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Laboratory of Computational Mathematics: an interface between academia and industry

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Abstract During the last decades there has been a growing demand for mathematicians for working in industry (SIAM, 1998). The importance of mathematical knowledge in an industrial context, became more and more relevant. Business, industry and government provide a fertile domain for application of advanced mathematics. To face this reality, universities feel the need to adapt their curricula in mathematics and to create better interfaces with industry.

The Laboratory of Computational Mathematics (LCM) of the Centre for Mathematics of the University of Coimbra (CMUC) was created to identify relevant social and industrial problems that could benefit with the expertise of mathematicians and to give visibility to the research done in CMUC that could be applied by the industry.

The aim of this paper is to analyse the work done in the LCM in two perspectives: the relationship between the university and industry and the relevance of the LCM activities in educational mathematical programmes

Introduction

According to several studies, "if Europe is to achieve its goal of becoming the leading knowledge-based economy in the world, mathematics has a vital role to play" (MACSInet, 2004). In spite of the fact that, in many industrial sectors, the value of mathematics is already proven, there is a need for positive action to promote the use of mathematics by European industry. A dynamic mathematical community interacting actively with industry and commerce, on the one hand, and the science base, on the other, have been pointed out as important ingredients for competing in the global market of the future where innovation will be the key to success.

The OECD report (OEDC, 2008) asserts that "while mathematics presents industry in the 21st century with major opportunities, it faces significant structural challenges in the industrial environment. A strong pressure to organise research and development around well-defined projects, combined with an increasing trend to outsourcing, has led even large companies to significantly reduce their investment in the mathematical sciences.[...] Nonetheless, strongly innovative companies that properly exploit mathematics can rapidly gain a commercial edge over their competitors. This is illustrated dramatically by the success of start-up companies selling custom-designed software."

It is widely perceived that graduate education in mathematics focuses almost exclusively on preparation for traditional academic research careers. Also, because of the interdisciplinary and diversity which non-academic employers typically demand, the knowledge of technical areas outside mathematics is of utmost importance in nonacademic positions.

In Portugal, the number of PhD and Master graduates with a degree in mathematics is small and the quantity of those having non-academic careers is almost imperceptible. Nevertheless, some indicators show the tendency for a slight change. With this scenario, there is the perception that the creation of institutional high level connections between academic mathematics groups and industry could produce a favorable impact (Vicente, 2006).

The activity in LCM

The Laboratory of Computational Mathematics was created in April 2005, integrated in CMUC, a research center that comprises most of the research-active members of the Department of Mathematics of the University of Coimbra (DMUC). Currently, the Centre has 65 members holding PhDs and 17 research students. The Centre makes a significant contribution to fundamental mathematics and includes research in Algebra, Analysis, Numerical Analysis, Optimization, Probability and Statistics, Geometry, History and Methodology of Mathematics.

The foundation of LCM followed the recommendations regarding the CMUC activities of the research unit evaluation panel in 2002 (FCT, 2002): "Computational Mathematics and Numerical Analysis are important subjects on which Portugal is somewhat lagging behind in spite of isolated pockets of expertise. The panel believes that this is well positioned and has the capacity needed to lead a nationwide initiative, and to provide a solid foundation on which to build a major Center of Excellence in Scientific Computing/Computational Mathematics in Portugal".

During its five years of existence, LCM has been promoting research in computational mathematics and scientific computing as techniques for the solution of challenging problems arising in biological sciences, engineering, finance, and management. The activity of LCM includes interdisciplinary research, high performance computing and the development of numerical software, in collaboration with industry, and also promotes Ph.D.'s and Master's graduate education.

The relationship with industry

The term "industry" has been used to denote business and commercial firms, research and development laboratories, commercial and not-for-profit research, and production facilities, i.e., activities outside the sphere of education and purely academic research.

As an interface with the University and industry, one of LCM's major tasks is to identify relevant social and industrial problems that should be tackled. The Portuguese Science Foundation, which supports most of the projects in LCM, has been considering the relevance of the project towards obtaining comparative advantages for Portugal a core criteria for funding, in accordance with the objectives stated in its strategic plan.

To identify such problems, contacts outside the mathematics community are important. To pursue this goal, LCM organized several workshops and an ECMI study group, where industry was invited to present problems that could be worked by mathematicians.

The project portfolio of the LMC includes 12 application-oriented projects, some having industrial partners, namely hospitals, banks and bank holding companies, data and software companies, and industrial firms.

As an example, we highlight the project "Simulation of a Moving Bed Reactor used in the Pulp and Paper Industry". The pulp and paper business is indeed one of Portugal's most important industries and an important mill of the major Portuguese firm Portucel, which is one of the world's biggest producers of bleached eucalyptus Kraft pulp for the packaging industry and one of Europe's top five producers of uncoated wood-free paper, is located

near Coimbra. In order to optimize the quality of the pulp, this industry has a real need for tools that enable the simulation of experiments that cannot be afforded or that might be risky in a real industrial context. The most critical piece of equipment in a Kraft pulp and paper plant is the digester, known as the heart of the mill. It is a very special and complex heterogeneous reactor where a moving bed of wood chips contacts and reacts with sodium hydroxide and sodium sulphide in a liquid phase (Kraft process), in order to dissolve lignin and therefore to release the fibers of cellulose. In this context, the incidence of the work developed at LCM is twofold: from an engineering point of view, the system of equations presented furnishes a description of the transient behaviour of the digester which allows the prediction of the quality of the pulp when some changes in the wood properties occur; from a mathematical point of view, the project gave the possibility to study a new kind of numerical methods, specially tailored to the phenomena that take place in each part of the digester.

"Reaction-diffusion in porous media" is another research project with many relevant real applications, namely the contaminant transport in groundwater which, in Portugal, has a big strategically interest. Nowadays, the pollution of the soils by fertilizers or pesticides is one of the most relevant environmental problems. The diffusion phenomenon can dramatically contribute to the contamination of groundwater and this can have serious social and economical implications. The evolution of contaminants in soils and the subsurface contaminant transport can be analyzed with the simulation of the models considered in this project. In particular, some areas in central Portugal are extremely polluted due to chemical industries. In the past, liquid effluents produced by these industrial units were discharged directly into several nearby streams. These effluents contained many different types of contaminants. Therefore, it is imperative to prevent and control this type of pollution and to have reliable information on mechanisms that track its evolution. The final goal of the project is to predict the evolution of this kind of pollution and to define strategies to reduce its environmental impact. The models studied during this project and the software package that are expected to be developed can also be used to study biological filters.

We must point out that in most of the projects at LCM, the degree of commitment of the companies involved is still less than it would be desirable since, in general, they don't contribute with funding. In addition, many of the on-going projects are engineering real problems but they don't target any particular industrial application.

However, the laboratory has strong interactions with engineers, physicists, physicians and finance specialists from Portuguese universities and also with computational mathematicians from elsewhere in Europe and in the US. Apart from numerous contacts with colleagues all over the world, the cooperation is formalized in a number of organizational frameworks.

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There has been a strategical effort to develop a variety of mechanisms to facilitate a constructive relationship between mathematics and industry. To achieve this objective, contacts and collaboration with industrial partners are vital.

In April 2009, LCM hosted the 69th ECMI European Study Group with Industry (www.mat. uc.pt/esgi69). The purpose of these one-week meetings is to strengthen the links between mathematics and industry by using mathematics to tackle industrial problems which are proposed by industrial partners. The academic participants, who were a diverse group of people with expertise in the mathematical sciences, including PhD students, postdoctoral fellows and professors, allocate themselves to a group, each of which works in one of the proposed problems with the industrial partner. The work was focused on five problems: "Optimizing a complex hydroelectric cascade in electricity market", "Management of stock surplus", "Estimating the price elasticity of water", "Fraud detection in plastic card operations" and "Reliability of a customer relationship management", proposed by the Portuguese firms REN, SONAE, Águas de Portugal, SIBS and Critical Software, respectively.

The experience of the study group was very fruitful, both for the University and the industrial partners. At the end the firms were asked to answer a questionnaire. The first question was "Did the workshop fulfill your expectations?" Next we summarize some of the comments. In the opinion of the representative of one of the companies: "Taking into account the shortness in time of the workshop and the complexity of the proposed problem, we consider that this initiative fulfilled our expectations, considering the given approach in solving the problem and the nice ambience and the contacts made." Other representative answered "It totally corresponded. The work addressed areas and questions which highlight the orientation of the working group for the applied mathematical analysis." Another relevant comment was given: "The initial result of the workshop exceeded our expectations. The work developed during one week was clear. The change of ideas and the results applied to the problem were well developed and presented."

Another question was "How could we improve the links between academia and industry?" One of the companies answered "I suggest the creation of a formal relation between institutions or between a pivot or a representative member of each part, which could often present problems, suggest and analyze possible approaches, debate the possible solutions and measure collaboratively the practical result of the achievements. In summary: partnership to debate ideas, solutions and results." Other idea was: "There are interesting tools like doctoral grants within companies, for relevant topics for the company."

We also asked if they intend to participate in future study groups and if they would recommend these events to other companies and all the answers were "yes". These answers re-

veal the desire of the industry scientists to stay in contact with current research being carried out at the universities. To enhance connections LCM proposes to promote meetings and study groups on a regular basis and scientific activity spreading actions. Another way to strengthen the links with the outside community is to offer a number of short-courses, with topics of interest to both industry and academia, open to members of the university as well other professionals and industry. These courses could be important to create institutional connections with local industry.

The educational programmes

Traditionally, most of the best undergraduate students in mathematics choose to continue their studies in pure mathematics. In recent reports it has been suggested the need to train more students in applied areas. The current crisis in the academic job market reinforced the attention in the preparation of mathematical students for non-academic employments.

LCM and DMUC think that the transition and integration into the job market of its students is an essential part of its mission. For this reason DMUC runs a Career Service, giving students a first working experience, preparing them for a better integration in the job market. The cooperation between the University and industry from all over the country has made this Career Service a success.

Several of DMUC's former students are now working in Industry. When they were asked about their academic preparation, they all tended to agree, according to what it was also pointed out in the SIAM report (SIAM, 1998), "that they were well educated for several important aspects of non-academic jobs: thinking analytically, dealing with complexity, conceptualizing, developing models, and formulating and solving problems. However, many felt inadequately prepared to attack diverse problems from different subject areas, to use computation effectively, to communicate at a variety of levels, and to work in teams".

Taking into account this scenario, there has been an effort to incorporate modifications in undergraduate mathematics curriculum in order to overcome these drawbacks. We point out that, in the current cycle studies in mathematics of DMUC, some of the courses are really problem-solving oriented and every student must have contact with courses that link mathematics and computing. The students are also encouraged to organize a regular interdisciplinary seminar focusing on a large variety of themes and non-academic mathematicians are invited to meet with students and to talk about their work. Each year DMUC promotes colloquia with former students that work in industry to speak about their experience and to explain the importance of their background in mathematics.

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The topics covered by LCM have a prominent place in the educational programmes at DMUC, especially at the Master level. The applied Master programs of DMUC are divided into several areas: Applied Analysis and Computational Mathematics, Computation, Statistics, Optimization and Financial Mathematics. In these Master specialities, which are problem-solving oriented, the students are in contact with real problems. Some companies, like Reuters, Critical Software and Mercer, support these Masters. Students have the possibility to develop their MSc thesis in these companies, being, in this case, supervised by a member of the mathematical faculty and a member of the company staff. Quantitative Methods and Financial Mathematics is another applied Master program of DMUC. This program, shared by DMUC and the Faculty of Economics of the University of Coimbra, receives students in mathematics and economics and involves companies like Bloomberg, Goldman Sachs and the Portuguese banks Millennium BCP and Montepio Geral.

One of the goals of the LCM is to incorporate students of all levels (undergraduate, master and PhD) in its projects. Since its foundation, LCM gives visibility to the work developed in CMUC in applied areas and, as consequence, the number of MSc and PhD thesis made under LCM projects has increased. As an illustration we give some examples. In the thesis "Optimization of a transport network", the work was done in the framework of an European Project named Civitas, a partnership between Critical Software and the local public transport firm, SMTUC. The major goal was to develop a platform to help the users of public transportation in Coimbra to obtain the best path to travel between two points. In the thesis "Variance analysis in the treatment of clinical data", a software to treat the clinical data of the Portuguese Society of Cardiology using both parametric and non-parametric variance analysis was developed. Other dissertations had been done is medical imaging. Two former students developed computational algorithms for the segmentation and registration of medical images and studied their mathematical properties, aiming at applications proposed by the Institute of Biomedical Research in Light and Image (IBILI), a research institution of the Faculty of Medicine of the University of Coimbra.

There are also several students that developed their PhD thesis or have on-going work in the scope of LCM projects. As an example we mention the thesis "Memory in diffusion phenomena", developed within the project "Non-fickian diffusion in polymers and medical applications" which studies mathematical models to simulate diffusion phenomena in materials with memory like polymers. Another PhD student is working on a thesis entitled "Controlled drug release". His goal is to develop a mathematical model and a software package to simulate the drug delivery from contact lens loaded with drug and containing particles, also loaded with drug, dispersed in the polymeric matrix. Both thesis have interdisciplinary character. Chemical engineers from the Chemical Engineer Department and a medical doctor from the Faculty of Medicine are also involved.

Since "applications have been the driving force in the science and mathematics" (Friedman & Littman, 1994), LCM strongly supports the idea that applications are extremely useful to motivate the teaching in mathematics. But, apart from the great effort to introduce real-world applications, we believe, agreeing with OECD report (OECD, 2008), that "curriculum should not become a light version of the accepted curriculum for future researchers". The students that want to study industrial mathematics should "be familiar with the standard canon of the discipline".

In spite of the work that has been done, there is an urgent need for more training in the area of industrial mathematics. It is essential to attract bright students to this area and to convey the challenge and the excitement of solving practical problems.

Conclusions and strategy for the future

LCM is a recent structure and for this reason is not yet possible to make a wide quantitative study about the achievements of this project. Nevertheless, the success stories indicate that there has been an increasing interest in strengthening the relation between academia and industry and we feel that mathematics can provide a competitive edge for Portuguese industrial organizations.

Based on our own findings and on the experience of other similar laboratories, we are lead in two directions: building better relations with non-academic organizations promoting the role of mathematics; developing strategies that might be useful to encourage shifts in the curricula in with the objective of promoting closer ties with industry.

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