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What is Industrial Mathematics?
Case Studies from MI-NET

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April 2019

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EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

MI-NET

Table of contents

Introduction

Case Studies from European Study Groups with Industry

Case Studies from Short Term Scientific Missions

Introduction

The **Mathematics for Industry Network** (MI-NET, COST Action TD1409, https://mi-network.org/) was set up in 2015 to 'facilitate the more effective widespread application of mathematics in all industrial sectors'. Here the word 'industry' is used to mean 'any activity of social or economic value' and thus includes government and non-profit-making organizations. This ambitious goal was achieved by running European Study Groups with Industry (ESGIs), Industrial Workshops, Modelling Weeks and Short Term Scientific Missions (STSMs). A particular aim was to increase awareness of industrial mathematics both within the academic community and industry.

The following collection of Case Studies has been put together in order to illustrate how interesting mathematics can be used effectively in a wide variety of fields. The Case Studies have been chosen from problems brought to ESGIs supported by MI-NET or carried out during an STSM funded by MI-NET. The 21 Case Studies span a diverse range of industrial sectors and utilize a wide variety of mathematical methodologies. The ESGI Case Studies come from nine countries across Europe and involve five small–medium enterprises (SMEs), four Large Enterprises (LEs) and one governmental unit. The 10 STSM Case Studies capture cutting-edge research collaborations between 11 countries. We have also included a Case Study on the modelling of coffee making from a one-day Industrial Workshop.

The intention is to address both industrialists and academics who are interested in industrial mathematics but have yet to get involved. Below we describe how both these communities can benefit from working together and then list some of the mechanisms that have been devised to facilitate such activities.

Background

Over the last 50 years the idea that mathematicians can work usefully on real problems has steadily gained ground. Many mathematicians find it stimulating to see their ideas put into practice and practitioners, be they academics from other disciplines or industrialists, often find that a mathematician can bring a fresh approach to problems.

In 2008 the Organisation for Economic Co-operation and Development commissioned a Report on Mathematics in Industry, which listed a number of recommendations. It was followed in 2009 by a further Report on Mechanisms for Promoting Mathematics-in-Industry, which described the state of the activity at that time from the academic point of view. We note that one of the recommendations of the first report was to create a 'network of experts'; MI-NET is an example of how effective such a network can be.

A further report, Forward Look: Mathematics in Industry, was sponsored by the European Science Foundation as one of its strategy documents for the European research community. This led directly to the publication in 2011 of European Success Stories in Industrial Mathematics, which describes 130 Case Studies where mathematical ideas led to useful practical results. In recent years, there have also been several publications with a national perspective (e.g., Currents in Industrial Mathematics, Springer 2015).

Europe has been a world leader in the field of industrial mathematics and several mechanisms have been devised to facilitate the transfer and exploitation of mathematical knowledge from academia to industry. These are briefly described in the Mechanisms section below.

To industrialists: How can mathematics help?

Almost any process can be modelled and a group of mathematicians brings a large toolbox of useful mathematical techniques. A model is almost inevitably an approximation to the real problem and the mathematician and the practitioner need to work closely together to be sure that they have captured the important effects in their model. This stage can often provide significant understanding even before any detailed calculations are made. Once a model is established there are still many ways to proceed; a straightforward prediction may be possible but it may be that there are still unknown parameters to be determined from data or that some form of optimization is required. Examples of all these approaches – model development, data analysis, optimization and others – will be seen applied to a variety of industrial problems in the Case Studies included here.

Once you have accepted that mathematics may help how should you find your mathematician? A number of mechanisms are described in the Mechanisms section below.

To an academic mathematician: Why work on real problems?

Of course, a mathematician can always think of a theoretical problem to study, but there is a particular excitement to using one's skills to solve a challenge that is of real interest to someone else. The question asked by an industrialist usually does not look like those in a mathematics textbook, but it may be even more challenging. There is often more difficulty in publishing the resulting work in a conventional learned journal. Having said that, several very good journal publications have arisen from collaborations with companies and other non-academic organizations that emerged from industrial mathematics activities. The attitude in Departments of Mathematics in universities across Europe is slowly changing as a broader understanding of the value of 'impact' is taken into account when assessing a researcher's

achievements. Furthermore, the use of real-life problems in curricula has transformed the way we train students in applied mathematics; modelling classes and group work on Case Studies stimulate their interest in the subject and increase their subsequent employability.

One effective way to see if this sort of mathematics is of interest to you is to attend a Study Group with Industry – these brainstorming workshops are held regularly worldwide and welcome any researcher prepared to take an active role. More details on ESGIs and other possibilities are described in the Mechanisms section below.

Mechanisms

There are a number of mechanisms that have been devised to help the process of doing industrial mathematics. The first four of the headings below are especially important for initiating collaborations. The labels I and A indicate whether this activity is aimed more at **I**ndustry or at **A**cademia.

1. **European Study Groups with Industry** (I&A)
   These week-long workshops are designed to bridge the gap between industry and academia. Teams of mathematical scientists work on business and societal challenges in close collaboration with industrialists. ESGIs were initiated at the University of Oxford in 1968 and since then they have been successfully organized in more than 25 countries; they are described in detail in the MI-NET Handbook for running a sustainable European Study Group with Industry. For companies and other non-academic organizations (non-profits, government) they are an excellent way to make contact with mathematicians, to learn how mathematics and mathematicians can help, to gain insights and often to make significant progress on their problem in a short period of time. The outlay of time and money is very small when compared to the possible rewards. In addition, the Study Group format allows informal interactions with mathematically proficient students leading to genuine recruitment possibilities. It is also an especially good way for students and academic mathematicians to find out about problems that arise outside academia with real-world implications. In fact, the format has proved so successful that it has now been adopted by other fields (e.g., the Mathematics in Medicine Study Groups in the UK or the Physics with Industry Workshops in the Netherlands). It has also been adapted to different, usually shorter, timescales and to more focussed topics.

2. **Centres for Industrial Mathematics Based in Universities** (I)
   Ideally the whole three-stage process of making contact, continuing the research and following through to deployment should be managed coherently and systematically but this

is only possible for organizations with sufficient resources. There are a number of such centres based in or close to universities so that they can benefit from local academic expertise as well as the possibility of developing links with industry via postdoctoral or student projects. Some of these centres, although the list is far from exhaustive, are:

- The Fraunhofer Institute for Industrial Mathematics, Kaiserslautern, Germany.
- The Fraunhofer–Chalmers Research Centre in Industrial Mathematics, Göteborg, Sweden.
- The Oxford Centre for Industrial and Applied Mathematics (OCIAM), Oxford, UK
- The Mathematics Applications Consortium for Mathematics and Industry (MACSI), Limerick, Ireland.
- The Institute for Mathematical Innovation, Bath, UK.
- The Technological Institute for Industrial Mathematics (ITMATI), Santiago de Compostela, Spain.

3. **European Networks** (I&A)
   There are two European networks that specialize in Industrial Mathematics and provide information about intellectual resources and events:
   - The European Consortium for Mathematics in Industry (ECMI) was founded in 1986 and is a consortium of over 100 academic institutions and companies in more than 25 European countries. It supports ESGIs, industrially focussed research groups and industrial mathematics educational activities. The ECMI website contains detailed information about all the institutional members, ESGIs and Modelling Weeks, a blog and regular job advertisements.
   - EU-MATHS-IN is a 'network of networks' whose aim is to improve the impact of mathematics on innovation in key technologies by enhanced communication and information exchange. The website also advertises jobs for industrial mathematicians in both academia and industry.

   Also, MI-NET in the four years it ran (2015-2019) evolved into an extensive and well-connected network, spanning 32 countries in Europe and beyond. It provided funding for several ESGIs, Modelling Weeks and short research visits that led to the solution of many business and societal challenges, enhancing at the same time the impact and visibility of industrial mathematics.

4. **National Networks** (I&A)
   Because the number of academic mathematicians interested in working directly with industry remains small (estimated at 10% of the applied mathematics community), in many countries it has proved essential to organize industrial mathematics on a national scale. National

networks based on an annual ESGI exist in several countries. For example, in the UK, the Netherlands, Denmark and Portugal there is an annual Study Group, which moves from one university to another each year. The local group is usually responsible for finding the problems for the workshop but interested mathematicians come from all over Europe (and beyond) to participate. As a highlight, the Spanish Network for Mathematics & Industry (math-in) is a well-developed national network, which offers a range of services to industry and the possibility of fruitful collaboration to academic researchers. It is a not-for-profit company whose headquarters are based in Santiago de Compostela. Over 40 research groups from all over Spain are members of math-in. Industrial companies who approach the network are provided with a contact with appropriate expertise. The network runs regular ESGIs, sets up and monitors collaborations and provides training courses to industrial scientists.

5. **Conferences and Workshops on Industrial Problems** (I&A)
   Many applied mathematics departments run regular workshops where companies can come to discuss their needs with a group of academics. These can vary from one-day workshops to ESGIs to short conferences and may involve one company or a number of different ones. A biannual conference on industrial mathematics is organized by ECMI, attracting more than 300 delegates from academia and industry.

6. **Student Programmes and Modelling Camps** (A)
   Students are one of the most valuable resources of universities and, by encouraging them to interact with external companies and other organizations, it has been possible to make the academic courses more relevant and to train the students in transferable skills that equip them for their future careers. Some mechanisms for training and engaging students are:
   - Modelling Weeks. These were pioneered by ECMI, which runs one or more each year. In several countries a Modelling Week is run as a preparation of the students for participating in a Study Group. MI-NET has funded several successful Modelling Weeks for PhD students. A booklet on how to run a Modelling Week has recently been prepared by MI-NET members.
   - Industrial projects, which can be at undergraduate, masters, doctoral or postdoctoral level and may be sponsored by a company. Various national funding agencies encourage such collaborations by support or partial support for the project. We highlight the Innovation Voucher Scheme through which SMEs can purchase services from universities and research institutes with a view to introducing innovations (new products, processes or services) in their business operations – see, for example, information on this scheme, as run in Ireland.

- Masters and Doctoral programmes, which include modelling and computational training and industrial projects, are now quite common. The European Commission has some doctoral schemes that support students to work with companies and across national boundaries, for example, the Innovative Training Networks (ITNs, Marie Skłodowska-Curie Actions).

7. **Internships and Industry/Academia Exchanges** (I&A)
   Internships where students work in a company on a short-term project have proved successful both in developing relationships and for recruitment. There are also a number of schemes where academics can spend time in a company or an industrial scientist can become an academic visitor – see, for example, the Royal Society Industry Fellowships in the UK.

8. **Consultancy** (I)
   This traditional method of connecting academia and industry has not proved so useful for mathematics as for more applied sciences. Nevertheless, it is possible that a relationship initiated through one of the mechanisms above may develop into a consultancy.

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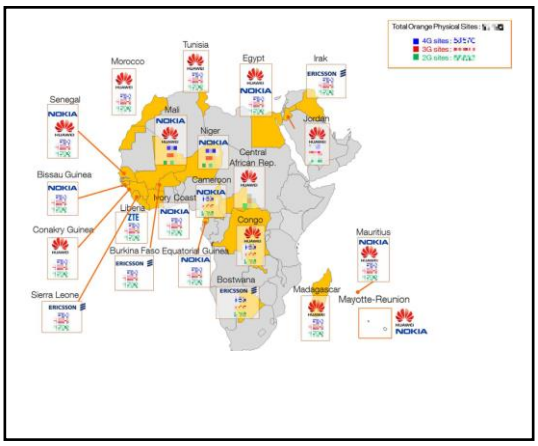
Case Studies from European Study Groups with Industry

European Study Groups with Industry (ESGIs) are week-long workshops where teams of mathematical scientists work on business and societal challenges in collaboration with industrialists.

Mobile networks migration optimization

Company: Orange Labs, France (LE)
Sector: Information and Communication Technology, Telecommunications
ESGI117, Université d'Avignon, France, 23–27 May 2016



Challenge

The Orange Group is a worldwide telecommunications operator. The design of effective five-year master plans for mobile networks transformation is a key strategic activity. The Study Group challenge was to decide which network technologies to invest in to handle bandwidth upgrade expectations at minimum cost. Investment costs include yearly network deployment, costs of changing the network generation and marketing incentives to users.

Key results and outcomes

The fraction of subscribers adopting a new technology in the presence of subsidies was defined to depend on the coverage of the technology. Two ways of modelling this 'upgrade function' were proposed and implemented using a Mixed Integer Linear Programming (MILP) formulation. Preliminary results were obtained for realistic instances provided by Orange Labs and a robust version of the problem was discussed.

A report was delivered to the company and the work, entitled "An Integrated MILP Approach to Mobile Network Expansion in Presence of Subscriber Migration", was presented at the ECMI 2018 Conference. A follow-up meeting took place at Orange Labs to discuss additional experiments. From this meeting a project for a PhD studentship was financed by Orange Labs, which started in November 2017.

Additional resources:

- www.maths-in-industry.org/miis/view/studygroups/esgi117.html
- ESGI Report: Di Puglia Pugliese, L., Figueiredo, R., Hayel, Y., Jimenez, T., Mantas, I., Santos, M.C. (2016) Mobile Networks Migration Optimization
- Contact: Dr Rosa Figueiredo, Université d'Avignon, rosa.figueiredo@univ-avignon.fr

Time reduction and efficiency increase of the packing process

Company: Savana Calçados SA, Portugal (SME)
Sector: Textiles, Clothing and Footwear, Footwear
ESGI119, Porto, Portugal, 27 June–1 July, 2016

Challenge

Savana specializes in the production of children's footwear. When a new line of footwear is introduced, the appropriate box size is selected manually from a limited choice. A container (a larger cardboard box) houses a given bulk order. Savana wished to improve the packing process by eliminating the manual box selection; reducing the choice of boxes and the empty space in a packaged box; and automating the container design and subsequent packing of the individual boxes.

Key results and outcomes

An algorithm for the box-selection process was developed with the constraint that the number of box types used should be minimized. The number of containers used for a given order to a single customer and the distribution of the boxes among the containers was determined by a heuristic algorithm, which is now used by the company and offers considerable time savings. An efficient programming model was developed to choose the appropriate container size and box placement. The proposed process automatically determines the boxes size and the optimal arrangement of the individual shoe boxes inside containers and reduces the space inside the boxes. Future implementation of this programming model should lead to further time and cost savings.

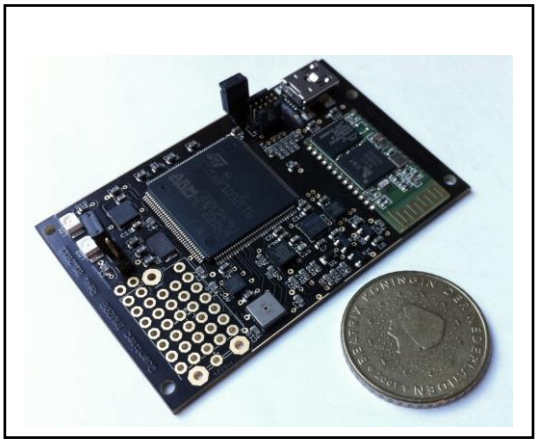
Journal article: Vieira, M.V.C., Ferreira, F., Duque, J., Almeida, R., J. Oper. Res. Soc. (under review).

Additional resources:

- www.spm.pt/PT-MATHS-IN/esgi-portugal
- ESGI Report: Almeida, R., Duque, J., Ferreira, F., Vieira, M.V.C. (2016) Time Reduction of the Packing Process
- Contact: Dr Eliana Oliveira da Costa e Silva, Politécnico do Porto, eos@estg.ipp.pt

Calibration of MEMS sensors

Company: BG Drilling Solutions Ltd., Bulgaria (SME)
Sector: Electronics, Measuring
ESGI120, Sofia, Bulgaria, 25–29 July 2016



Challenge

In directional drilling, MEMS sensors (accelerometers, gyros, magnetometers) could be used to determine the borehole orientation. Those sensors are well-known to suffer from various deterministic and stochastic errors. Thus, they need to go through an initial calibration in order to be further used. The challenge was to develop an algorithm that allows one to calibrate MEMS accelerometer sensors that will be used for measuring toolface and inclination angles of the drilling tool.

Key results and outcomes

An algorithm for calibrating MEMS accelerometers was formulated. It was specifically designed for initial calibration for the purposes of inclination and toolface measurement. From a mathematical point of view, the algorithm solves a parametric identification problem, by modifying a classical approach, known in the literature. Validation tests were carried on experimental data from low cost MEMS sensors. The latter showed a moderate improvement in accuracy. Those were promising results that inspired a further collaboration and further research on the subject. Thus, taking into account the limitations of the existing at the time experimental setup, a very satisfactory accuracy within at most
1°-2° was obtained.

A report was delivered to the company and a journal article was published: Ivanov, T., Lyutskanova-Zhekova, G., Studies in Computational Intelligence, (2019).

Additional resources:

- http://esgi2016.fmi.uni-sofia.bg/
- ESGI Report: Ivanov, T., Lyutskanova, G., Aleksov, D., Kounchev, O. (2016) Laboratory Calibration of MEMS Rate Sensors
- Contact: Dr Tihomir Ivanov, Sofia University, tbivanov@uni-sofia.bg

Aquifer water management

Company: Water Development Department, Cyprus (Governmental Unit)
Sector: Energy and Environment, Water
ESGI125, Limassol, Cyprus, 5–9 December 2016

Challenge

The Germasogeia aquifer supplies water to a large part of Limassol, the 2nd largest town of Cyprus. It is 5.5km long and approximately 0.2 km wide, starting at a dam and ending at the sea. Water flows in from a dam and it is also supplied artificially (recharge) by the Cyprus Water Development Department (WDD), at designated points, through a recharge process. Two challenges were tackled: (i) What is the optimal recharge strategy to save water? (ii) If the aquifer is polluted how fast and where will the pollution spread?

Key results and outcomes

A model for the water flow in the aquifer was developed, using Darcy flow for porous media. The water height and velocity were determined as a function of the dam flow rate and the recharge and extraction rates. The model agrees well with WDD's data and predicts the water height. Subsequently, an optimized recharge strategy was developed for various scenarios (different seasons, varying number of recharge and extraction points). The results indicate that WDD could save water by adopting the proposed optimization strategy. Contaminant concentration was modelled with an advection–diffusion equation and various scenarios were considered. For example, for a continuous contamination source the aquifer would be polluted everywhere in 10 years.

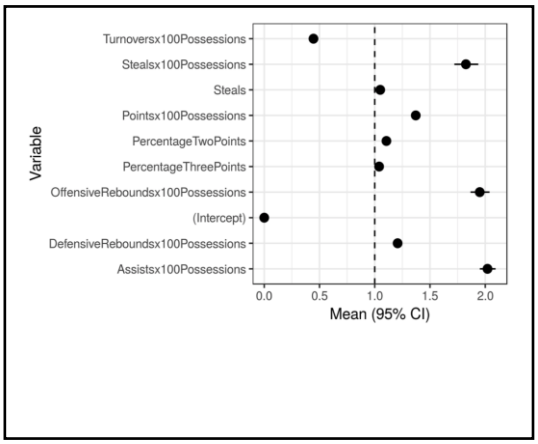
WDD, MI-NET and Oxford funded a follow-up project. A journal article was published: Mondal, R., Benham, G., Mondal, S., Christodoulides, P., Neokleous, N., Kaouri, K., J. Hydrol. (2019).

Additional resources:

- www.esgi-cy.org/esgi125
- ESGI Report: Benham, G., Frolkovič, P., Ivanov, T., Mondal, R., Mondal, S., Rottschäfer, V., Kaouri, K., (2017) Mathematical Modelling of the Germasogeia Aquifer
- Contact: Dr Katerina Kaouri, Cardiff University, KaouriK@cardiff.ac.uk

Big data in sports: predictive models for basketball players

Company: Xpheres Basketball Management, Spain (SME)
Sector: Service Management, Sports
ESGI131, Bilbao, Spain, 15–19 May 2017



Challenge

Xpheres Basketball Management, one of the leading basketball player representation agencies in Spain and Europe, works with a platform called Aryuna© that allows advanced data analytics of men's professional basketball statistics to be performed. The aim of this project was to perform data analytics and provide statistical evidence to characterize the most important factors for predicting a successful professional career in this sport.

Key results and outcomes

The 131st ESGI team provided new insights to the company and provided innovative perspectives to basketball management and sports data analytics. The members of the company that took part in the event described it as a great experience: "We are thankful to the participants of the 131st European Study Group for their work. The ESGI has been a useful place for brainstorming and interaction between researchers and our project. The work developed through mathematical models couldn't be better for us; it provided useful ideas and inspiration for the Aryuna© platform and our databases."

This ESGI challenge presented new opportunities in the sports industry, in particular to shape the skills in data analytics for young researchers that might be interested in seeking a career in the sports analytics industry.

Additional resources:

- https://wp.bcamath.org/esgi131/
- ESGI Report: Lee, D.-J. and Garritt, L. (2017) Big Data in Sports: Predictive Models for Basketball Player's Performance
- Contact: Dr Dae-Jin Lee, Basque Center for Applied Mathematics, dlee@bcamath.org

Salmon size prediction

Company: Off Shore Fish Farming (SalMar), Norway (LE)
Sector: Agriculture and Fishing, Fishing
ESGI137, Ålesund, Norway, 7–12 June 2018

Challenge

In the cage-culture production of Atlantic salmon (*Salmo salar*) the fish are kept in large circular cages ('pens') in the ocean, and fed over the course of 18–24 months, after which they are slaughtered and sold.

It is important to be able to predict from samples taken at various times the distribution of weights for the total number of salmon in the pen. This distribution is rarely normal, and in fact is often seen to develop bi-modality.

Key results and outcomes

Even from the simplified deterministic models for the growth of average weights, one can see that parameter estimation needs to be performed as late as possible in the evolution of the distribution function.

Using data provided by the company, the Study Group team constructed a detailed statistical model to provide a forecast, with uncertainty, from the samples and the times they were taken, the weight distribution of both male and female fish, at harvest time.

The group implemented the model in two web-based applications and the **R** code was given to SalMar.

MI-NET supported this first Danish–Norwegian Study Group with Industry (ESGI137). A report was delivered to SalMar, along with codes for the statistical models.

Additional resources:

- www.ntnu.edu/imf/esgi-137
- ESGI Report: Batarfi, H., Cao, Y., Hjorth, P.G., Hömberg, D, van Albada, S., Tyssedal, J. (2019) Predicting Salmon Weight
- Contact: Assoc. Prof. Poul Hjorth, Technical University of Denmark, pghj@dtu.dk

Equivalent thermo-mechanical model for ceramic cups

Company: ArcelorMittal, Spain (LE)
Sector: Materials, Ceramics
ESGI139, Santiago de Compostela, Spain, 9–13 July 2018

Ceramic cup reconstruction. Source: ArcelorMittal.

Challenge

The ceramic cup of a blast furnace (BF) is a masonry formed by hundreds of refractory bricks glued with mortar. Due to its location inside the BF's wall, it sustains extremely harsh operation conditions, with temperatures reaching 1500°C. To perform simulations that accurately assess its thermo-mechanical behaviour, the brick and joints must be considered as different materials. This leads to unfeasible computational costs for a mesh compatible with the masonry design. The challenge is to get a good result with an incompatible mesh.

Key results and outcomes

A representative unit cell of the masonry was defined to obtain an equivalent mechanical material. On the unit cell, six numerical uniaxial compression and shear tests were simulated, and the properties of an equivalent homogeneous material were computed. These were found to be compatible with a transversely isotropic material. The response of the homogenized material was compared to the real masonry, showing good levels of agreement between both approaches, the former being much less computationally costly. According to the company, "the main outcome is the improvement of the ability to perform numerical simulations at the BF, which is the most critical part of the steelmaking process".

A report was delivered to the company. There is ongoing work with ArcelorMittal to apply this procedure in other areas of the BF.

Grants: Ministry of Economy, Industry and Competitiveness (MTM2015-68275-R, BES-2016-077228) and FEDER and Xunta de Galicia (ED431C 2017/60).

Additional resources:

- www.math-in.net/139esgi/en
- ESGI Report: Barral, P., Fanjul, M., Pérez-Pérez, L.J., Quintela, P., Sánchez, M.T. (2019) Equivalent Thermo-Mechanical Model for Ceramic Cups
- Contact: Prof. Peregrina Quintela Estévez, Universidade de Santiago de Compostela and ITMATI, peregrina.quintela@usc.es, peregrina.quintela@itmati.comperegrina.quintela@usc.es

Evaluating water meters performance

Company: Infraquinta E.M., Portugal (SME)
Sector: Energy and Environment, Water
ESGI140, Barreiro, Portugal, 4–8 June 2018

Challenge

Infraquinta manages the drinking and waste-water services of the tourist community Quinta do Lago, Algarve. They wished to determine the break point of a water meter by using historical data (hourly water consumption), and hence predict when meters should be replaced. The main challenge concerned the segmentation of the hourly water consumption data into different contributions: seasonality, trend (meter performance) and noise.

Key results and outcomes

A combination of two statistical methodologies was shown to detect the water-meter break points. This has the potential to lead to automatic prediction of when to replace the meters. Armed with this knowledge may allow the company to make more informed decisions and enable future cost savings. A report was delivered to the company and the work was disseminated through two events[1,2]. The company is a participant of the research project Water Intelligence System Data, WISDom (DSAIPA/DS/0089/2018) involving four former ESGI140 academic delegates.

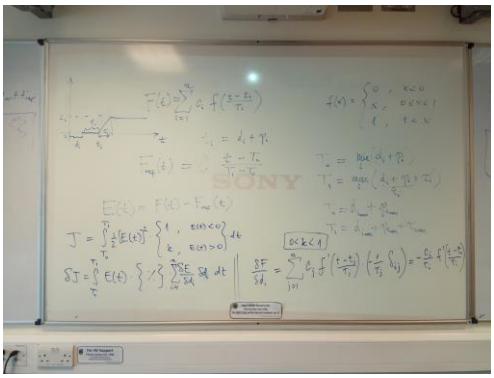
[1] Andrade, M., Teodoro, M.F., Fernandes, S., Carriço, N. (2018), 12th Workshop on Statistics, Mathematics and Computation, Covilhã, Portugal.
[2] Borges, A., Cordeiro, C., Casimiro, R. (2018) 11th Intl. Conf. of the ERCIM WG on Comp. & Methodological Stat, Pisa, Italy. (Poster)

Additional resources:

- www.esgi140.ips.pt/
- ESGI Report: Borges, A., Cordeiro, C., Carlos, C., Sebastião, F., Teodoro, F., Inácio J., Andrade, M., Duarte, R., Aleixo, S., Fernandes, S., Guerra T (2018) Evaluating Water Meters Performance (Confidential)
- Contact: Dr Raquel Barreira, Polytechnic Institute of Setubal, raquel.barreira@estbarreiro.ips.pt

Optimal scheduling of distributed power generation

Company: Captured Carbon (SME)
Sector: Energy and Environment, Electricity
ESGI141, Dublin, Ireland, 25–29 June 2018



Challenge

Captured Carbon supply power to Eirgrid using many small power generators. The supplied power is assumed to increase linearly over a 'ramping time', after which the station generates power at full capacity. Any departure from this linear increase leads to losses or fines. The challenge was to control the delay time for the start of each small power generator so that their combined power output is as close as possible to a linear-increase ramping curve.

Key results and outcomes

Optimization theory was employed, whereby a quantity (objective or cost function) that depends on the system variables (the delay times) is minimized under certain constraints. Both direct methods (gradient descent, mixed integer linear programming) and heuristic methods (bin packing, systematic adjustment, ramp tracking, and a modified simulated-annealing approach) were employed. No two methods gave the same values for the system variables that minimize the cost function, indicating that the cost function has several local minima.

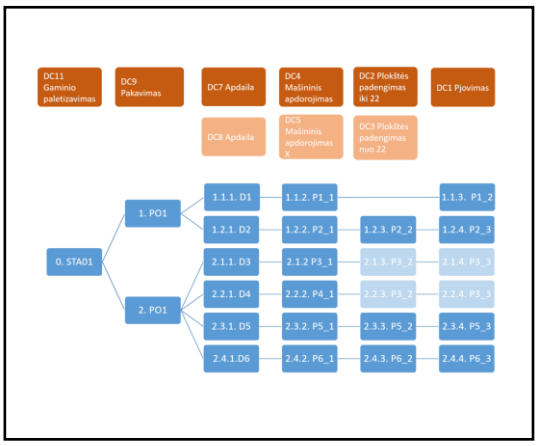
The leaders of the research group presented the results and a report was delivered to the company. A more detailed report is now in preparation that will form a journal article. Future interactions will address the practical implementation of the methods and explore generalizations, e.g., ensuring that not always the same small power generator is started first.

Additional resources:

- https://maths.ucd.ie/esgi141/
- ESGI Report: Devine, M., Fennell, S., Grant-Peters, J., Bustamante, M.D., Beagon, P., Hall, C., O'Keefe, G., Kerci, T., Hill, R. (2018) Optimal Scheduling of Power Generators
- Contact: Assoc. Prof. Miguel Bustamante, University College Dublin, miguel.bustamante@ucd.ie

Optimization of manufacturing processes in the furniture industry

Company: JSC Concern SBA, Lithuania (LE)
Sector: Mechanics and Mechatronics, Furniture
ESGI142, Palanga, Lithuania, 11–15 June 2018



Challenge

JSC Concern SBA produces flat-pack furniture. The necessary manufacturing operations for the individual pieces of furniture are performed in specialized operation centres with a given capacity. The challenge of this Study Group was to offer advice on how to automatically generate an optimal daily work production plan for the centres so that the weekly production quota is met. The result should take into account retail demand and other constraints.

Key results and outcomes

A model for the optimization of the furniture manufacturing process was developed using the flexible-job-shop scheduling problem methodology and solved by a genetic algorithm (GA). The GA contains information about the jobs sequence and identification of the machines where the jobs will be processed. The suitability of the predicted schedule is evaluated by the 'fitness function', which incorporates all aspects of optimality, including task duration and idle times.

The ideas were implemented and deployed for test cases to demonstrate the algorithm's potential. Daily production schedules were generated manually in each of SBA's plant; eventual automation will lead to more efficient production and less idle time.

A report was delivered to SBA and a partnership with the company is ongoing. The company is now a regular participant of Lithuanian ESGIs.

Additional resources:

- https://mathworkshop.ktu.edu/
- ESGI report: Gooran Orimi, A., Hamid Mousavi, S., Kavaliauskas, D., Listopadskis, N., Lukšys, K. (2018) Optimization of Manufacturing Processes in order to Ensure the Fastest Possible Fulfilment of the Production Plan
- Contact: Assoc. Prof. Audrius Kabašinskas, Kaunas University of Technology, audrius.kabasinskas@ktu.lt

A roadmap for coffee modelling

Company: Dark Woods Coffee, UK (SME)
Sector: Food, Beverages
Industrial Workshop, Huddersfield, UK, 1 May 2018

Challenge

Mathematical models of various aspects of the coffee brewing process have been developed, but there is a gap between the predictions made by these models and the information baristas and other practitioners need for these models to inform practice.

Workshop practitioners were asked to develop a roadmap for improving coffee modelling, prioritizing additional factors to be included in models and identifying data needed.

Key results and outcomes

During the workshop the group discussed the factors that influence coffee quality such as soluble content of grains, temperature and composition of the water and grind size distribution. Some experiments were carried out to investigate the role of grind size distribution in determining the taste of coffee.

The group identified unsaturated flow within the coffee grains and coffee bed as a particularly important process that has been neglected by modelling and developed a plan to improve existing models to correctly model the initial infiltration of water into a dry coffee bed. A paper has been submitted with academic and industrial workshop participants as the authors.

This workshop was supported by MI-NET, the University of Huddersfield (UK) and the Mathematics Applications Consortium for Science and Industry (MACSI, Ireland).

Additional resources:

- https://minetworkdotorg.files.wordpress.com/2018/12/minet_report.pdf
- Contact: Prof. William Lee, University of Huddersfield, w.lee@hud.ac.uk
- Note: This case study is related to a one-day industrial workshop supported by MI-NET (and not to an ESGI).

Case Studies from Short Term Scientific Missions

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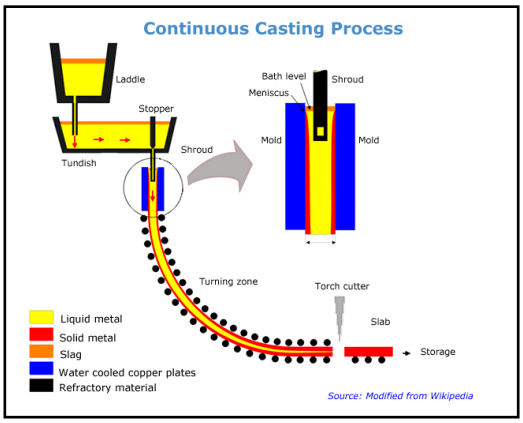
Modelling of oscillation marks in continuous casting

Researcher: Kevin Devine, MACSI, University of Limerick, Ireland
Host: Dr Michael Vynnycky, KTH Royal Institution of Technology, Sweden



Project goals

55% of the world's steel is produced by continuous casting. This process can result in undesired imperfections on the steel surface. This research project aimed at addressing a common problem: oscillation marks, which affect the mechanical properties of the steel, making it liable to cracking.

Outcomes

Asymptotic and numerical analysis of existing mathematical models was undertaken in order to develop a greater understanding of how oscillation marks are formed and how their depth can be controlled.

During the STSM, a more complicated model was analysed and important parameters were identified through non-dimensionalisation. By ignoring smaller and therefore less important parameters three key components were identified, namely the heat-transfer coefficient, thermal contact resistance and the flux–viscosity relationship. Their effect on the process was then explored and results compared against experimental data. This work was presented at the 20th ECMI conference in Budapest, 2018.

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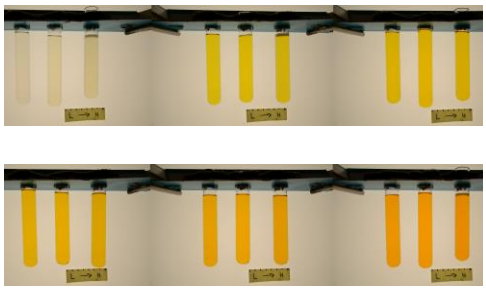
Experimental determination of system parameters

Researcher: Joshua Duley, MACSI, University of Limerick, Ireland
Host: Dr Richard Katz, University of Oxford, UK



Project goals

Parameter values are essential to any model of a physical system. However these values are not always known, which then limits the application of the work.

This STSM concerned an experimental procedure for the determination of key parameter values involved in state-change reactions as well as the rates of reactant diffusion.

Outcomes

We first considered specific chemical solutions that colour according to their concentration. It was shown that it is possible to generate a colour map between the [RGB] triplet of a point in an image and a concentration profile for active systems. The profile may then be matched to known concentration curves. Secondly, we considered two chemicals that react and colour on contact. We demonstrated that, by separating the chemicals with a permeable piece of gelatin, their point of first reaction and the time would be apparent. Using known concentration curves the experimental result could be reproduced and so the reactive concentration deduced. This exploration demonstrated a proof of concept and suggested experimental constructions to be followed up on in the near future.

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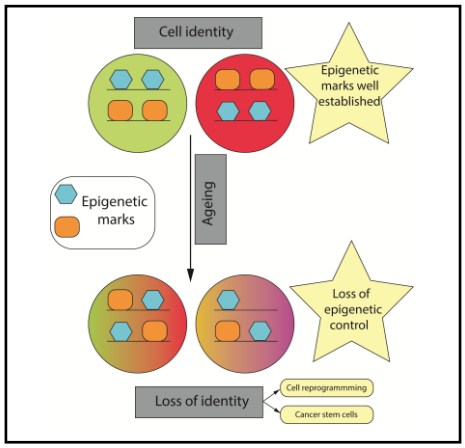
In search of eternal youth: rejuvenating our cells

Researcher: Núria Folguera-Blasco, Centre de Recerca Matemàtica (CRM), Spain
Host: Prof. Helen Byrne, University of Oxford, UK



Project goals

Cell reprogramming allows differentiated cells to become stem cells and may enable the rejuvenation of aged tissues. However, it may also cause the appearance of cancer stem cells. In this project, we aimed to elucidate the mechanisms that control cell identity and how they become disregulated with ageing.

Outcomes

The primary outcome was the formulation of a multiscale stochastic model to study the effects on cell reprogramming of changes in the abundance of epigenetic marks.

Epigenetic marks, in charge of silencing or activating certain parts of the DNA, change their abundance over time. Our multiscale model allows the investigation of all possible scenarios, i.e. from when they are abundant in the media to when they are scarce (there is competition for them). By applying bifurcation and linear-stability analyses, we identified when cell reprogramming is reversible and when it is not (pathological cell reprogramming). We also identified possible ways to rescue cells from pathological reprogramming, which is the aim of drugs that target ageing. A publication highlighting these results will be submitted to an international journal in the near future.

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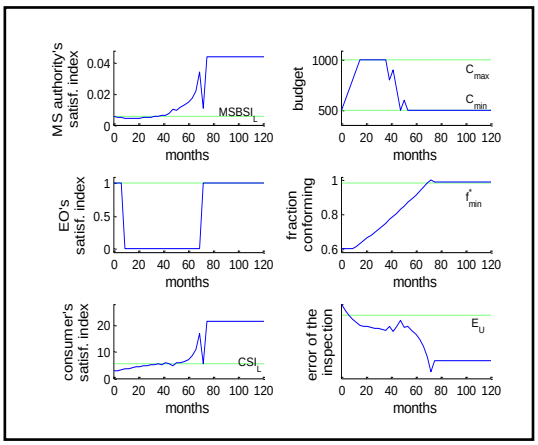
A mathematical model of marketing surveillance system

Researcher: Biljana Jolevska-Tuneska, University Ss. Cyril and Methodius, Skopje, Republic of North Macedonia
Host: Prof. Ana Vukelic, University of Zagreb, Croatia



Outcomes

Market surveillance refers to activities carried out and measures taken by public authorities to ensure that products comply with the requirements set out in the relevant documents. Actions taken by a market surveillance authority have effects on producers, and further on, on the consumers. There is also a feedback that brings behaviouristic concepts into the market surveillance system.

Project goals

The project goal was to develop a mathematical model to create a solid base for the study of market surveillance that will help in decision making and to develop sustainable policies.

The main result of this research was the development of a dynamic market surveillance model and a MATLAB program based on it. The project will continue with future research focussing on bringing the model closer to the reality by including strategies to deal with delays in the decision-making process.

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Calcium signalling in embryogenesis

Researcher: Dr Katerina Kaouri, Cyprus University of Technology, Cyprus
Host: Prof. Philip Maini, University of Oxford, UK

Project goals

Calcium (Ca2+) signalling is a very important mechanism of information propagation in the body. In embryogenesis, the interplay of calcium and mechanics is critical to healthy development but is poorly understood. We aim to develop mechanochemical models to elucidate embryo malformations, such as spina bifida.

Outcomes

We have developed a deterministic mechanochemical model capturing Ca2+ oscillations and tissue mechanics, assuming the tissue is a linear viscoelastic material. We updated earlier models with the experimentally verified mechanism of Calcium-Induced-Calcium-Release, capturing the release of Ca2+ to the cell's cytosol. With no mechanics, the model predicts Ca2+ oscillations for a certain range of IP_3 levels. Adding the coupling to mechanics and employing linear stability and bifurcation analyses and simulation, we found that increasing the strength of coupling the Ca2+ oscillations are eventually suppressed, which is linked to embryo malformations. The collaboration continued after the research visit and a related article was recently published: Kaouri, K., Maini, P.K., Skourides, P., Christodoulou, N, Chapman, S.J., J. Math. Biol. (2019).

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Deep learning for trading strategies

Researcher: Dr. Daniel Kucharczyk, Wroclaw University of Science and Technology, Poland
Host: Prof. Dr. Jörg Osterrieder, ZHAW School of Engineering, Switzerland

Project goals

As a result of technological advancements, financial markets have become increasingly complex, making it harder to model the movements of assets using conventional methods. This project aims to perform research on the application of deep-learning methods to trading strategies.

Outcomes

An extensive literature review of studies investigating possible ways of applying deep-learning techniques to trading strategies has been conducted. As a result, the risk–return profile of the biotechnology index, IBB portfolio, has been replicated using a deep learning neural network (autoencoder). In addition, the long short-term memory (LSTM) and convolutional neuronal network (CNN) have been applied to predict the directional movements of the selected stocks of the S&P 500. The results produced by the CNN model outperformed the competitive LSTM model. Apart from the research activities, several meetings and knowledge-exchange sessions took place, which in turn represent an excellent starting point for further collaboration and research projects.

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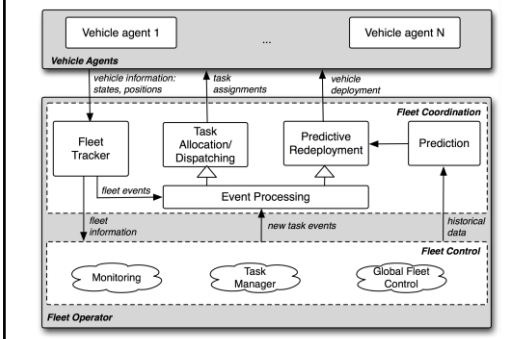
Emergency fleet break assignment problem considering area coverage

Researcher: Assoc. Prof. Marin Lujak, IMT Lille Douai, France
Host: Prof. Holger Billhardt, University Rey Juan Carlos, Spain



Project goals

In emergency fleets, prolonged focussed work periods decrease efficiency with a related decline of attention and results. The scheduling of breaks should take into account area coverage by idle vehicles (related to the arrival time to incidents) and the vehicle crews' requirements for breaks.

Outcomes

We proposed a break assignment problem considering area coverage (BAPCAC) and formulated a mathematical model for this problem. Based on available historical spatio-temporal incident data and service requirements, the BAPCAC model indicates the dimensioning of a fleet's size and appropriate strategies for break scheduling. The model computes the best locations for idle vehicles in each period and arranges vehicles crews' work breaks subject to the break and coverage constraints.

Lujak, M., Garcia Sánchez, A., Ortega Mier, M., and Billhardt, H. Break Assignment Problem Considering Area Coverage in Emergency Fleets. In Press, Proc. of OR 2018, Brussels, Belgium.

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IMT Lille Douai
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IMT-Université de Lille

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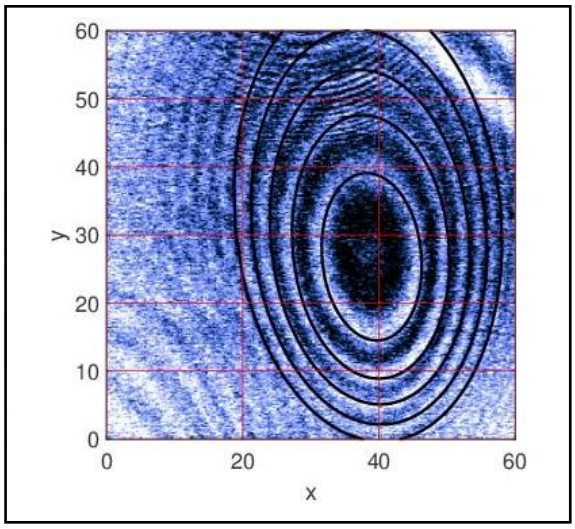
Lensless imaging of nanoparticles

Researcher: Tim Myers & Helena Ribera, Centre de Recerca Matemàtica, Spain
Host: Prof. Wolfgang Bacsa, Centre d'Elaboration de Matériaux et d'Etudes Structurales, France



Project goals

It is well-known that the wavelength of light (400–700nm) is too large to observe nanoparticles. Hence their observation typically requires the use of expensive microscopy, which then requires a vacuum or low-pressure environment. It is therefore desirable to be able to use a less invasive optical method within an ambient atmosphere.

Outcomes

Research scientists at CEMES developed an experimental technique which indicated the presence of nanoparticles through an interference pattern (an example is shown in the figure). The equipment was very simple, involving a laser and an optical fibre in collection mode.

During the STSM a mathematical model was developed to describe the pattern. It was found that by taking only two measurements (the length of the first two major axes) the position of the nanoparticle could be accurately determined. In the figure we show the predicted maxima of the fringes superimposed on the experimental ones. The particle causing this pattern is predicted to be at coordinates (42, -23). The work has been presented in a number of international conferences, a paper was submitted to Phys. Rev. A and a large grant proposal was submitted to improve the technique and equipment.

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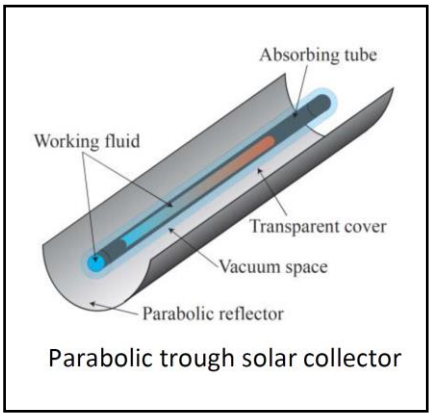
Modelling nanofluid-enhanced direct absorption solar collectors

Researcher: Gary O'Keeffe, University of Limerick, Ireland
Host: Prof. Tim Myers, Centre de Recerca Matemàtica, Spain



Parabolic trough solar collector

Project goals

DASCs absorb solar energy directly into a carrier fluid. However, due to their low absorptive properties the process is inefficient. Recent experimental studies have shown that nanofluid enhanced DASCs have the potential to harness solar energy significantly more efficiently than traditional solar collectors. The goal was to study NEDASCs and improve their design.

Outcomes

During the the STSM a model was developed for the flow of a parallel plate collector containing a flowing nanofluid and subject to solar radiation (a nanofluid is a suspension of nanoparticles in a carrier fluid). This led to predictions for the efficiency of such a device and provided design guidelines (e.g. flow rate, particle volume fraction).

The project continued beyond the STSM. Subsequently the model was extended to analyse different collector designs (such as that shown in the figure), as well as to incorporate laminar or turbulent flow, different nanoparticle types, coatings and mirrors. Recommendations were made for each modification. In total three articles were published following the STSM work: two in the journal Solar Energy and one in Int. J. Heat Mass Trans. O'Keeffe's PhD was successfully defended in 2018.

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Investing with cryptocurrencies

Researcher: Dr. Alla Petukhina, Humboldt University of Berlin, Germany
Host: Prof. Dr. Jörg Osterrieder, ZHAW School of Engineering, Switzerland

Project goals

The emergence of cryptocurrencies and their exponential growth has significantly changed the nature of the financial sector. This project aimed to perform research on the application of machine learning methods to trading strategies for cryptocurrencies.

Outcomes

During the stay, we worked on a research project that focuses on a combination of a number of traditional strategies for asset allocation using techniques of mathematical optimization in order to further diversify risk and enhance portfolio performance while retaining the interpretability of traditional portfolio-optimization models.

In addition to the main project, we had an excellent opportunity to promote a platform for software sharing, “Quantnet”, which supports an approach of transparent and reproducible research. Finally, the undertaken activities provided a solid outline for the subsequent submission of a joint paper to a peer-reviewed academic journal.

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