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INDUSTRIAL MATHEMATICS - IDEAS AND EXAMPLES

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Industrial Mathematics - Ideas and Examples

Industrial Mathematics - a new subject or just a new name, the „emperor's new clothes"? What should be the difference between applied and industrial mathematics? But what is the difference between applied and pure mathematics, if any at all? „Applied Mathematics is Bad Mathematics" writes Halmos [2] in his article with just that name, „it isn't really, but it is different". And he compares the picture of the real world provided by applied mathematics with the police photograph of a wanted criminal, meanwhile that of pure mathematics with a portrait by Picasso. And now, worse, industrial mathematics - even more useful, but even less beautiful?

Halmos also claims that applied mathematicians do not accept a difference between pure and applied, while pure mathematicians do. This, maybe, is the first difference between applied and „industrial" mathematicians: We do see a difference.

Most applied is „applicable" mathematics - mathematics, which hopes or expects to be applied, but still is not. And this is the second difference: Industrial mathematics has its industrial applications; it treats problems posed by industry, questions of technical, organisatorial or economic nature, which are posed by companies.

Let us finish with looking for differences, defining the subject just by saying how it differs from other subjects; let us say, what it is: Industrial Mathematics means, to transform these technical, organisatorial and economic problems originally posed in a nonmathematical language into mathematical problems, to "solve" these problems in general by approximative methods of analytical and/or numerical nature and reinterprete the results in terms of the original problems.

In short: Industrial Mathematics is Modelling and Scientific Computing of industrial problems. Of course, modelling and asymptotic analysis appear in science and in „classical" applied mathematics as do numerical methods. And, of course, industrial mathematicians need a wide and broad knowledge on mathematical ideas, algorithms and computer. But they need more: They need an understanding of the problems in industry, they have to understand and speak the language spoken in industry.

Industrial Mathematicians are bridge builders: They build bridges from the field of mathematics to the practical world; for that they have to know about both sides, to know problems from some companies and ideas and methods from mathematics.

They have to be generalists, not specialists. If you enter the world of industry, you never know, which kind of problems you will find, which kind of mathematical methods you will need: Problems, where signals or images have to be processed and methods of Bayessian statistics, time series analysis, wavelets, energy functionals etc. are used; problems of optimizing the transport or the storage of industrial goods with all these new methods of combinatorial optimization; problems of predicting the outcome of complicated systems which do not allow to understand the mechanisms behind and methods of adaptive system theory, of learning, of neural networks etc.; problems, where complicated multiphase flow happens in porous media, forming fronts and drops and the methods of homogenization, level set methods, front tracking algorithms etc.; problems of the interaction of flexible structures (fibres, papersheets) with a flow around and multigrid methods, particle methods etc.; problems of optimizing the properties (elasticity, heat conductivity etc.) of compound materials and again methods of homogenization, regularization of inverse problems, optimal shape design.

We may go on and on - the selection here is based on our personal experiences. But we hope, it is obvious: Industrial mathematicians have to be generalists, they have to know a large variety of mathematical concepts and methods; they have to know modern mathematics, should know more and more advanced methods than scientists and engineers: Industrial mathematics is not engineering mathematics. But it is not a new subject in itself like Statistics, Optimization, Computational Mechanics or even Finance Mathematics; it is another kind of getting problems, looking at problems, interpreting and using solutions. It is a new discipline. Is it less beautiful than pure mathematics? This is, of course, a question of taste. But inspite of the beauty of a Picasso painting, which we see as Halmos did, we may have as much fun in developing algorithms for the identification of criminals as in searching for a „grammar" of Picasso's paintings. From the point of view of human creativity, industrial mathematics is one of the most exciting, adventurous, joyful activities a mathematician could find.

And, inspite of being different from pure and even applied mathematics, it needs both: Industrial mathematics stands on the shoulders of mathematics at all; industrial mathematicians use ideas of others and, if they do not find appropriate concepts and algorithms, invent new ones. Vice versa, mathematics profits from industrial mathematics, mainly by offering new challenging problems, better chances for young mathematicians, higher prestige outside the mathematical community, financial support. Very often, Murphys principle holds, if one tries to apply a standard theory to a practical problem: What can go wrong, goes wrong. The right hand side of the differential equation is of course not Lipschitz continuous, the noise is not white, the operator not compact, the system too stiff, the material parameters too much oscillatory, the problem ill-posed etc. etc. Almost each practical problem asks meaningful questions, creates new concepts.

Why this new uprise of industrial mathematics worldwide (there is the European Consortium for Mathematics in Industry = ECMI, which gathers many activities of this kind in Europe, there is the Division of Mathematics and Statistics at CSIRO in Australia, an Institute for Industrial Mathematics in Israel, the IMA in Minneapolis, the Claremont Clinic in Pasadena and some more in the US)?

Modelling has several thousand years of history! But the tool to evaluate the models is new and becomes more powerful every year: Computer! Therefore, industrial mathematics is, to large extent, also numerical mathematics: not numerical analysis, but scientific computing, algorithms and their implementation. In this respect the computer scientist is our partner; but he is not, as some believe, the „owner“ of this field. Developing algorithms - to optimize, to solve pde's, to process images, to predict stocks - is a genuinely mathematical task, which mathematicians should claim.

The basis of our statements and the source of our examples is mainly based in Europe. One of us (H.N.) has introduced a new educational master programme „Technomathematics“ 18 years ago, which by now was spread out to 15 German and ca. 20 other universities all over the world; he was a co-founder of the above mentioned

ECMI, which organizes eduction and research in industrial mathematics in Europe; and, finally, 1995 he founded a new „Institute of Industrial Mathematics“ (ITWM) in Kaiserslautern, which earns today ca. 65% of the total budget, i.e. ca. 5 million DM, from industrial projects. The other one (A.H.S.) tries since years to implement the discipline in India, quite often facing hurdles. But we are convinced that mathematics will gain new momentum, new prestige, better students by integrating this new discipline in countries like India. Several years ago the Nobel Prize Winner from Pakistan, Prof. A. Salam, who founded the ICTP in Trieste, wrote that it is a kind of Machiavellism to export technology to the third world without developing science there. We would like to add that it seems to be Machiavellism too, to cultivate „pure“ science without explaining how it can contribute to the industrial development. Teaching and practising industrial mathematics could be step away from this Machiavellism.

The paper will give a survey

- on the teaching activities in the field of industrial mathematics in Europe,
- on the research activities mainly carried out at the „Institute for Industrial Mathematics“ in Kaiserslautern,
- on our experiences with implementing the field in 3rd world countries.

I. Teaching Industrial Mathematics: Experiences from the ECMI Programmes

ECMI, the European Consortium for Mathematics in Industry was founded in 1986 by mathematicians from several European Universities, f.e. by Eindhoven (Netherlands), Firenze (Italy), Glasgow (Scottland), Kaiserslautern (Germany), Linz (Austria), Oxford (England). It had three main goals, namely

to promote the use of mathematics in industry,
to educate industrial mathematicians,
to cooperate on a European scale.

During the last decade ECMI was quite successful: It has now centres in more than 10 European countries, where a Postgraduate Programme „Industrial Mathematics“ is organized. This programme has two branches: Technomathematics and Economathematics. Technomathematics deals with applications of mathematics in technology and focusses on differential equations and its applications in mechanics, electrodynamics, thermodynamics etc., on signal analysis, image processing and inverse problems and mainly on numerical methods too; economathematics treats organisatorial problems by mathematical methods, is therefore concentrated mainly on discrete mathematics, f.e. combinatorial optimization and graph theory and on statistics.
Both programmes differ from classical applied mathematics programmes by using quite a big part for modelling and scientific computing. Of course, there are general aims. After completing the programme the student should have the following capabilities:

1. Proficiency in the formulation of real world situations into qualitative or quantitative mathematical models, and in the use and the analysis of mathematical models;
2. experience of the use of mathematical models in the industry and in the handling of mathematical methods for answering practical questions and for solving problems from the real world;
3. sufficient knowledge of the mathematics that is relevant for 1 and 2 and further reaching knowledge of some special field of interest;
4. knowledge of numerical methods and simulation, and experience in the intelligent use of computers;
5. background knowledge of computer science and pure mathematics;
6. experience in team work and in making a personal contribution to a team project;
7. sufficient knowledge of some scientific field where mathematics is used in practice (for example: physics, mechanics, chemistry, electrotechnics, economics, industrial engineering), and to be able to communicate with experts in this field;
8. to be able to give oral and written presentation of their scientific work in such a way that not only mathematicians but also interested laymen get the main messages.

But what does all that mean practically? Let us try to describe a bit of the important details:

1. Students, who enter the programme, should have a certain preknowledge, provided by a Bachelor, Vordiplom or equivalent degrees awarded in different countries. Of course, a bachelor here is not the same as a bachelor there; a master at a second class university may know less than a bachelor from a first class institution. Even a PhD in pure mathematics from some places should find the programme to be challenging. In short: Titles are not enough to describe the prerequisites.

   So, let us try otherwise:

   a) Calculus is not enough, but we would expect some knowledge in analysis, for example different kinds of convergence (i.e. a bit of topology), an understanding of the problems in changing limit processes, Poincaré's lemma etc.
   b) Linear algebra should include finite dimensional vector spaces, linear operators and their normal forms, spectral theory. But we would like students to be able to compute the Jordan normal form of a matrix, not only knowing everything about structures but nothing about algorithms.
   c) Ordinary Differential Equations should include the main ideas about existence and uniqueness, phase space interpretations of dynamical systems, linear systems of ode's, stability (including Ljapunov functions) and periodicity.
   d) Numerical methods should deal with linear and nonlinear systems (including linear and nonlinear regression), large symmetric systems and eigenvalue problems, interpolation and approximation (including splines and Bézier techniques), numerical integration.
   e) Functional analysis should include the basic concept: Hilbert and Banach spaces, bounded and compact operators and their spectral properties.
   f) In optimization we expect some knowledge in linear programming and basic ideas like gradient methods in nonlinear optimization.
   g) Probability should consist of „elementary probability theory" (conditional probability, independence, Bernoulli schemes, random walks).

Besides these mathematical preknowledges we expect students to be able to handle a computer and a language (f.e. C^+) and to have solid knowledge in physics (for the Techno branch) or in microeconomy (for the Econo branch)

Of course, not every student entering the programme has this knowledge. Therefore the first semester is used as a possibility to fill the gaps. Quite often there are many gaps and this semester is very stressing. Some have good knowledge in pure mathematics - their gaps are mainly in numerics and computing; others are good in physics and computing, but have their difficulties for example with functional analysis. Wherever the gaps are: After one semester they must have disappeared.

2. The core courses, taught in all centres in a similar way, should offer the basis for Techno and Economathematics respectively. In Technomathematics this means a lot of differential equations: Advanced analytical and numerical methods for ode's and pde's, control and system theory; moreover time series analysis, and nonlinear and discrete optimization. In Economathematics it means mainly advanced methods in optimization (network, graphs etc.) and stochastics (stochastic processes, queuing theory). There were attempts to give introductory „cross courses": Technomathematics for Economathematicians, Economathematics for Technomathematicians. But it does not seem to work.

   The central activity from the 2nd semester onwards is the <u>modelling seminar</u>: Problems from the real (mostly industrial) world are presented in a nonmathematical way to groups of 4-5 students; these groups work one semester under a supervisor, who plays the role of an industrial client but not as a mathematical expert. They transform the problem into a mathematical model (using their knowledge and the library), they evaluate the model using the computer facilities, they reinterprete the results in terms of the original problem, they present their results orally and as a written report. It is a lot of work, but is is more rewarding than any lecture or book: Mathematics, especially „Industrial Mathematics", is only learnt by doing! Modelling seminars are the opposite of „learning by heart", it „creates creativity". And this is, what industrial mathematicians need: Creativity to create innovation.

3. The third semester is open for special courses - besides another modelling seminar. Special courses depend on the special knowledge of each department. Here a list of titles we have seen during the last years, at different ECMI centres - possible topics, changing with time and mainly changing with industrial projects: Asymptotic analysis; Mathematical and computational methods in fluid dynamics, elasticity and plasticity, thermo dynamics; Flow in porous media, free boundary problems; Inverse and ill-posed problems, parameter identificaiton; Multigrid methods, domain decomposition; Boundary and/or Finite Element methods; Particle methods, pseudorandom numbers; Advanced system theory, adaptive systems, neuronal networks, fuzzy control; Signal analysis, image processing and pattern recognition, wavelets; Information theory, coding and cryptography.

   In Economathematics topics could be Insurance mathematics, Finance mathematics; Experimental design, reliability and quality control; robust statistics and nonlinear models in statistics; Dynamic optimization, production planning, location theory; Scheduling and routing, location theory; Simulated annealing.

4. The master thesis should deal with a problem, which comes from industry; the student should spend several months in the company, who posed the problem. However, the scientific responsibility remains with the supervisor at the university; he makes the contacts with industry, negotiates the details, prepares the student before he spends his time in the company, supervises the scientific work after the return of the student and evaluates the thesis. Master theses in the ECMI programme take officially 6 months, inofficially it is often 3 months (the holiday months) more.

So much about a European attempt to organize a common programme on „Industrial Mathematics“. There are similar attempts worldwide - some just using the new name to get better support for what they have ever done („the emperor's new clothes“ - but not his „new mind“). Others try really hard - then their central activity is always similar to our modelling seminar (see for example the „mathematical clinic“ in Claremont, US). There are weeks, months, even years dedicated to work on practical „real world“ problems, on modelling and computing.

For 3rd world students, the 2 years master programme „Industrial Mathematics“ at Kaiserslautern with ca. 12 scholarships per year seems to be one of the larger efforts in this direction. This programme is connected with the ECMI programme and quite similar to it. Graduates from this programme - more than 50 meanwhile - form a Technomathematics family with close contacts with each other (contacts from Trujillo in Peru to Fuzhou in China, from Kathmandu in Nepal to Malawi) and a summerschool family meeting every 3 years.

The programme has become more popular in industry during the last years - certainly correlated with growing popularity of these countries as future markets and source of labour. Why not using this interest?

II. Examples for a scientific cooperation with industry

Of course the literature is full with examples - we refer only to 8 proceedings volumes from ECMI-conferences or to a series of books by Avner Friedman (see for example [1] and [5]).

They contain to a high percentage problems really posed by industry; but even there we may find 2 categories: Problems, whose solution is academically exciting, but of minor industrial interest - and those, who are of „burning“ interest for the company, i.e. the company pays for it. In the academic world the value of work is measured by the number of good publications - in industry it is measured by the price paid for it. Industrial mathematicians are squeezed between these two criteria. The „Institute for Industrial Mathematics“ (ITWM), one of us (H.N.) is directing, has to earn money <u>and</u> scientific reputation; the results are paid and published.

We shall try to give a short description of the kind of problems at ITWM; quite some of them are „weakly“ classified (since they are paid): The mathematics might be published, but not the use of it. These problems would miss the point we try to make - so we have to restrict our selections.

A) There are some problems in the field „flow in porous media“ - but not as the flow of oil in reservoirs (this is more important in „oil countries“ like Norway), but as a flow of different liquids through woven and nonwoven fabrics: Flow in diapes, blood flow in test stripes, oil flow in filters, resinflow through fibres to produce compound materials, flow of sweat in shirts etc. etc. Mathematically all that means of course Darcy's law, Richards equation, i.e. nonlinear parabolic or elliptic pde's. But there is a lot of modelling: The structure of a fabric is different from the structure of rocks, the scales are different and lead to corrections. The fluid is different, sometimes Non-Newtonian, we need Darcy's law with memory etc. Many of these equations exist already in literature, but reasonable numerics is often missing. Look for example at a filter, whose task is to extract oil drops from an air flow. There are several layers of nonwoven fabrics and if you look closer to what happens in and between these layers, you see a phantastic world: Oil drops coagulate to become a film, bursting into new droplets and so on. Richards equation, free boundaries, mean curvature flow - front tracking, level set methods and more. Details cannot be given here. The message only is: There are plenty of beautiful mathematical problems in that area (the Oxford study group has discovered this fact many years ago). For flow in porous media we may refer to [3], which offers a typical mathematical approach; a vast engineering literature exists too.

B) Another research field is „interaction of a fluid with flexible structures", the fluttering of sheets or fibres in wind. This is an even more sensitive area and we are not able to describe the real applications. But the problem is clear: A surface or curve is immersed in a gas flow, moved by the flow and changing the flow. Modelling is not so complicated, but the numerics! There is a moving boundary (the surface or - even worse - the 1-dimensional curve), which has its own life. Grids run in troubles, the systems get very stiff; our way out is to use gridfree methods, particle methods: Not as accurate as classical methods (multigrid etc.), but able to handle very complex situations with sufficient precision. The well known particle methods like „Particle in Cell" and its modern relatives, others like „Smoothed Particle Hydrodynamics", have to be improved to do the job - new methods like those based on kinetic ideas, lattice Boltzmann gas etc. must be further developed. Further applications of these methods are found in space flight simulation, where generalized Boltzmann equations are ruling the game, in granular flow (transport of grains in silos, of ashes on conveyor belts) and even in the simulation of traffic flows on highways (see for example [5] and [6]). There is much mathematics used: Measure theory, functional analysis and probability, even number theory.

C) Heat flow is a very traditional subject and many commercial packages are able to handle it - if radiation is not involved. But quite often it is: For example, when glass is cooling down and the stresses have to be controlled. This is a very old problem, but in order to organize an optimal control the transport of heat by radiation should be simulated. In 3d nontrivial configurations this is still a tremendous task - no problem, if diffusion approximation holds, but otherwise ray tracing is still too elaborate even for very fast computers. Our way out is domain decomposition and matching: Do approximations wherever it is possible, but use ray tracing where it is necessary. And find appropriate boundary conditions between the domains to match the computations. This is a general strategy, which seems to become more and more important: To combine analytical (i.e. asymptotic) with numerical methods to get results as cheap as possible but as precise as necessary. Ray tracing has some features of particle methods: Again number theory (Quasi random numbers), but also computational geometry, CAGD-methods and more.

D) Image processing is a wide field, normally „conquered" by computer scientists, but a genuinely mathematical task. Data compression by fractal image analysis or by wavelets, segmentation by Mumford-Shah or similar functionals, filtering by anisotropic diffusion, pattern recognition by Bayesian statistical methods, stochastic geometry: It is an enormous bunch of mathematical ideas (see for example [4]). And the variety of problems is as big: There is never „the" solution for a class of problems - each individual problem needs its special trick. Our main task is quality control of surfaces - the homogeneity of fabrics has to be measured, very little errors should be detected in surfaces of cars; the errors must be classified - often a job for neural networks. Medicine offers a wide field for image processing - with the advantage that the time needed for the processing is not as limited as for example in on-line quality control.

E) Adaptive systems are - in general - parametrized input-output mappings, which „learn" the parameters permanently from the experience and use the newly gained knowledge to predict the future. Whether the class of mappings you consider is given by linear control systems, by neural networks or something different, depends on the problem you have (the less one knows the more one tends to use neural networks - are they really as flexible as the human brain?); in the end it always turns out to be a parameter identification problem - very often ill-posed and highly demanding for regularization. Modelling and optimizing - that's, what you also do in describing chemical reactions and even risk assessment for financial products. Finance mathematics, things like option prizing, is a new highlight for mathematicians all over the world (but again: many talk about it, but only a few outside of the banks produce something useful) - and it provides jobs for our graduates.

We could continue, but want to conclude: Mathematics we need is very wide spread, asks for tools to do modelling and computing and, optimally, both things together. If the industrial problem comes first, one is sure that the mathematics used is applied and not only applicable. If the method comes first, the result may be beautiful, but often you have to refer to future applicability: A completely legitimate argument but only for very few, very good pure mathematicians.

III. Industrial Mathematics in 3rd world countries

Of course, the situation of industrial mathematics in third-world countries is different from that in Europe, US and Australia. One of us (A.H.S.) founded an Indian Society for Industrial and Applied Mathematics in 1992 and implemented a programme at his Aligarh Muslim University. The other one (H.N.) has trained more than 50 third-world students in a two-year programme, who went home and tried to apply their new knowledge in their home countries; almost 30 of them came back to Germany September 1996 and reported on their experiences. We believe to have a quite clear picture of the situation there.

i) Managers of companies in 3rd world countries are even less aware of the role of science and especially of mathematics than their „western“ colleagues. This opinion may originate from the fact that some companies have their research labs in Europe or the US, only doing the production here. Moreover, it is a general belief that mathematics is only useful for high tech companies; if their production or products are not high tech, they do not consider mathematics as a valuable tool. But what is „high tech“? There was a kind of definition by David, who wrote the famous report of the NSF in the US about the support for mathematics: „When we entered the era of high technology, we entered the era of mathematical technology.“ Changing a word of David Hilbert we may say: In any technology is as much „high technology“ as is mathematics in it. The consequences of these statements simply are, that one may change every product into a high tech product by investing more science and especially more mathematics in its production. As mentioned before, mathematics for basic technologies as textile, furniture, glass, metal processing, food has become very popular, the same holds for the simulation of environmental events as avalanches, water waves, pollution, breaches in dams etc.

   In short: There is much need for mathematics in any technologies, but less demand - a disadvantage for industry and for mathematics as well.

ii) There is a general tendency of managers in 3rd world countries to prefer software products from industrialized countries. It is more expensive but much easier to buy a commercial software tool even if it is not really appropriate for the problem to be solved than thinking and programming himself. But it is the wrong solution especially since the capacity of producing special software is already available: Why else would high tech companies all over the world establish software branches in India, Indonesia, Korea, Malaysia, China, who produce new software tools?

(iii) Only recently the 3rd world began to receive the message of Industrial Mathematics. Therefore, there is an acute shortage of properly educated mathematicians. There are, of course, some excellent pure mathematicians and quite a number of good applied mathematicians in the traditional British sense. But their work is mainly „method driven“ („I do, what I am able to do“), but not problem driven („I do, what should be done"). Academic careers make this attitude necessary: One has to belong to a scientific family (even if it is very small), one has to publish (even if it is a generalization of a generalization) in order to be promoted. Who dares to work on a modelling problem, when he/she does not know, which kind of mathematics is needed, what the result will be, where it should be published, who (besides maybe a company) will be interested in? However: Real career jumps need surprising results, new problems and new ideas - all that could not be expected without taking a risk! Moreover, senior professors do not need a security belt when working on new problems; they could go ahead and give the young scientists a chance and some credit to work on industrial problems. Obviously, the pressure comes from outside: Governments press scientists to contribute to the economic welfare of their countries. Does this really mean a cultural loss? Once more: The very few very best have some right to maintain that - and it is the duty of the many others to protect them, to protect them by proving that their ideas and mathematics as a whole is one of the most useful and valuable technologies.

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