Mathematics for Society, Industry and Innovation

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Abstract
Mathematics, modelling and simulation, so called mathematical technology is emerging as a vital resource to achieve competitive edge in knowledge based industries and development of society. Especially it means a challenge for university education and mathematics teachers’ training. A modern view of mathematics should be reflected in curricula and educational practices. The challenge is to find ways to make the theoretical content transparent and communicate to the students the end-user perspective of mathematical knowledge. The educational change should be visible in curriculum development, up-to-date contents, innovative teaching methods and educational programs. Development of modelling education is a crucial part of this endeavour. I discuss the challenge from the curriculum level and also as a challenge of university pedagogy of applied mathematics. Implication for teachers training programmes and practices at school level are also suggested. I refer to case examples of industrial math projects illuminating the educational challenge. I report about developments in the MS curricula and novel practices that have been introduced in Europe. I also report about some recent and ongoing surveys and campaigns related to mathematics-industry interaction.

Keywords: Industry, simulation, interdisciplinary, system, curriculum.

1. Introduction

Mathematics, modelling and simulation, so called mathematical technology is emerging as a vital resource to achieve competitive edge in knowledge based industries and development of society. This vision about the role of mathematics has inspired efforts to enhance knowledge transfer between universities and industry. Especially it means a challenge for university education. A modern view of mathematics should be reflected in curricula and educational practices. This has implication for the way how mathematical modelling should be inserted to the curricula at various levels.

The main focus of this article is on undergraduate teaching at tertiary level. However some important implications are suggested concerning the schools preparing students for universities.

2. Computational Technology

The development of technology has modified in many ways the expectations facing the mathematics education and practices of applied research. Today’s industry is typically high tech production. Sophisticated methods are involved at all levels. Computationally intensive methods are also used in ordinary production chains, from brick factories to bakeries and laundry machines. The increased supply of computing power has made it possible to implement and apply computational methods. Terms like mathematical technology, industrial mathematics, computational modelling or mathematical simulation are used to describe this active contact zone between technology, computing and mathematics.

A mathematical model is assumed to represent the structure and the laws governing the time evolution of the system or phenomenon that it was set out to mimic. Once we are able to produce a satisfactory model, we have a powerful tool to study the behaviour and hence to understand the nature of the system. The models can be used to
-again understanding of intricate mechanisms by testing assumptions about the systems nature.
-carry out structural analysis tasks
-replace or enhance experiments or laboratory trials.
-evaluate the systems performance capabilities
-forecast system behaviour and analyse what-if situations, to evaluate the effects of modifications, consequences of changes to systems parameters.
-perform sensitivity analyses and study the system behaviour at exceptional circumstances.
- analyse risk factors and failure mechanisms
- create virtual and/or visualized images of objects and systems in design processes
- create imaginary materials and artificial conditions prior to the possible synthesis or construction.
- optimise certain values of design parameters or the whole shape of a system component.
- perform intelligent analyses on the measurement data which is produced by the process monitoring, experimenting etc.
- manage and control large information systems, networks, data-bases

3. Industrial Mathematics, Educational challenge

The computer age has generated a need and a window of opportunity for a new kind of expertise. This presents a challenge to the educational programmes and curriculum development. Some universities already offer specialized MS-programs oriented towards the industrial needs. There are excellent programs that equip the students with the skills that are needed in the professional use of mathematics. In general there is still room for improvement.

A good educational package would contain a selection of mathematics, computing skills and basic knowledge of physics, engineering or other professional sector. It would be very important to train oneself to work in a project team, where the interpersonal communication is continuously present. To become a successful applied mathematician ready to tackle the fascinating tasks and challenges, development questions in modern industry, the student need a solid and sufficiently broad theoretical education and operational skills in the methods of applied mathematics.

There is a special need to revise the university pedagogy of applied mathematics. Reflection to the preparatory levels of high school should be elaborated. Regarding the undergraduate programmes at universities the following means should be considered: revision of syllabi and curricula, use of computing experiments, data tools and novel teaching methods. The curriculum should contain knowledge of theoretical mathematics and a collection of applied courses. The students should have also knowledge of some applied science or application fields, knowledge in physics, engineering or other “client discipline” of mathematics. The quality of classroom examples is important. Problem based learning, topical fresh exercises are called for. Mathematics teachers should have interest for different areas of modern professional life. Modelling examples can be found from work places, hobbies, talking with people from various professions, sometimes reading newspapers with mathematically curious mind. Interesting modelling cases can emerge from bakery, laundry machine, brick manufacturing, fermentation process of food or bioprocesses in gardening.

However, the most important single skill is the experience in projects. For successful transfer of mathematical knowledge to client disciplines the theme of mathematical modelling is a crucial educational challenge. The lectures, books and laboratory exercises are necessary, but the actual maturing into an expert can only be achieved by “treating real patients”.

4. Industrial Mathematic as Profession

The computer age has generated a quest for new special expertise. Many universities offer specialized MS-programs that equip the students with the skills that are needed in the mathematical projects in the R&D-sections in industry. The job title in industry is very seldom that of a mathematician. It can be a researcher, an engineer, a research engineer, systems specialist, development manager. The tasks he/she is doing can be associated to
- advanced information systems
- modern production systems
- simulation and performance analysis of systems
- virtual design and product development
- building and testing process models
- data analysis
- experimentation and measurement technology
- advanced methods for computer science
- financing and insurance systems
- risk analysis and management
- strategic planning and decision support
- data mining, informatics

Industrial mathematics is team-work. Success stories are born when a group of specialists can join their expertise and visions together in a synergic manner. The team-work makes communications skills a necessary matter. It would be very important to train oneself to work in a project team, where the interpersonal communication is continuously present. To become a good applied mathematician one should be curious about other areas as well, to be interested and learn basic facts from a few neighbouring areas outside mathematics.

We should bring the flavour of a fascinating art to the classroom, to convey the vision about mathematics at work, the diversity of application areas and practical benefits. The challenge is to find ways to make the theoretical content transparent and communicate to the students the end-user perspective of mathematical knowledge.

The educational challenge should be visible in curriculum development, up-to-date contents, innovative teaching methods and educational programs. Many innovative practices have been adopted to facilitate the knowledge transfer. Development of modelling education is a crucial part of this endeavour. There is educational challenge from the curriculum level and also as a challenge of university pedagogy of applied mathematics.

Curriculum development project and networks of collaboration have been introduced in Europe since 80ies. This has resulted in Masters Programmes where the objective of real world interaction and connections with industry has been built in. The objective is also to identify common guidelines for universities in their efforts to develop mathematics masters education for the present challenges of the world.

5. Sphere of Applications

In the following I describe the increasing sphere of areas where modelling simulation and intelligent systems are a crucial vehicle of development. I refer to case examples of industrial math projects illuminating the educational challenge.

Economics and management. The daily functioning of our modern society is based on numerous large-scale systems. Examples are transportation, communication, energy distribution and community service systems. The planning, monitoring and management of these systems offers a lot of opportunities for mathematical approach.

Corporate management uses methods in which mathematical knowledge is embedded in different levels. Econometric models are used especially at the banking sector to describe the macro level changes and mechanisms in the national economy. Risk analysis, game theory, decision analysis etc are used to back up strategic decisions, to design a balanced financial strategy, to optimise a stock portfolio. The mathematics of the financial derivatives (options, securities) has been a sector of rapid mathematical development in recent years. Examples could be analysis of liquidity, risks in interest rates and evaluation uncertainty margins. Figure 1 shows electricity price variation in a given geographic area, figure 2 shows water reservoir level in the same period.

Figure 1
Product design and geometry. The modern toolbox of analytic and numerical method has made mathematics a real power tool for design engineers, production engineers, architects etc. Mathematics is a natural tool to handle geometrical shapes, like the surfaces of car bodies and in the visualization techniques in CAD and virtual prototyping. In fact, entertainment industry, computer games and the vivid special effects in movies are big clients for mathematical knowledge. In space technology modelling of the mechanical properties of the manmade structures in the spatial orbit lead to advanced mathematical questions. Each individual space mission represents a massive task for dynamical modelling and optimal control.

Performance analysis, manufacturing systems. The added value in using mathematical methods comes from the possibility of simulate devices, mechanisms, systems prior to their physical existence. A whole new system - like an elevator system in a high rise building, a microelectronic circuit containing millions of elements, or a high tech manufacturing system – can be designed and tested for its performance and reliability. Simulation of multibody systems and integrated design of complex mechanisms are examples where computational modelling means real competitive advantage. High speed train carriage, timber manipulator, multi component crane arm, robotics etc. are examples of such mechanisms.

Maritime and offshore industries use advanced mathematical methods in the design of ships and mechanical analysis of offshore structures. An example is the dynamical behaviour of floating structures under wave force effects and wind conditions. One particular challenge is the modelling of the sea and the wave conditions itself for the sake of simulation purposes.

In semiconductor industry the modelling of the single transistor has generated a lot of research. The industry wants accurate device models describing the performance characteristics of a chip prior to its production. To find the optimal architecture for an integrated circuit demands heavy calculations. The procedure of etching or beam lithography that is used during the manufacturing of the integrated circuit leads to interesting mathematics.

Chemical reactions and processes. Chemical processes are being modelled on various scales. In the study of molecular level phenomena mathematical models are used to describe the spatial structures and dynamical properties of individual molecules, to understand the chemical bonding mechanisms etc. Chemical factories use large models to monitor the full-scale production process. Many modern fields like fuel cells and polymers are based on mathematical models. Increasingly important area of environmental monitoring benefits from models of biochemical processes.

Materials behaviour. Materials science is one of the active fields where the mathematics based methods have proved their necessity and power. The aim is to understand the microlevel effects, subtle engineering of special compounds etc. The behaviour of non-typical or new materials like semiconductors, polymers, composite materials, piezoelectric or optically active compounds, optical fibres can be investigated with mathematical models. The models can further be used to design and control the manufacturing processes.

The study of materials behaviour at the micro level is of great importance and huge economic value and it is dependent of industrial mathematics. The nanoscale phenomena and design processes can only be understood and controlled with the help of computational models. Genomic research and pharmaceutical product development are based on modelling of dynamics of macromolecules, analysis of chemical reaction kinetics and ingenious analysis of astronomic volumes of experimental data.
Metal industry. The whole production chain of metals starting from mining industry, enrichment processes, furnace, casting, hot rolling, sheet forming, profiling etc. contains a lot of challenge to mathematical models. Quite modern and sophisticated methods are employed, like optimal control theory, free boundary problems, optimisation and advanced probabilistic methods. Delicate questions are the modelling of the material deformation during manufacturing, the phase change in the heat treatment and the fatigue mechanisms.

Food and brewing industry. Mathematics has to do with butter packages, lollipop ice-cream, beer cans and freezing of meat balls. The food and brewing industry means biochemical processes, mechanical handling of special sorts of fluids and raw materials. These less typical constituents lead into non-trivial mathematical questions. The control of microbial processes is quite crucial and adds to the complexity. Food chain security issues and ecological sustainability are becoming a major global problems and there is demand for sophisticated models.

Flow phenomena. The ability to model sophisticated phenomena, including non-linear effects, the possibility to solve the equations with advanced numerical methods, combined with the latest visualization tools have created a luxury environment for mathematical engineering. The computational simulation can be used to support the design of systems from tooth paste tubes, regional heating networks and aircraft fuselage design to ink-bubble printers. Below figure 3 indicates a river flow system. One application might be the study of penetration of saline water from the sea into the estuary (figure 4).

Systems design and control. The design engineers and systems engineers have always been active users of mathematics in their profession. The possibility to set up realistic large-scale system models and the development of modern control theory has made the computational platform a powerful tool with new dimensions. Remote control of traffic systems, monitoring and maintenance of power transmission networks, control of windmill farms would be examples of large systems where a need for advanced intelligent control appear. In traffic systems the analysis of traffic flow, scheduling, congestion effects, planning of timetables, derivation of operational characteristics, air traffic guidance systems and the flight control etc. need sophisticated models. The illustration (Figure 5) describes measurement data from thickness of a 1500 m long paper web. The image is actually a product of a simulation model that mimics the actual performance of the paper machine.
Measurement technology, signals and image analysis. The computer and the advanced technologies for measurement, monitoring devices, camera, microphones etc. produce a flood of digital information. The processing, transfer and analysis of multivariate digital process data has created a need for mathematical theory and new techniques. Examples of advanced measurement technologies are mathematical imaging applications. Applications range from security and surveillance to medical diagnostics (Figure 6). Recognition of harmful mold spores in air quality samples or bacteria from virological cell cultures.

Experiments and data analysis. Intelligent methods are needed for the utilization of experimental data. The process control and monitoring systems, the sampling procedures etc have to be designed. The quality inspection and testing procedures for the finished products all involve questions for intelligent data techniques.

Media and entertainment industry are heavy users of mathematical models. The visualization techniques, special effects and simulated motion of virtual reality are based on multidisciplinary approach using mathematics, mechanics and computing power.

An example could be the sympathetic character of Gollum from “The Lord of the Rings” movie. The odd and alien skin of the character was created by a technique of simulate subsurface scattering, a combination of modelling, physics of light reflection and computing skills. (Figure 7 taken from www.ew.com/ew/article/0,,702019,00.html).
Weather science uses mathematical models to simulate the dynamics of atmosphere. We are enjoying the benefit of these models in the form of weather forecasts which are done by combining sophisticated mathematical models and the flow of measurement data from weather stations. Below (Figure 8) is a simulation of large scale weather phenomenon, actually typhoon created by Earth Simulator, a huge super computer at Yokohama, Japan.

6. Modelling as a Course Subject

Many departments have introduced modelling courses in the curriculum in recent years. A course in modelling may contain study of case examples, reading texts and solving exercises. The actual challenge and fascination is the students’ exposure to open problems, addressing questions arising from real context. The real world questions may be found from the student’s own fields of activity, hobbies, summer jobs, from the profession of their parents etc. Reading newspapers and professional magazines with a mathematically curious eye may find an idea for a modelling exercise. A good modelling course should

(a) contain an interesting collection of case examples which stir students’ curiosity
(b) give an indication of the diversity of model types and purposes
(c) stress the interdisciplinary nature, teamwork aspect, communication skills
(d) tell about the open nature of the problems and non-existence of “right” solutions
(e) bring home the understanding of practical benefits, the usage of the model
(f) tie together mathematical ideas from different earlier courses

The modelling courses have been run in different forms. Traditional lecture course with weekly exercise session is a possibility. It would be important to implement group work mode and PC-
lab activities in the course. The most rewarding form of activity might be projects and weekly session where the student report and discuss about their work and progress on the problems.

7. Modelling problems challenging undergraduates

The illustration (Figure 9) describes a city network of water pipes, water storages and wells. Assume that some harmful contamination enters the network at some point. Describe by a model the spread of the pollution concentration in the network. Next question could be to evaluate certain attempts to clean the system.

![Figure 9](image.png)

![Figure 10](image.png)

Nontrivial modelling examples are created by some non-usual pendulum variations like the one in figure 10. Describe the system behaviour. Study the system equations limit as the radius of the obstacle goes to zero.

The following example is a true problem in timber industry. Logs are cut into different wood products of standards sizes. Given the measurements of the various standard products and the diameter of the log, what is the optimal strategy to cut the log (Figure 11)?
A metal chain or rope is laid on a floor. One end is slowly lifted off the ground (Figure 12). Find the shape of the chain. Try to model the movement of the point where the chain is detached from the floor. This is so called moving boundary problem - and far from trivial.

8. Modelling weeks

One of the innovative educational practices introduced in the recent decades is Modelling Week, an intensive mathematical problem solving workshop which simulates the real life R&D procedures. Students from all over Europe come together and work in teams of five or six on modelling real world problems. The cases originate from industry, different organisations or branches of society. The problems are brought in and presented by the problem owners. The teams are guided by a group of academic staff members. The “instructors” usually play the role of the problem owners.

The students are allocated to problem-teams on the basis of their areas of interest and mathematical expertise. The week starts with the problem owner giving a brief outline of the problem, the industrial context and the relevance of the problem for his/her company. The team questions the problem owner about the problem and the expectations.

To identify and understand the “real” problem may take some time. The students must formulate a model and recognize the typically non-unique mathematical problem. The analysis follows leading to analytical studies and efforts to find techniques for numerical solutions. Typically the group arrives at an approximate solution. At the end of the week the student groups have to present their findings in public. Further they are assumed to produce a decent written report, often a short article that will be published in the proceedings of the Modelling Week.
9. Initiatives on public arena promoting math and modelling

Industrial innovation is increasingly based on scientific knowledge and techniques. Such research is both underpinned and driven by mathematics. Given the intimate connection between innovation, science, and mathematics it is important to ask whether the interface between these three activities is functioning in an optimal way.

Recognising this, the Global Science Forum (OECD) decided in 2007 to sponsor an international survey to assess the present state of this interface in the participating countries and to identify mechanisms for strengthening the connection.

A workshop on “Mathematics in Industry” was held in Heidelberg, Germany in 2007 to analyse the relationship between the mathematical sciences and industry, to identify significant trends in research and the mathematical challenges faced by industry in the global economic environment, and to identify and analyse the implications of the trends for the relationships between academia and industry and to formulate action-oriented practical recommendations for the main stakeholders, scientists, industries and governments.

A report of the OECD survey was published in 2008.

The report summarises the deliberations, and presents the findings. Recommendations are addressed to the academic community, governmental and other funding agencies, and industry. They are designed to stimulate the interaction; to enhance the curricula; to improve the infrastructure for increased interactions, and to strengthen coordination and cooperation at national and international levels.

Some of the recommended actions are: Interdisciplinary research centres, faculty positions for industrial mathematics, research internships, special interest groups, direct research collaboration, study groups and student activities, translation of technology to ferment knowledge transfer, mathematical consultancy and software companies.

Another survey as a follow-on was conducted to map the ways in which the various mechanisms cited in that report have been implemented around the world. The results are published in a report:

Report on Mechanisms for Promoting Mathematics-in-Industry

With an aim of helping governments, industries and academia to see how to use mathematics as a resource for research and training and to gather information for a compendium of projects that have successfully bridged the gap between industry and academic mathematics.


In Europe European Mathematical Society and European Science Foundation launched in 2009 a Forward Look project to analyse the implications of OECD and other recent reports. The purpose is to enable the scientific and industrial communities, together with policy makers, to develop medium to long-term strategies for research policies.

http://www.ceremade.dauphine.fr/FLMI/FLMI-frames-index.html

10. Modelling education, how much and when?

The presence of mathematical modelling on today’s technology agenda and in the challenge of knowledge based society indicates the importance of the questions of teaching of mathematical modelling in curricula at various levels of education.

Does this support the idea that modelling education should be promoted for all children at all school levels? How much, in what way and when?

These questions should be discussed seriously in the math education community.

The skills of mathematical modelling mean an essential competence which is needed in many science related fields, technology, engineering, economics, biomedical professions etc.
Modelling means a set of specialized science based skills that can be compared with the expert skills of, let us say, airline pilots and brain surgeons.

Our society really needs these skills but we do not arrange mini courses in airline pilots and surgery on primary school levels. This somewhat provocative statement is meant to emphasize the important question of how mathematical modelling should be inserted to the educational system.

The overall understanding of mathematics in today’s world should be explained in mathematics classroom. Examples from applications should be used as pedagogical fermentation of the learning process. The joy of problem solving and the use of mathematics for real life situations is an ideal way to build interest and enthusiasm in the classroom.

However the pedagogical challenge must not be overlooked. The phrase of professor Helmut Neunzert at ICTMA14 “…modeling can be learnt but not taught in a usual way” contains an important message. One should also remember that often educational fashions or New Math reforms tend to drift to overdrive or hype level.

Teacher training is a key question. The new generation of math teachers should have a sound overall understanding about the important role of mathematics in today’s world so that he/she can bring to the classroom a flavour of the fascinating special skills of mathematics, modelling, simulation and computing. The children hopefully will become aware of several new professional career opportunities in the field of science based professions where mathematical models are the modern space-age toolkit.

11. European FP7 programme Science and Society

European Union launched within the 7th Framework programme a call with title Science and Society. Natural Sciences, Mathematics, Informatics, and innovation are vital to increasing competitiveness, enhancing and expanding the economy and improving the quality of life and promote international competitiveness. Europe needs to generate more trained scientists, engineers and researchers to meet the challenges of global competition. This is essentially the content of the Lisbon Agenda.

A key question is the interest of youth in science and engineering education. In the last 20 years an alarming decrease in the number of youths studying Science and Engineering has been observed [“Science Education Now: A Renewed Pedagogy for the Future of Europe”, Michel Rocard group report on Science Education, 2007]. The trend seems to continue and the phenomenon is known worldwide.

The Universities, as initial and continuous teacher trainers, need to change their approaches to train new and in-service Science teachers. Inquiry based and problem based learning strategies are known to develop student attitudes to their studies of the Science such as raised interest, curiosity, commitment, autonomy in study and interdisciplinary and awareness of the context and real life.

This is a challenge for varied local stakeholders: schools, universities, governmental and non-governmental organisations, local authorities, education research laboratories, science centres, libraries, citizens’ associations, local media, enterprises and technological parks.

I suggest that a theme “Mathematics and society – real life perspective in mathematics education should gain attention in this discussion. The attitudes of young people for math and science teaching and learning are affected by

- teaching methods, syllabi and educational content
- teacher’s knowledge about their subject and the world around the subject (other sciences, society, industry, technology, R&D activity, including development challenge in public governance)
- organization and administration of education as a national enterprise
- public awareness about the role and significance of science, technology and the science education within general public
- competition in the minds of the students between our subject and many other fascinating topics (entertainment, fitness, environment, peace, democracy, global responsibility, self expression, fashions and tribal cohesion, family values and friendship).

A big question is how the demanding science education can be promoted in the challenging, complex, multifaceted cultural arena. No doubt main objective should be fermentation of interest, curiosity, commitment and diligence in the minds of students.
Teacher training is a key question. The new generation of math teachers should have a sound overall understanding about the important role of mathematics in today’s world so that he/she can bring to the classroom a flavour of the fascinating special skills of mathematics, modelling, simulation and computing. The children hopefully will become aware of several new professional career opportunities in the field of science based professions where mathematical models are the modern space-age toolkit.

The teachers should be able to bring to the classroom the enthusiasm and vision of mathematics at the service of society and the advancing front of development. The idea of computational technology and modelling as a component in creativity and innovation in all science and science based professions should be brought to the attention of 15-18 year old boys and girls by their science teachers backed up by media and other stake holders.

This goal can be achieved only if the curricula in undergraduate and graduate level in universities and teacher training programs are developed. Universities should offer courses, seminars, project experience for student about "Mathematics applied to real world". Mathematics teachers should have been exposed to such material at undergraduate level and in graduate studies.

- general lectures about industrial mathematics
- courses in mathematical modelling
- problem seminars, project work about small modelling cases
- possibility to participate in Contests of Mathematical Problem Solving, etc.

We should apply this viewpoint to the teacher training and re-training programmes, curriculum development at undergraduate and graduate level, development of teaching culture at universities and programmes preparing teachers for high schools and colleges.

12. Acknowledgement


Bibliography:


