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The Education of Mathematical Engineers

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(The present article reproduces an invited address at the Fifth International Congress on Mathematics Education. It describes a successful programme of training of mathematicians for industry. A developing country like India badly needs such a programme. It is hoped that some Indian universities, IIT's or engineering colleges will be in a position to start a similar programme adapted to the needs of our country. Some additional references, not given by the author are also given.)

FOR ROUGHLY twenty-five years the technological universities in The Netherlands have been offering a programme in 'mathematical engineering' which has been highly successful. There are a few other places in the world where something similar is being done, but it is remarkable (and sad) that the idea has not been copied (adapted to the local situation) by many more countries. In 1981, the Alfred P. Sloan Foundation sponsored a conference in Chatham, Mass. (USA) to discuss possible programmes in mathematics designed for people who will immediately enter industrial employment. There was a general agreement that there was a great need for such programmes in the USA (and obviously in many other countries). At this meeting I had the opportunity to describe the programme which had been offered in Eindhoven from about 1962 to 1982 (recent changes will be discussed below). The participants at the conference showed considerable appreciation for the mathematical engineering programme. It was clear to all that the goals of this programme would take at least six years to achieve and probably more in countries where the level of the output of secondary schools is lower. It seems worthwhile to give a more detailed description of the programme than is internationally available at this moment and this meeting is a good place to do it. Whether

one can profit from reading this presentation is a question we shall go into, in Section 5.

1. What is a mathematical engineer?

We have already pointed out that we are interested in a programme for mathematicians who will enter industrial employment. A large part of the following description is quoted from the inaugural address of G. W. Veltkamp² who helped design the Eindhoven programme. We are talking about the education of a mathematician who will typically be a consultant, either more or less as free-lance mathematician or as a collaborator in a research group. In many cases he could be the only house mathematician of some small firm. His work will consist of the following steps:

- (a) Recognising, understanding and analysing a problem whose nature can be physical, technical, economic or related to business management. This first step is very important and often involves extracting the real problem from the non-mathematician seeking advice (= the customer).
- (b) Constructing the mathematical model. Since it will often be necessary to introduce simplifications, this second step

sometimes also involves consultation with the customer.

- (c) Solving the mathematical problem (analytically or numerically) and estimating the reliability of the results.
- (d) Interpretation of the results and translating them into a form which is useful and understandable for the customer.

This description of typical activities leads to the following requirements for the mathematical engineer.

- (A) He must be a good mathematician with a solid knowledge of basic techniques (analysis, algebra, probability, computing) and some knowledge of a large number of specialised areas of mathematics. A certain amount of creativity is clearly essential.
- (B) He must have knowledge of one or more technical or physical sciences and/or economics and management.
- (C) He must be able to follow the patterns of thought and the language of his (non-mathematical) customers. Furthermore he should be able to convince them of the value of his advice.
- (D) He must be interested in and willing to work on the problems of others.

From this description it should be clear that the education of a mathematical engineer is a difficult task which will take considerable time and produce an extremely useful person. Furthermore we all know that the education of this kind of mathematician has in general not been the goal of most of the programmes of present day universities.

In the remainder of this description, I shall describe the situation in Eindhoven between 1962 and 1982. In the period mentioned above about 250 mathematical engineers were produced. Where do they work? To give some idea I have introduced four categories of employers and given the percentage of our graduates they have hired.

- 1. Large industrial research laboratories (Philips, Shell, AKZO, etc.): 25 per cent.

- 2. Research institutes attached to some government organisation (such as the Postal System, Telegraphs, Space Agency, Navy, etc.): 25 per cent.
- 3. Small industries, banks, computer companies: 15 per cent.
- 4. Teaching and research (both university and secondary): 35 per cent.

The trend is that employment possibilities of type 4 are decreasing rapidly, type 2 is stable and 1 and 3 are still increasing.

2. What should the responsible mathematics department look like?

In my opinion only a fairly large department of mathematics can offer a programme in mathematical engineering. Since the last part of the programme involves about a year of some kind of research activity there should be groups doing research in several of the areas which are important for the engineer (such as discrete mathematics, applied analysis, statistics and operations research, and computer science, which are the four main groups in Eindhoven). It is essential to have these groups in one department as colleagues are not, as so often happens, in different and sometimes antagonistic departments. Each student will be involved with all these groups for several years.

3. The first half of the programme

To understand the first part of the programme it is necessary to know something about the input. We have no selection mechanism except the required high school diploma. In The Netherlands high school education involves knowledge of foreign languages, mathematics including a year of calculus, several years of physics and chemistry. Only a small part of the twelve to eighteen year age group completes this prerequisite programme. Nevertheless a large percentage of our freshmen is clearly not suited for our mathematics programme and one of the goals of the first year is a selection procedure (and good counselling concerning alternatives for those who do not make it). The first three years are devoted to the basic mathematical skills, subjects such as physics, economics,

Table 1 Composition of the first part of the programme

	Subjects	Classroom hours
First year	Caculus and Linear Algebra	275
	Algebra and Analysis	165
	Mechanics and Physics	165
	Modelling	65
Second and third year	Calculus + complex variables and Linear Algebra	180
	Algebra and Analysis + Linear Analysis	180
	Mechanics and Physics	220
	Numerical Analysis, Programming, Computing Science	220
	Economics, etc.	50
	Probability and Statistics	100
5 chosen from these 10	Discrete Mathematics 1 and 2	30 + 30
	Measure theory + Lebesgue Integration	30
	Function theory	40
	Applied mechanics	
	Advanced physics courses (2)	40 + 40
	Linear models	40
	Decision theory	40
	Stochastic processes	40

etc. (the disciplines of future customers), modelling, and some knowledge of each of the major research areas mentioned in Section 2. Most of this programme consists of compulsory courses. Table 1 gives an idea of the programme.

An important point that should be clear to the reader is the following. This first half of the programme provides a solid basis and using this basis the actual forming of the mathematical engineer takes place in the second half of the programme. This second half would have very little chance of success without the solid basis and on the other hand the basis itself does not make an engineer. It is this argument which shows that the job cannot be done in much less time.

4. The second half of the programme

For the last two years (usually slightly more) the student chooses one of the research areas mentioned in Section 2 as his main direction and one of the professors from this area as supervisor.

Together with the supervisor he decides on a set of courses to be taken in the fourth (and in a part of the fifth) year. Many of the courses will be special topics from the chosen direction but there will also be some advanced courses from the other areas. Besides this, a choice of a few courses provided by other departments (engineering, physics, econometrics) is compulsory.

An interesting element in this phase are the two periods (ranging from one to three months) of 'apprenticeship', preferably at some industrial establishment where the student participates in current research or works on some special problem. Here he gets a taste of his future activities and it often happens that the firm where the apprenticeship takes place offers the student a job after he graduates. To make this system work it is necessary for the supervisor to have several contacts with industry. The apprenticeship can also take place at the university. Many of my own students with coding theory as direction, work for a while in the information theory and communica-

tion theory research group of the electrical engineering department. In his last year the student works (under the guidance of his supervisor) on a real recent mathematical problem, usually connected to a technical or industrial problem. Here he does the kind of work he will be doing during the rest of his career. The research which he does is not necessarily original but quite often it is. Since the writing of reports on his work will be a major activity in the future a lot of weight is attached to the master's thesis which is the result of this last year. From the list of theses written during the period this report treats, I give below a few samples to give the reader some idea of the kind of problems students work on.

- (1) On linear error protection codes.
- (2) Strong graphs and block designs.
- (3) The solution of boundary value problems for large systems of linear differential equations using the Riccati transformation.
- (4) Ray-optical analysis of reflection in an open-ended flanged waveguide.
- (5) Longitudinal motions of a uniform bar.
- (6) Design and construction of programmes for solving transportation and network problems.
- (7) On a telephone exchange system that allows overflow.
- (8) A model and a prediction algorithm for SO_2 concentration in the Rijnmond area.
- (9) Simulation and analysis of quality control schemes for peanuts.
- (10) A syntax and semantics checker for Concurrent Pascal.
- (11) A theory of real number and its presentation in Automath.
- (12) On the implementation of SASL with combinatory logic.

The reader should realise that in The Netherlands there are no course requirements for a Ph.D. (only a thesis) and that in fact many of the masters' theses mentioned above would qualify as Ph.D. theses in several other countries (including the USA).

The points (A) to (D) mentioned in the description of the work of a mathematical engineer all play a role during the apprenticeship. The thesis is often mainly concerned with the last two (due to the environment where the work is done).

5. Copying or altering the idea

In my opinion there is going to be an increase in employment possibilities for the type of mathematician described above, certainly in the highly industrialised parts of the world. Furthermore it is clear to me that a watered down version simply will not work. It is not a coincidence that we have had very many students who had great difficulty in completing the first half of the programme and subsequently developed into excellent engineers. The *broad* and *sound* basis is a necessary condition. However, by itself, it is of very limited use and does not yield the desired product.

A difficult question is whether, in some countries and for other purposes, part of this idea (say a specialised version) could be copied. The philosophy described in Section 1 would be the same, but the level lower. This depends on local needs. Of course there is nothing new in the idea of educating statistical analysts, computer programmers, systems analysts, etc. Programmes in applied mathematics have existed in many places for years. Therefore I believe that it is not possible to deviate in an essential way from my earlier description and nevertheless give the output the same names.

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