{,}000 / 340{,}000 = 0.61$$

Note: This number seems a bit high, especially for large public institutions but will be used as computed in the body of this paper.

Estimates for δ_2, and δ_4:
The values of the feedback coefficients δ_2 and δ_4 can be assumed somewhere around the value of 0.002 since higher values result in atypical system oscillation and lower values produce an insignificant effect. We assume that the effect of δ_4 will be larger than that of δ_2 because it is nearer the time of graduation. We therefore choose $\delta_2 = 0.0015$ and $\delta_4 = 0.0025$.

Estimate of N_o:
The predicted value of N_o should agree with the actual observed number of B.S. degrees granted in the U.S. Numerous sources provide this information but we will here use the value reported in Figure 4-11 of the NSF report "Science & Engineering Indicators – 2000". The figure carries the title Bachelor's degrees earned in selected S&E fields: 1966-96. The value reported is:

$$N_o(1990\text{-}1996) = 62{,}000 \text{ B.S. diplomas}$$

Appendix 2

In this appendix we propose to illustrate, through actual runs of the model, the significance of the model's application to the problem of increasing the number of B.S. degrees.

The first analysis shows the system's capability of producing an increased number of B.S. degrees in response to a change in the input parameter N_{req}. Figures 10, 11, and 12 show the model's operation. The input represents a condition wherein the required number of B.S. degrees increases from the present value of 72,000 to 82,000 over a decade interval.

First, observe the model printout shown in Figure 10. (This figure is shown on the next page.) Every line represents the model state for one time interval. The first column represents discrete sequential time intervals. The first 35 intervals can be assumed as initialization intervals, necessary to start the model and reach steady state. The second column represents real time after the initialization steps. This column starts at step 35 with a value of zero, and represents real time from that time on. Each step is one year. The next five columns contain the values of the system coefficients K_1 through K_5. The system can be run for different profiles of any or all of the K's by simply entering into these columns appropriate magnitudes at different values of time. The values assumed for the parameters δ_2 and δ_4 are time invariant and entered into cells at the top of the spreadsheet. The next two columns are the inputs specifying the number of students in middle school, N_i, and the number of engineers required by our social system, N_{req}. The next five columns represent the computed node values as specified in Equations (2-6) of the body of the paper. The last column of this group, N_o, is the system output and the number of B.S. degrees produced by the system. The last column, N_{req}-N_o, is the error term required by the system equations.

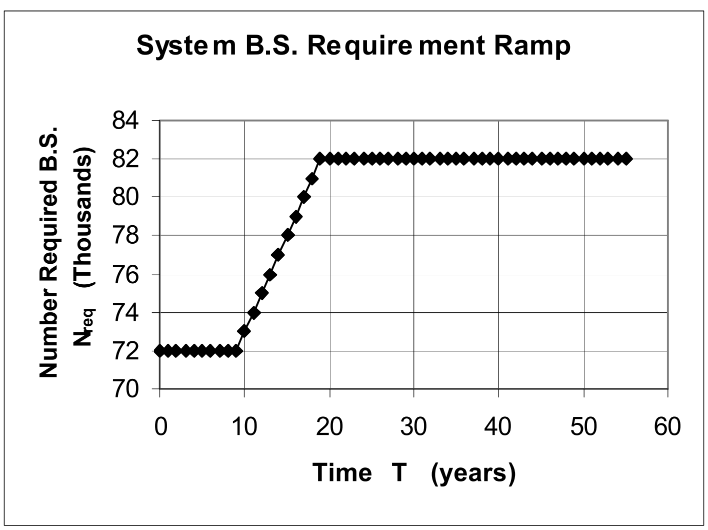

Figure 11: A graph showing the applied input N_{req} ramps from 72,000 to 82,000 in one decade starting at year 10.

					BS Engineering Educati on Model									
										Del2	Del4			
										0.0015	0.0025			
				Coefficient Values						Node Values				
Steps	Time	K1	K2	K3	K4	K5	Ni	Nreq	N1	N2	N3	N4	No	Nreq-No
0		0.18	0.75	0.81	0.22	0.61	3500	72	630	473	383	84	51.4	21
1		0.18	0.75	0.81	0.22	0.61	3500	72	630	492	383	104	51.4	21
2		0.18	0.75	0.81	0.22	0.61	3500	72	630	492	383	104	51.4	21
3		0.18	0.75	0.81	0.22	0.61	3500	72	630	492	383	104	51.4	21
Hidden rows of syst em stabiliz ation														
32		0.18	0.75	0.81	0.22	0.61	3500	72	630	483	394	99	60.7	11
33		0.18	0.75	0.81	0.22	0.61	3500	72	630	483	392	98	61.1	11
34		0.18	0.75	0.81	0.22	0.61	3500	72	630	483	393	97	61.3	11
35	0	0.18	0.75	0.81	0.22	0.61	3500	72	630	483	392	97	60.4	12
36	1	0.18	0.75	0.81	0.22	0.61	3500	72	630	483	391	97	60.5	11
37	2	0.18	0.75	0.81	0.22	0.61	3500	72	630	483	391	97	59.6	12
38	3	0.18	0.75	0.81	0.22	0.61	3500	72	630	484	391	97	59.4	13
39	4	0.18	0.75	0.81	0.22	0.61	3500	72	630	484	392	98	59.1	13
40	5	0.18	0.75	0.81	0.22	0.61	3500	72	630	485	392	98	58.9	13
41	6	0.18	0.75	0.81	0.22	0.61	3500	72	630	485	392	99	59.4	13
42	7	0.18	0.75	0.81	0.22	0.61	3500	72	630	484	392	99	59.3	13
43	8	0.18	0.75	0.81	0.22	0.61	3500	72	630	485	393	99	59.9	12
44	9	0.18	0.75	0.81	0.22	0.61	3500	72	630	484	393	99	60.0	12
45	10	0.18	0.75	0.81	0.22	0.61	3500	73	630	484	392	98	60.4	13
46	11	0.18	0.75	0.81	0.22	0.61	3500	74	630	484	392	98	60.5	14
47	12	0.18	0.75	0.81	0.22	0.61	3500	75	630	485	392	99	60.2	15
48	13	0.18	0.75	0.81	0.22	0.61	3500	76	630	486	392	99	60.3	16
49	14	0.18	0.75	0.81	0.22	0.61	3500	77	630	487	392	101	59.9	17
50	15	0.18	0.75	0.81	0.22	0.61	3500	78	630	489	393	102	59.8	18
51	16	0.18	0.75	0.81	0.22	0.61	3500	79	630	490	394	104	60.2	19
52	17	0.18	0.75	0.81	0.22	0.61	3500	80	630	490	395	105	60.7	19
53	18	0.18	0.75	0.81	0.22	0.61	3500	81	630	491	396	106	61.5	20
54	19	0.18	0.75	0.81	0.22	0.61	3500	82	630	491	397	106	62.2	20
55	20	0.18	0.75	0.81	0.22	0.61	3500	82	630	491	397	107	63.2	19
56	21	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	398	107	63.9	18
57	22	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	398	106	64.5	18
58	23	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	398	106	64.9	17
59	24	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	397	105	65.1	17
60	25	0.18	0.75	0.81	0.22	0.61	3500	82	630	488	397	104	65.4	17
61	26	0.18	0.75	0.81	0.22	0.61	3500	82	630	488	396	104	64.8	17
62	27	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	396	104	64.4	18
63	28	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	396	104	63.9	18
64	29	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	395	104	63.5	18
65	30	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	396	105	63.4	19
66	31	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	396	105	63.1	19
67	32	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	397	106	63.5	19
68	33	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	397	106	63.7	18
69	34	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	397	106	64.1	18
70	35	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	397	106	64.3	18
71	36	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	397	105	64.5	18
72	37	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	397	105	64.7	17
73	38	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	396	105	64.5	18
74	39	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	396	104	64.4	18
75	40	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	396	104	64.1	18
76	41	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	396	105	63.9	18
77	42	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	396	105	63.8	18
78	43	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	396	105	63.7	18
79	44	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	396	105	63.7	18
80	45	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	397	105	63.8	18
81	46	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	397	105	64.0	18
82	47	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	397	105	64.1	18
83	48	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	397	105	64.2	18
84	49	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	397	105	64.3	18
85	50	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	397	105	64.3	18
86	51	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	396	105	64.3	18
87	52	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	396	105	64.2	18
88	53	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	396	105	64.1	18
89	54	0.18	0.75	0.81	0.22	0.61	3500	82	630	489	396	105	64.0	18
90	55	0.18	0.75	0.81	0.22	0.61	3500	82	630	490	396	105	63.9	18

Figure 10: Sample printout of a run with N_{req} incrementing from a steady state value of 72,000 per year to 82,000 starting at year 9 and reaching a new steady state by year 19.

Figure 11 shows the value of N_{req} as a function of time. It assumes that the initial value of 72,000 B.S. engineering degrees exists at year zero. The number of engineers required will increase over the decade from year 10 to year 20 to a new steady state value of 82,000 B.S. degrees. Figure 12 shows that with the present system parameter values, even though N_{req} is 72,000, only 60,000 engineers can be produced. The difference between the 72,000 needed and the 60,000 being graduated in the U.S. is associated with the large number of non-national engineers being hired on temporary H-1B visas.

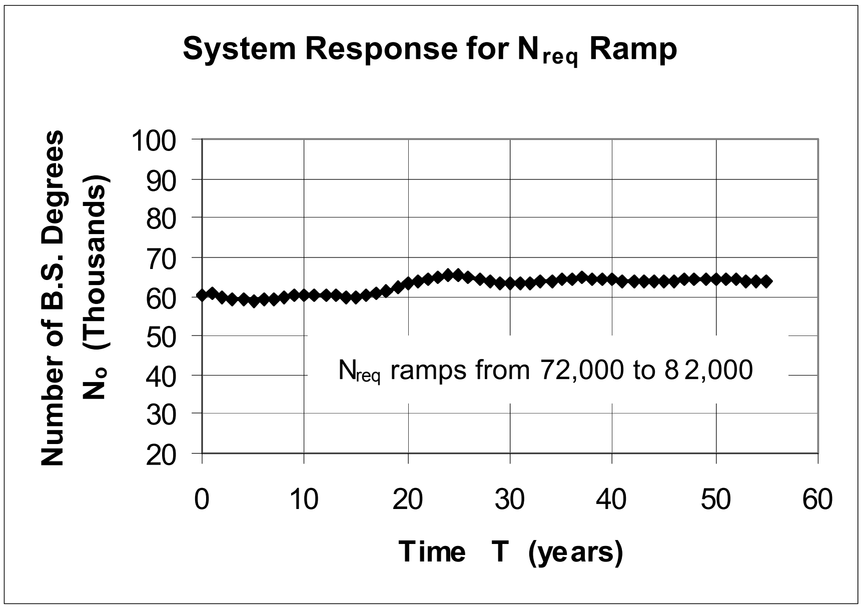

Figure 12: System response with present coefficient values resulting from a ramp change in N_{req}.

Looking at Figure 12, we see that the actual number of engineers produced is at the present stable value of 60,000 and then at year 10 it increases, reaching a steady state of about 64,000 after an additional decade. Thus, the system is simply incapable of producing the 82,000 of B.S. degreed engineers needed. The only solution is to increase the values of one or more of the K coefficients.

One typical approach used in the past is to attempt to obtain the needed extra B.S. degrees by increasing the engineering program's retention figure. NSF pipeline data indicates the average undergraduate retention is about 61%. It seems unlikely that we can ever realistically expect retention to be anywhere near 80%, but let us suppose that we could somehow increase retention to this 80% value. Figure 13 shows the system response to such an increase. In this figure, we see the result of changing K_5 from 61% to 80%.

Figure 14 shows the time variation of K_5 basically increasing linearly starting at year 10 and increasing to the new steady state value over a decade. Figure 13 shows the system output rising to about 75,000, still significantly lower than the required value of 82,000 new degrees per year. This shows the futility of trying to meet realistic needs by improving engineering retention rate. Even at a retention rate of 80%, the required number of new degrees cannot be achieved.

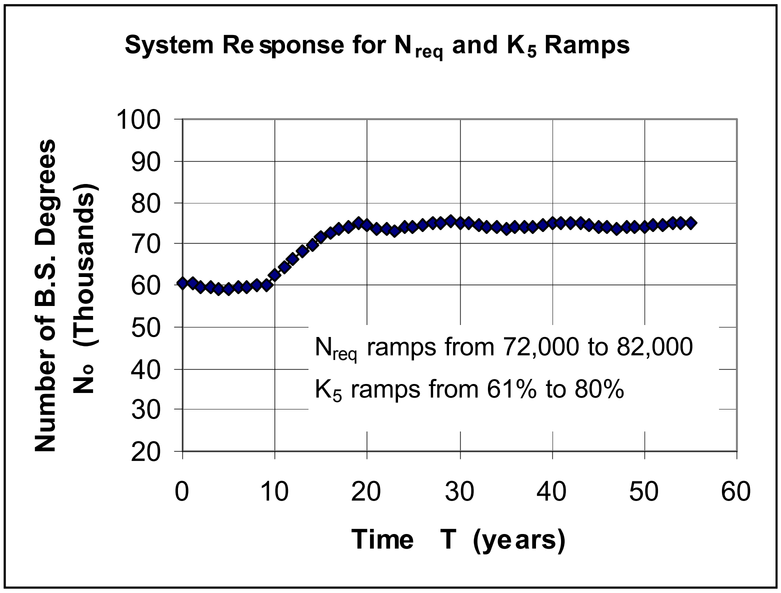

Figure 13: System response to a ramp increase in K_5 taking place over a decade time interval.

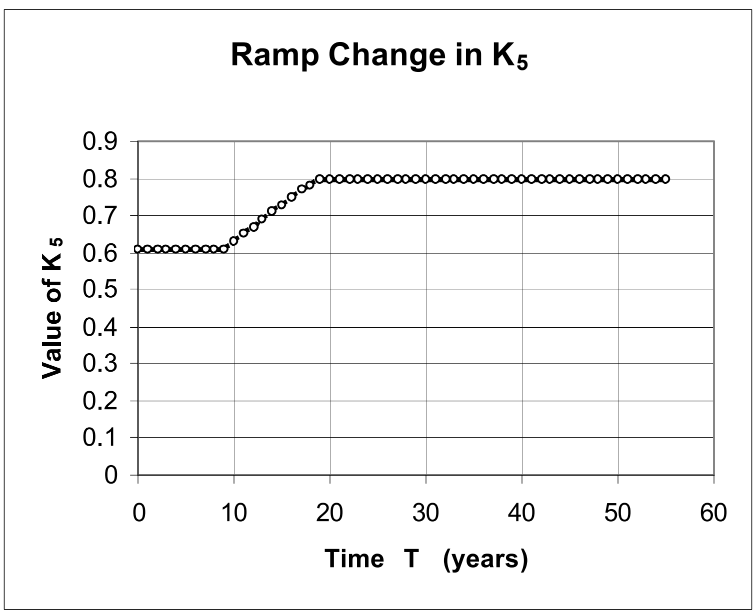

Figure 14: Graph showing the time increase assumed for engineering program retention from 61% to 80%.

Rather than placing so much effort on changing the retention rate, let us look at the effect of changing other system parameters. Figures 15 and 16 show the effects of changing K_1, the fraction of students ready to take high school math, physics, and chemistry classes. The system analysis presented in the body of the paper indicated that the output value is most sensitive to changes in K_1. This is intuitively logical since the quantity of potential candidates is very large at the system input. Thus only a small change is required at this point to produce a significant effect in the system output. Yet, even being intuitively obvious it has not previously been proven. Figure 15 shows the system response if we assume K_1 changes from its initial present value of 18% to a new value of 24% over a decade beginning at year 10, a change of only six percentage points.

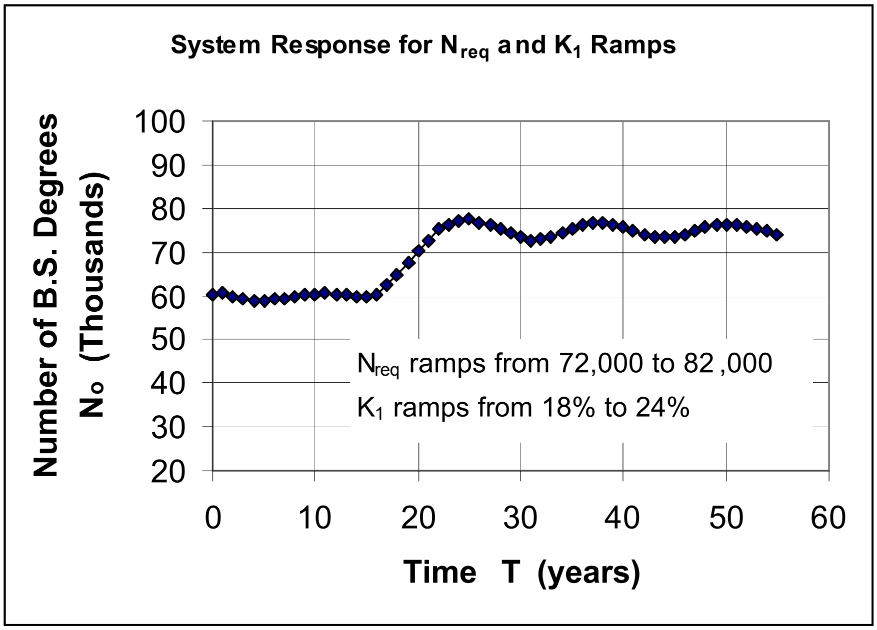

Figure 15: System response for a ramp change in K_1.

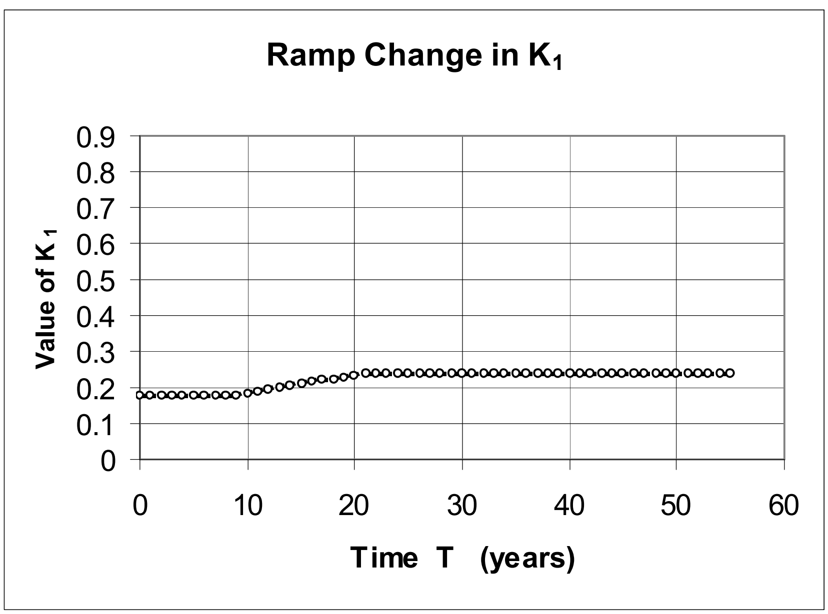

Figure 16: Time ramp in value of K_1 assumed from which the system response shown in Figure 15 is obtained.

This assumption is shown in Figure 16. The system response shown in Figure 15 evidences a long delay, about seven years, before the output begins to change; but once it begins, the change is significant. The system reaches a steady state value of 75,000 with a change of K_1 increasing from 18% to only 24%. This is surely an easily obtained increment. Note, we have not even taken into account the fact that most programs that would increase K_1 would probably also increase K_2 and hence produce a larger output than projected here. Clearly the desired value of N_o = 82,000 could be obtained by a slightly larger increase of K_1; however, it probably makes sense to increment one of the other K values in addition to the change in K_1.

It has previously been shown that the output was most sensitive to the K_1 and K_4 coefficient magnitudes. The coefficient K_4 is the fraction of students who are prepared for engineering school who actually enroll in engineering. Figure 17 shows the effect of changing both K_1 and K_4 over the decade of time from year 10 to year 20. In this run we assume K_1 changes, as before, from 18% to 24%, and that simultaneously K_4 increases from 22% to 26% (an increase of only four percentage points.) Note that the output rises to the desired average value of N_o = 82,000.

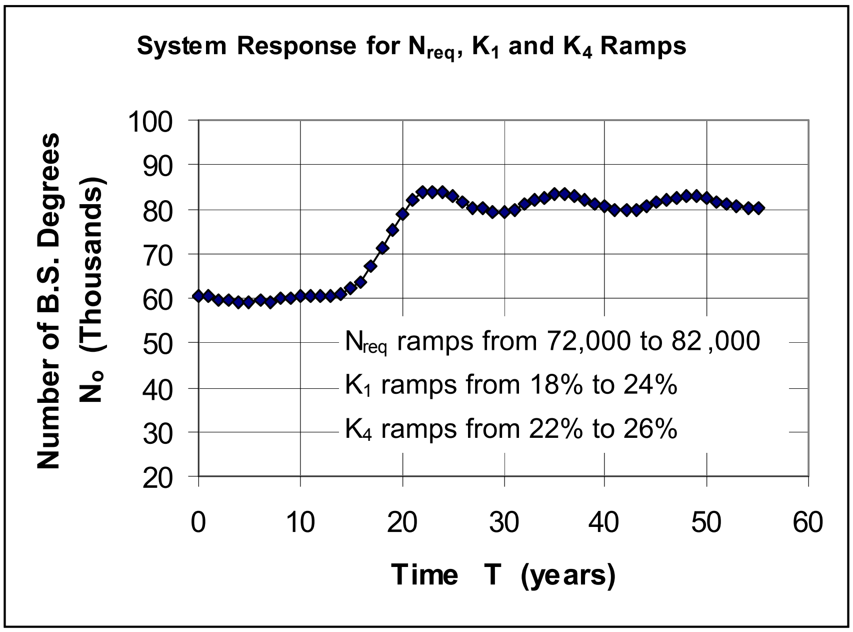

Figure 17: System response from applying ramp changes in both K_1 and K_4.

Thus the model gives us a straightforward approach to arrive at a solution to the basic problem. It does not tell us "how" to change the values of any of the coefficients, but it tells how the system will respond to a specified change. It is our responsibility to design programs that will modify particular K values.

One example might be illustrated. Ohio Northern has proposed to NSF a program directed towards increasing K_1. In this program, middle school students will come to the engineering college building once per week for the entire school year. The program is called TechTivities. Hands on engineering based experiments will be performed along with data collection, algebra applications, programming activities and first hand interaction with engineering students and faculty. Evaluation of student enrollment will be carried out to measure the outcomes effect of this program on preparedness for and enrollment in math, physics, and chemistry high school courses. ONU has proposed additional programs for specifically modifying other coefficients.