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How Can Mathematics Support a Deeper Learning Approach in Applied Engineering Subjects?

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The mathematics that is taught at engineering universities in Sweden and other countries has been about the same for a very long time. With the shift towards a greater use of mathematical numerical tools in many engineering subjects, the content and manner of teaching in mathematics have been undergoing profound changes. Since mathematics is often taught early in a curriculum, it is of interest to investigate how the students' learning of mathematics will affect their learning in applied engineering subjects. The paper discusses how changes in mathematics education influence the way of teaching and learning for the engineering subjects. Furthermore, some thoughts are provided on how the changed mathematical knowledge and skills amongst the students might affect particular engineering subjects, such as chemical reaction engineering and bioprocess engineering, important subjects within the bioengineering programme.

INTRODUCTION TO CHALMERS

Chalmers University of Technology in Göteborg is a technical university on the west coast of Sweden with 5,100 (26% women) Masters students, 1,800 (19% women) Bachelor students and 1,130 PhD students (23% women) and about 2,300 employees.

Each year, around 250 PhD and Licentiate degrees are awarded as well as 850 MScEng and MArch degrees. Around 40% of Sweden's graduate engineers and architects have been educated at Chalmers. Chalmers' turnover is approximately SEK 1.7 billion per year, more than two-thirds of which is related to research. The separate schools involve, for example, mechanical, computer, electrical, civil and chemical engineering, engineering physics and architecture.

At Chalmers there are also 10 different Master of Science programmes, which require 4.5 years (180 credits) for an MSc degree. The schools have different curriculum for their education but some coherence can be seen from their individual curricula. Usually (and this does change) the first three years consist of compulsory courses and the last 1.5 years comprise elective courses and a diploma work (half-year). In the first year, mathematics and natural sciences dominate the course selection. The second year is more applied, but still with a great deal of mathematics and computer science. In the third year, the applied engineering courses dominate and very little mathematics is taught.

MATHEMATICS

The mathematics that has been taught for many years is generally traditional, with the main focus on analytical solutions to simplified problems, in many universities around Sweden and other parts of the world. Applied courses and their problem-solving training are then of course adapted to the students' abilities gained in mathematics. The use of computers in mathematics does not match the needs as a whole. Computer use and programming are usually covered by special courses such as those on programming and within the subject numerical analysis.

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Long-term Project

Currently, there is a long-term project going on to change the way the mathematics is taught (and learned) and applied in the coming applied engineering subjects in the second, third and fourth years of the Masters programme. This learning project, which is strongly supported by Chalmers University of Technology (and it should be noted, the students), presently concerns two separate educations titled Chemical Engineering with Physics and Bioengineering. The annual number of students taken for these courses is 35 and 70 respectively. This is a suitable small group for a development project of this kind.

Since the great success has so far been realised, a broadening of the project is at hand. In autumn 2001, the students in the chemical engineering programme (about 100 in the first year) will also attend the new mathematical programme. This means that a total of 200 students will actually start a completely new mathematical education in their first and second year at the school of chemical engineering in their Masters programme.

In this paper, the implications of this change in mathematics teaching on applied subjects for the education in bioengineering are discussed, including their obvious advantages and possible drawbacks.

BIOENGINEERING EDUCATION

The biotechnology education is a new education, which started in 1996 with 35 students taken in annually (70 in 2000). The number of applicants for this education has so far been very high: about six to 10 students for every position. In other words, it is the top students that will start this education and this imposes many requirements for a good and well-planned curriculum. In 2000, the first students from this course graduated and applied for positions in industry, research centres and universities (so far mainly in universities). The related curriculum is shown in Figure 1. For the last year, a number of directions are possible such as medical and molecular biology, food science, forest and environmental science and the more traditional bioprocess engineering sciences. New directions in the field of biophysics, bioinformatics and biomechanics are under development presently.

The primary goals for these students are to:

- Identify, solve and interpret biotechnological problems.
- Carry out and analyse advanced experimental investigations.
- Design and monitor biotechnological processes.
- Manage both engineering language and the language of biology.

The means for achieving these goals are in:

- Training in problem-solving and computer skills.
- Good knowledge of biochemistry, physical chemistry, and molecular biology.
- Chemical engineering competence.
- Sufficient insights into biology, organic chemistry and inorganic chemistry.
- An open and creative academic environment.

MATHEMATICS LEARNING APPROACH

Virtual reality and computer-based simulations bring new and useful tools to science and technology. New systems' configurations and products can be designed and developed and in the later stage tested through computer simulations. This testing can be performed on time scales, and at costs, which are of a smaller magnitude than using the traditional technique, for example, extensive lab-work, rules of thumb and direct calculations by hand.

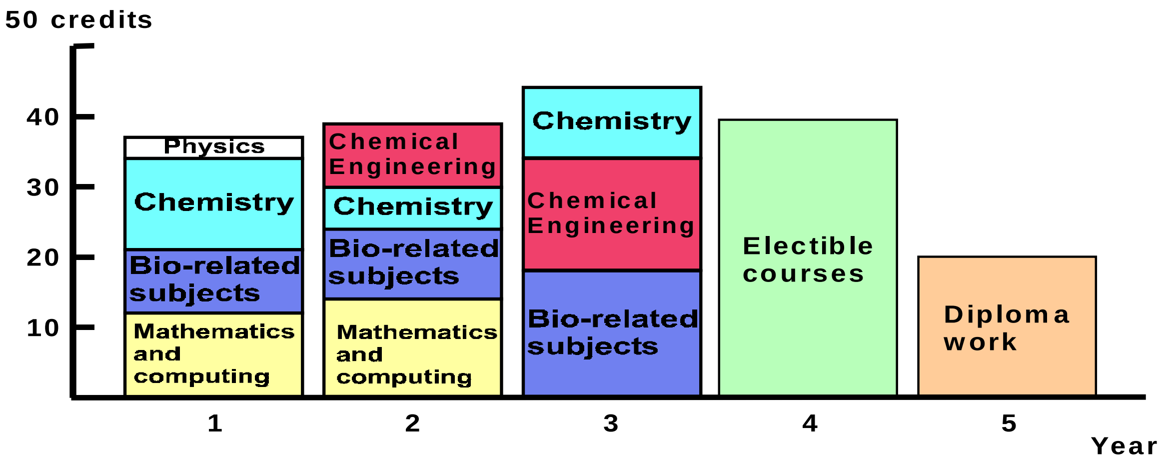

Figure 1: Chalmers' Masters programme in Bioengineering (180 credits).

In the sciences of, for example, bioengineering, environmental- and chemical engineering design and chemical reaction engineering, microbiology and metabolic flux analysis economy and medicine, computational modelling can be applied with great success and also with the aim of getting a greater fundamental and deeper understanding of the phenomena involved.

Computational mechanics, physics, fluid dynamics, electromagnetics, chemistry and biology are all subjects that involve the solving of systems of differential equations by using computers. Nowadays, reactor analysis can be considered to be at the heart of a process design procedure. But in the future, the heart of process design might be moved into the new fields of new simulation techniques such as Computational Mathematical Modelling (CMM) and Computer Aided Design (CAD).

At present, the need to modernise engineering education is very challenging. The new tools of calculation, especially CMM/CAD, will be very interesting in this context. This technology can be used to build bridges between subjects, schools and courses previously considered to be separate. The form as well as the content, from basic to graduate level, should be changed with this in mind.

The way that mathematics is introduced and taught (learned) is a foundation of the applied sciences in all schools and at all levels, since engineering and science are largely based on mathematical modelling. The quality and level of mathematical learning determine the status of the total education. Modelling in the engineering subjects and education has changed towards the use and development of computers. An integrated education is therefore necessary for a successful engineering education. This integration is planned and discussed in many technical universities at present. The variance and spectrum of how much and what should be changed differ, according to whether one asks mathematicians or computer scientists.

Engineering subjects often consider today's traditional mathematics to be of little use. Problem formulation and solution in these subjects has therefore been limited to analytical solutions. The topic (and solving) of differential equations is kept at an elementary level for this reason. Careful selection of problems and instructions is the reason for this procedure in mathematics education. The reduction in mathematics education in some schools at Chalmers can be understood from this fact. Mathematics is indeed difficult and hard to penetrate in a useful way, but in the age of computers this is not a good trend for mathematics all over the world. The USA, especially, has some development of new mathematics and its part in the curriculum has taken place.

The project at Chalmers deals with a synthesis of mathematics, computation and the handling of differential equations in the form of a general computational methodology. This project is deeper and goes further into non-linear systems already in the first half year (compared to the previous curriculum). The programme involves a more constructive education with active student participation and feedback communication between student and teacher. Including of realistic and applied examples helps and motivates in this context.

After the new preparation, students actually penetrate deeper into problem solving and interpretation with fewer instructions and less teacher interaction and guidance. The programme can be seen as a synthesis between the computer and mathematics with the aim of coming as close as possible to reality and its complexity. This will lead to a new basis for interaction with all engineering courses in the second and third years for the programmes in Bioengineering and Chemical Engineering with Physics. This is necessary in order to fully utilise this new type of knowledge that the students have learned.

STUDENT INTERACTION

Every week, the students and teacher meet in four-hour lectures (traditional) and in exercises of four to six hours in tutorial groups (eight students) including problem-solving, projects, and case studies with written and oral presentations. Two teachers lead these exercises: one more experienced and one PhD student. Senior students have been used with great success in autumn 2000.

These exercise classes also gives the students more time to reflect and solve problems and also interpret the results early in their mathematical training. More applied examples are brought into the education at an early stage. Material for the first courses have been developed in a compendium (to be published in traditional book format in the near future) [1]. However, the book by Eriksson and co-workers is also used in this learning strategy [2].

The applied mathematics is taught parallel to computer sciences, which means that problems are sometimes solved by the writing and use of individually student-made computer programs and subroutines. While MatLab is the computer program utilised, the students do not use the toolboxes available in this program. As part of their mathematical training they construct their own subprograms for this purpose. This is important because otherwise the pedagogic effect would be weaker and less constructive.

TEACHING FACILITIES

Autumn 2000 saw some new teaching facilities introduced for the new engineering mathematics. The studios (see Figures 2 and 3) are a combination of traditional computer rooms with the possibility of lectures, demonstrations and student active learning.

The number of studios is presently two but the school of chemical engineering is planning to expand these facilities further. In one studio, there are 24 computers and 48 students seats. Actually, only the screens and the keyboards are physically in the studios since the computers are in another room for safety and for avoiding adverse heating problems for students and computers.

ENGINEERING COURSES

The applied compulsory and voluntary engineering courses in the 2nd, 3rd and 4th year of the Bioengineering curriculum are for example:

- Transport phenomena
- Chemical reaction engineering
- Bioprocess engineering
- Chemical engineering design

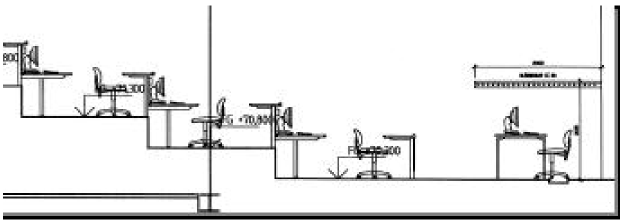

Figure 2: Lecture room style seating for the new studios.

- Experimental planning and evaluation
- Mathematical modelling in chemical engineering
- Metabolic modelling

As two examples of what can be achieved in these courses as a consequence of this new mathematics knowledge, Bioprocess Engineering and Chemical Reaction Engineering are discussed further.

Chemical Reaction Engineering

The teaching in Chemical Reaction Engineering has so far included laboratory exercises with seminars, lectures and calculation classes. The examinations have been traditional (problems requiring analytical solutions) for a number of years. This limitation in problem formulation has been a great disadvantage when trying to make the students approach the subject in a deeper and more fundamental way. The new preparation makes the subject more concentrated on discussing the phenomena involved in a more quantitative and basic manner. It is also possible to add new areas within the subject such as multiphase flow in different reactor configuration.

Through the use of computers (the students are now used to applying computer science and mathematics for applied subjects) the teaching situation is gradually changing from developing analytical solutions by dribble with mathematics to discussion of the problem formulation, solution and result interpretation.

The opportunity for improving student interaction in a teaching situation is more like a forthcoming work situation where the answers are not always given in exact two digits. This emphasises a basic understanding of the subjects. The chance to use computer simulation for understanding chemical engineering phenom-

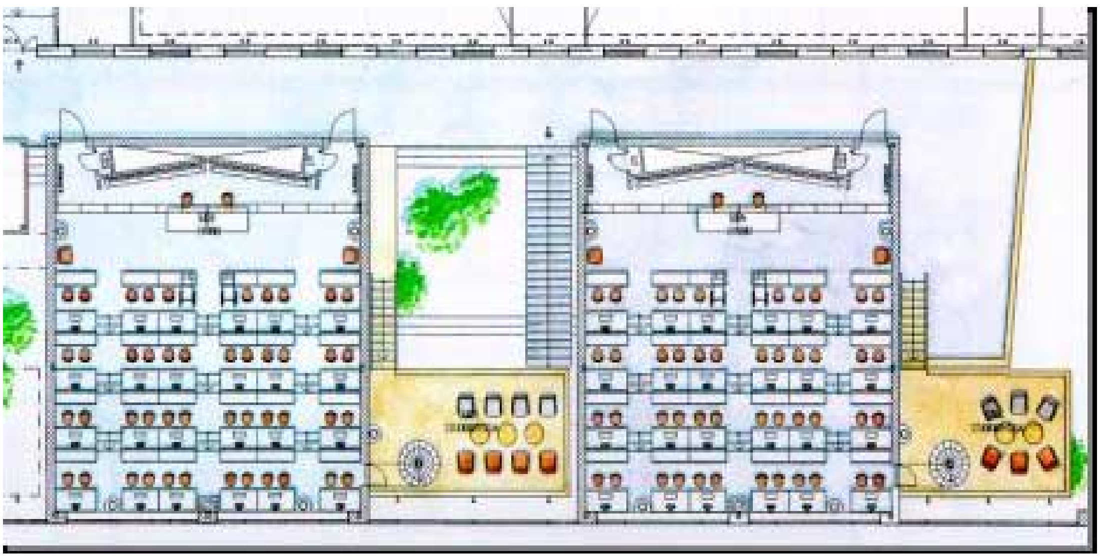

Figure 3: Overhead plan of the new studios for the teaching of engineering mathematics.

ena and to examine the sensitivity and probability of a solution will further strengthen the goals. Parameter sensitivity, model building, prediction and discrimination are other subjects that can be penetrated deeper in these simulations.

Bioprocess Engineering

The Bioprocess Engineering course involves the subjects' material and energy balances, reactor analysis mass, transfer and scale up of biological production systems. The course consists of quite traditional lectures and calculation classes, a large part being the laboratory-training course. The lab consists of the start-up (batch) and running of a continuous reactor (chemostat). This lab lasts for two weeks for each group, which means that the students are occupied for this period.

The applied mathematics in this course has so far involved a number of calculations where the solution has been suited for analytical solution with very little discussion and interpretation of the results. With this

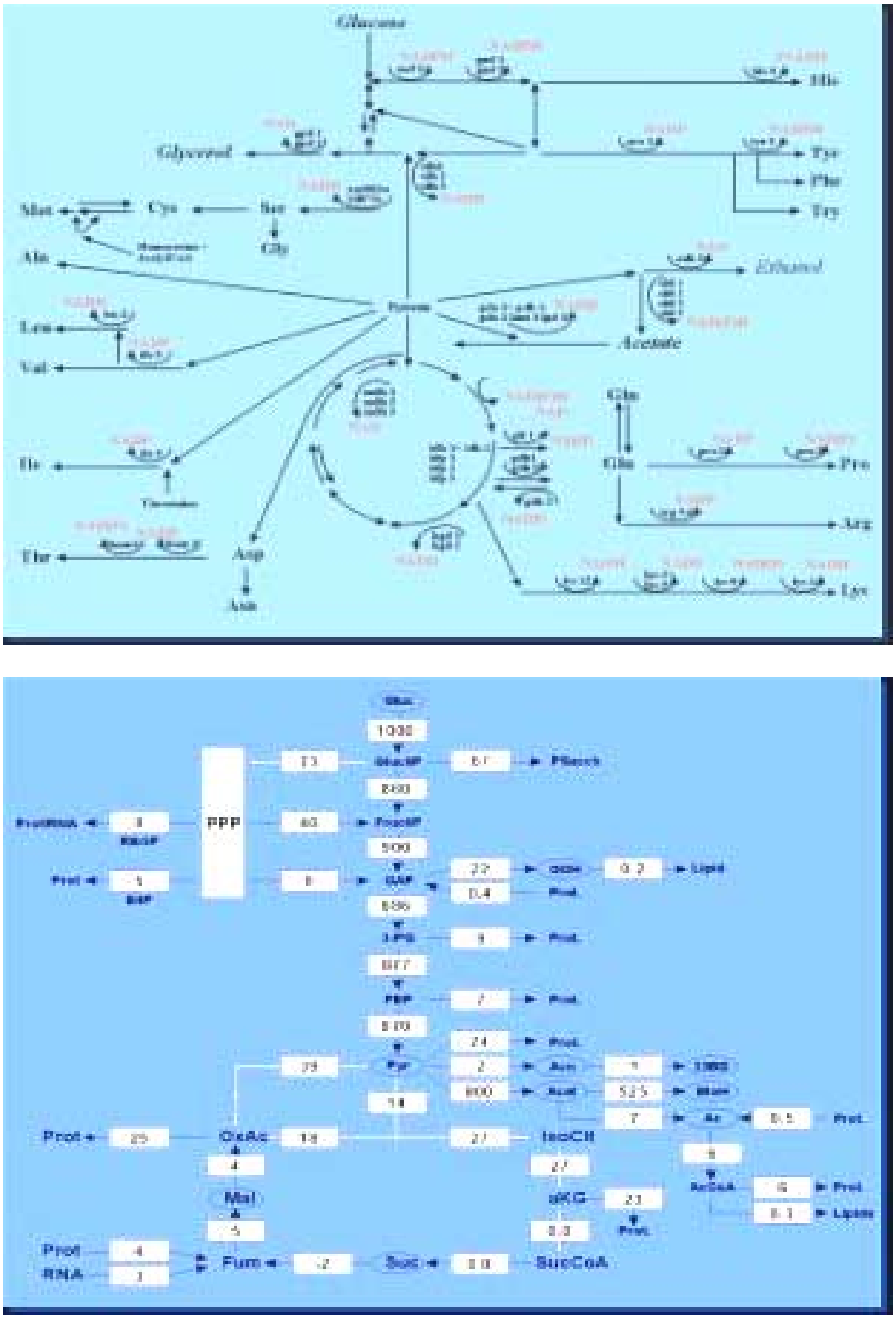

Figure 4: Display of glucose metabolism - metabolic flux analysis (S.cerevisiae).

new background for the students in applied mathematics and computer science, the teaching can directly pass to interpretation of bioreactor analysis and design results.

In this subject it is important to understand the fundamental cell-metabolism, how it works and what controls it. For this purpose, there are fairly new tools for mathematical handling of metabolic flows in cells, so called Metabolic Flux Analysis (MFA) and Metabolic Control Analysis (MCA). Further details of these techniques can be found in Ref. [3]. One example of how the metabolic fluxes can be described in *S.cerevisiae* is given in Figure 4.

By use of these mathematical tools, a more fundamental understanding of the cell-metabolism can be achieved. This basic understanding of cell metabolism has so far only been demonstrated by teacher guidance and on computer screens. Now the student can actually work (learning by doing *wrong*) and will then also experience the great advantage of using modern technology on biological systems.

So far the mathematical handling of biological systems have been limited by the complexity of the systems but with this new mathematical education the new mathematical and numerical tools can be used in a more thorough way directly in the learning situation. Bioinformatics, which is the systematic handling and interpretation of large amount of biological information, is a subject that will need and gain on this change in mathematics education. A Masters programme in Bioinformatics at Chalmers began in 2000 [4].

These two courses are only some of the examples of how different courses will benefit and gain new and interesting knowledge for the students by this new mathematics. In the near future, there will probably be many new examples in the engineering field.

Presently, the Schools of Mathematics and Chemical Engineering are planning new pedagogic projects where the new knowledge of use of mathematics in the engineering subjects can actually further improve the mathematics in the first years. In this way, the mathematics can benefit from feedback from the experiences found in the engineering subjects.

EVALUATION

The exams in mathematics are a combination of hand-in problems, project performance and presentations (oral and written), as well as the final written exam. The change in educations in mathematics is presently evaluated by a number of mathematicians and pedagogic experts. Pedagogues and engineering teachers will later further evaluate the implication on the engineering subjects.

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Claes Niklasson received his Masters degree in chemical engineering with physics in 1981, followed by a PhD in chemical reaction engineering in 1988. Prof. Niklasson manages teaching and research projects in the bioprocess technology field at the Department of Chemical Reaction Engineering at Chalmers University of Technology in Göteborg, Sweden. As the Head of the Department since 1991, he has been responsible for the total economy and administration. He is the Head of the Research School of Chemical Engineering and Director of studies for the Bioengineering Education. He is also a lecturer and an examiner for two courses (Bioprocess Engineering and Design of Biotechnical Processes) at the School of Chemical Engineering. He has been involved in a number of pedagogical projects at Chalmers and participates as a consultant in PhD courses concerning pedagogy at Chalmers. He is presently the Vice-Dean in the School of Chemical Engineering at Chalmers responsible for the undergraduate programmes.

He is the author and co-author of about thirty research papers and seven papers on pedagogical issues. His research fields include on-line monitoring and control of fermentation processes, cell physiology, dynamic modelling, microaerobicity in bioprocesses and biotechnical ethanol production from renewable resources, and is also very interested in teaching and the development of new projects concerning learning for students.

Said Irandoust holds a Masters degree in chemical engineering (1984) and a PhD in chemical reaction engineering (1989). Since 1998 he has been a professor in chemical reaction engineering and has been lecturing since 1989 in several courses, including at Chalmers University of Technology in Göteborg, Sweden, plus other universities in Sweden, as well as Indonesia. Prof. Irandoust has received a number of pedagogical awards from students and Chalmers University. He is the author and co-author of about thirty research papers within chemical engineering and engineering education. He was also an active member of the pedagogical network at Chalmers and was involved in a number of pedagogical projects. He was the Vice-Rector of Chalmers University of Technology and also worked part-time in the Centre for Educational Development. He was appointed the President of the University College of Borås in Borås, Sweden, on 1 January 2001.

His research interests lie in heterogeneous catalysis and chemical reactors, specially emphasising monolithic reactors, and he has a great interest in educational issues.

The Global Journal of Engineering Education

The UICEE s *Global Journal of Engineering Education* (GJEE) was launched by the Director-General of UNESCO, Dr Frederico Mayor at the April meeting of the UNESCO International Committee on Engineering Education (ICEE), held at UNESCO headquarters in Paris, France, in 1997.

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