History of CPSE
Professor Roger W.H. Sargent founded the Centre for Process Systems in 1989 through an EPSRC Research Council Grant. It is part of two universities: Imperial College London and University College London (UCL). Based at Imperial College London, we have 31 faculty members from nine academic departments:

Imperial College London
- Department of Chemical Engineering
- Business School
- Centre for Environmental Policy
- Department of Computing
- Department of Earth Science and Engineering

University College London (UCL)
- Department of Chemical Engineering
- Department of Biochemical Engineering
- UCL Centre for Artificial Intelligence
- Department of Electronic and Electrical Engineering

CPSE Expertise
CPSE is the leading authority in Process Systems Engineering. Our expertise is multi-disciplinary and includes Chemical Engineering, Mathematics, Physics and Chemistry. The research we conduct has relevance to many industries such as Oil and Gas, Petrochemicals, Fine Chemicals, Polymers, Food and Beverage, and Consumer Sectors, to name a few. Our excellence ensures that we successfully attract research grants and are recognized by many awards, including the Royal Academy of Engineering MacRobert Award (the UK’s highest award for innovation and engineering).

CPSE Research Programme
Our research programme is divided into two headings: Competence Areas, which are divided into four areas; and Application Domains, which are divided into six domains.

Competence Areas:
- Process and Product Design
- Operations and Control
- Modelling and Model Solution Tools
- Computational Optimisation and Machine Learning

Application Domains:
- Chemical Manufacturing Systems
- Molecular Systems Engineering
- Biological Systems Engineering
- Supply Chains of the Future
- Energy Systems Engineering
- Environmental Systems Engineering

Influential and Dedicated Academic Staff
CPSE academic staff are internationally recognised as leaders in their area and are dedicated to advancing knowledge in process systems engineering. In addition to publishing influential research, they deliver numerous plenary lectures on research and education, are active
participants in advisory bodies for public organisations (Government, international research centres, funding bodies) and they contribute to the broader public discourse through briefing papers, workshops and outreach events.

**High Calibre Students and Researchers**  
We have highly motivated and intellectual students and researchers and they are encouraged to take advantage of CPSE’s unique interdisciplinary research environment by engaging with company members, academics, fellow students and researchers at Imperial College London and University College London and the many departments that make up CPSE.

**Industrial Consortium**  
We have a unique relationship with industry which has been cultivated over many years through our Industrial Consortium membership. Our company members receive a tailor-made service and privileged access to CPSE academics, research staff and students. Members are further provided with a platform where they can participate with us in European and Research Council projects and provide case studies to on-going research projects which complement their Industrial Consortium participation.

**Workshops and Short Courses**  
We provide engaging short courses and workshops that are delivered with enthusiasm and the versatility required in today’s rapidly changing environment. CPSE’s innovative short courses maximise training by delivering practical tips, hints, tools and techniques for attendees to use immediately.

**CPSE Management Team**  
CPSE Management Team has seven members from Imperial College London and University College London and are headed by the CPSE Director.

**Director**  
- Professor Claire Adjiman, FREng

**Deputy Director**  
- Professor David Bogle, FREng

**Associate Directors**  
- Dr Benoît Chachuat  
- Dr Graham Elkes  
- Professor Paul Rutter  
- Professor Nilay Shah, FREng  
- Professor Wolfram Wiesemann

<table>
<thead>
<tr>
<th>Industrial Consortium Company Members</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Company</td>
<td>Friend</td>
</tr>
<tr>
<td>ABB Corporate Research</td>
<td>Professor Nina Thornhill</td>
</tr>
<tr>
<td>AkzoNobel</td>
<td>Professor George Jackson</td>
</tr>
<tr>
<td>BP</td>
<td>Professor Nilay Shah</td>
</tr>
<tr>
<td>ExxonMobil</td>
<td>Dr Ruth Misener</td>
</tr>
<tr>
<td>Petronas</td>
<td>Professor Amparo Galindo</td>
</tr>
<tr>
<td>PSE</td>
<td>Professor Costas Pantelides</td>
</tr>
<tr>
<td>Procter and Gamble</td>
<td>Professor Erich Müller</td>
</tr>
<tr>
<td>Shell Research &amp; Technology</td>
<td>Professor Geoffrey Maitland</td>
</tr>
<tr>
<td>Syngenta</td>
<td>Professor Claire Adjiman</td>
</tr>
</tbody>
</table>
Over the past two years, the CPSE community has gone from strength to strength, producing outstanding research results and building ever stronger collaborations with its industrial partners. This report gives a flavour of the many ways in which CPSE academics, researchers, students and partners have worked together to harness the complexity of industrial and natural systems.

Highlights

Recollections for CPSE

Founding Father

CPSE’s founding father Professor Roger W.H. Sargent sadly died in 2018. His immense scientific contributions spanning over 50 years continue to be recognised. In 2015, Roger was awarded the Institution of Chemical Engineers’ (IChemE) inaugural MM Sharma Medal which recognises an outstanding, sustained contribution to chemical engineering research. A further accolade was given to Roger when he became the recipient of the Sir Frank Whittle Medal for outstanding and sustained achievement at the Royal Academy of Engineering’s Annual General Meeting in September 2016—exactly 40 years since the inaugural meeting of the Academy of which he was a founding Fellow. Roger’s 90th birthday was also honoured with a special issue of the IChemE journal Chemical Engineering, Research and Design in December 2016.
New Academic Members

Department of Chemical Engineering, Imperial College London:

Professor Christos Markides (Professor of Clean Energy Technologies) specialises in applied thermodynamics, fluid flow and heat/mass transfer processes applied to high-performance devices, and technologies and systems for thermal-energy recovery, utilizing, conversion, or storage.

Dr Salvador García Muñoz is a Senior Engineering Advisor for Eli Lilly and Company and works on the development and commercialisation of new medicines. As Visiting Professor, he teaches an intensive course on Process Analytics using Multivariate Tools.

Dr Paul Oram is Upstream Chief Engineer for Instrumentation, Control and Electrical at BP. As Visiting Professor, he is responsible for developing BP funded research opportunities, supervising undergraduate projects and supporting the teaching of process control and automation.

Department of Chemical Engineering, University College London (UCL)

The research activities of Dr Luca Mazzei (Associate Professor) lie in the field of polydisperse multiphase systems, in particular fluid—solid systems. The research interests of Dr Matteo Salvalaglio (Lecturer) include crystallization, nucleation, protein—ligand binding, protein chromatography, molecular-dynamics simulations, and enhanced sampling techniques.

Department of Electronic and Electrical Engineering, University College London (UCL)

The research activities of Dr Mahdi Sharifzadeh (Honorary Lecturer) are in the field of integrated design and control in process systems, with recent applications in energy and power systems and membrane processes.

Honorary Academic Staff

Professor Michael Georgiadis (Honorary Senior Research Fellow) is with the Department of Chemical Engineering and head of the process systems engineering laboratory at Aristotle University of Thessaloniki, Greece.

Professor Nina Thornhill (Honorary Senior Research Fellow) is with the Department of Chemical Engineering and the Clean Energy Processes (CEP) laboratory at the University of Thessaloniki, Greece.

Dr Salvador Garcia Muñoz is a Senior Engineering Advisor for Eli Lilly and Company and works on the development and commercialisation of new medicines. As Visiting Professor, he teaches an intensive course on Process Analytics using Multivariate Tools.

Dr Paul Oram is Upstream Chief Engineer for Instrumentation, Control and Electrical at BP. As Visiting Professor, he is responsible for developing BP funded research opportunities, supervising undergraduate projects and supporting the teaching of process control and automation.

Excellence in External Collaboration and Partnerships

Imperial College London awarded CPSE the President’s Medal in Excellence in External Collaboration and Partnerships in 2018. CPSE Director Professor Claire AdJimAn said: “It is an honour to get this award, which recognises the work of our dedicated team across Imperial and University College London, who have been working with companies for nearly 30 years. The award recognises the symbiotic relationship between those partners, driven by the understanding of issues in industry and our research results that feed into industry successes.”

Spin-off Companies

Solar Flow, a company founded by Professor Christos Markides was launched in 2018. Solar Flow commercialises the solar panel design created in the Clean Energy Processes (CEP) lab and integrates two existing solar energy technologies into a single panel. It was awarded an Energy Entrepreneurs Fund grant from the Department of Business, Energy & Industrial Strategy (BEIS) to develop a prototype. Christos’ research, which resulted in the technology, was also awarded an IChemE Global Award for Best Research Project.

The company Flexciton was co-founded by Dr Dionysios (Dennis) Xenos (supervisor Professor Nina Thornhill) in 2016. Flexciton uses AI technology to optimise the planning and scheduling decisions for complex manufacturing plants. It has been selected one of the top 100 most disruptive companies in 2018 and 2019 (Disrupt 100 index).

Octoract, a company co-founded by Nikolaos Kazazakis (supervisor Professor Claire AdJimAn) and Gabriel Lau (supervisor Professor George Jackson) was launched in 2017. Octoract develops massively parallel deterministic global optimization software.

Selected Awards and Recognitions – Academic Staff

The IChemE’s 2017 Frank Morton Medal was awarded to Professor Eva Sorensen for being a key driver for innovation in teaching and learning, inside and outside her own institution. She was noted by the committee to have worked tirelessly over several decades to promulgate best practice in chemical-engineering education. Eva was also awarded SEFI Fellowship Award in 2018. SEFI is the largest network focused on engineering education in Europe.

Professor Nina Thornhill received the Nordic Process Control Award at the 22nd Nordic Process Control Workshop at the Technical University of Denmark. The award was for Nina’s novel contributions in research to developing innovative approaches, tools and methods for process monitoring, fault diagnosis and detection and optimal operation of large-scale production facilities. The awarding body also recognised Nina’s work in coordinating several European Marie Skłodowska-Curie projects, which bring together industrial and academic partners to train early-stage researchers in the field of process automation and control.

Professor Nilay Shah received IChemE’s 2018 Sargent Medal which recognises a major contribution to research in the area of computer-aided product and process engineering. Professor Costas Pantelides was the recipient in 2015.
Dr Ruth Misener was winner of the RAEng Engineers Trust Young Engineer of the Year competition. The awards are presented to early-career researchers whose achievements are recognised as outstanding and having a major impact in their respective fields. Ruth was also the recipient of the EPSRC Early Career Fellowship (2017 – 2022), Sir George Macfarlane Medal (2017) and Georgia Tech Mellichamp Lecture (2018).

Professor Marc Deisenroth was awarded the Google Faculty Research Award for 2016. The one-year award supports the work of world-class, permanent faculty members at leading universities around the world with the aim of advancing cutting-edge research in computer science, engineering and related fields. Marc was also the recipient of the Microsoft PhD Scholarship for his work on “Data-Efficient Reinforcement Learning from Image Pixels.” The scholarship provides four-year funding for PhD students and the unique opportunity of working closely with researchers at Microsoft Research Cambridge.

Professor Amparo Galindo was awarded Imperial’s Lilly/Royal Academy of Engineering Research Chair in Pharmaceutical Molecular Systems.

Professor David Bogle was elected Scientific Vice President of the European Federation of Chemical Engineers (EFCE) for a two-year term of office (1st January 2018 to 31st December 2019). Since 1953 the European Federation of Chemical Engineering has promoted scientific collaboration and supported the work of engineers and scientists in 30 European countries and represents more than 100,000 chemical engineers in Europe. David also became Chair of the National Review of the Concordat for the Career Development of Research Staff. The Concordat was launched in 2008 and is an agreement between funders and employers of research staff to improve the employment and support for researchers and research careers in UK higher education.

The UNIHEAT project, led by former CPSE Director Professor Sandro Macchietto, and his team received the Imperial President’s Medals for Outstanding Research Team. The team has eighteen members of whom there are three CPSE academics: Professor George Jackson, Professor Erich A Müller and Professor Christos Markides.

A team led by Professor Erich Müller won the 9th Industrial Fluid Properties Simulation Challenge beating seven of the best modelling teams in the world. The challenge involved predicting the interfacial tension of water/oil mixtures at high pressures and temperatures, conditions at which there were no published data. Erich’s team employed the SAFT coarse-grained force fields developed within the Molecular Systems Engineering group at CPSE.

Ilaria Gimondi and her supervisor Dr Matteo Salvalaglio were the recipients of the Richard A. Glenn Award for most outstanding contribution ACS, Energy & Fuels Division for their work on the computational study of carbon dioxide polymorphic transition at high pressure and the effects of confinement on the ordering of supercritical CO₂.

Chiara Heide (supervisor Dr Cleo Kontoravdi) founder of startup Brightcure won the White City Innovators’ Programme for a device that could revolutionize the treatment of local microbial infections.

Matthew Darby (supervisor Dr Michail Stamatakis) and Suela Jonuzaj (supervisor Professor Claire Adjiman) were awarded a EPSRC Doctoral Prize Fellowship which supports them for post-doctoral research.

Radu Baltean-Lugojan (supervisors Dr Ruth Misener and Dr Panos Parpas) was awarded the 2017-2018 IBM PhD Fellowship Award. This Fellowship honours exceptional PhD students who have an interest in solving problems that
are important to IBM and fundamental to innovation in many academic disciplines and areas of study.

Erin Johnson (supervisor Professor Nilay Shah) was awarded the 2017 Ashok Kumar Fellowship. This Fellowship is jointly funded by the IChemE and the North-East England Process Industry Cluster (NEPIC). The award provides the opportunity to work for three months at the Parliamentary Office for Science and Technology (POST).

Major Grants

**Pharmaceutical Systems Engineering Lab (PharmaSEL).** This £5m collaboration between Imperial, UCL, and global pharmaceutical company Eli Lilly seeks to transform medicines manufacturing. Over a period of 6 years, PharmaSEL will apply PSE methods to the pharmaceutical industry in order to increase efficiency, decrease wastage and resolve quality-control issues across the manufacturing process. Professor Claire Adjiman (CPSE) and Dr Salvador García-Muñoz (Eli Lilly) are leading this collaboration, which involves academics from both Departments of Chemical Engineering at Imperial College London and UCL.

**PRONTO: PRO cess Ne twork Optimization for efficient and sustainable operation of Europe’s process industries taking machinery condition and process performance into account.** Professor Nina Thornhill is leading this European Training Network (ETN) that contributes to the EU’s Societal Challenges of resource efficiency and long-term sustainability by optimisation of the installed assets of the process industries. PRONTO provides coherent academic-industrial PhD training for a cohort of Marie Skłodowska-Curie Early Stage Researchers (ESRs) to identify, analyse and solve operational challenges in the process industries of Europe.

**Integrated Development of Low-Carbon Energy Systems (IDLES): A Whole-System Paradigm for Creating a National Strategy.** Professor Nilay Shah, Professor Wolfram Wiesemann, Professor Christos Markides and Dr Adam Hawkes are co-investigators on this £7m EPSRC Programme Grant. They are tackling the very challenging modelling required for integrated energy systems by combining multi-physics optimising techno-economic models with machine learning of human behaviour and operational models of emerging multi-vector networks and conversion technologies.

**Software Platform for Multiscale Modelling of Reactive Materials and Processes (ReaxPro).** Dr Michail Stamatakis is the principal investigator on this Horizon 2020 grant for Software Platform for Multiscale Modelling of Reactive Materials and Processes. The project seeks to upscale academic software tools and integrate them with commercial software into an industry-ready solution for catalytic material and process design. The ReaxPro Software platform and associated services will be made available via the European Materials Modelling Marketplace and aims to reach the target technology readiness level of 7.

**Greenhouse Gas Removal (GGR).** The UK launched an £8.6m national research programme on how to remove greenhouse gases from the atmosphere – the World’s first research programme dedicated to this topic. Dr Niall Mac Dowell won a £2m grant from NERC on Greenhouse Gas Removal (GGR). The goal is to explore the real-world potential of “negative emissions” technologies (NETs), including soil carbon management, afforestation, bioenergy with carbon capture and storage (BECCS), enhanced weathering and direct capture of methane from the air. The GGR research programme is designed to investigate their potential, as well as the political, social and environmental issues surrounding their deployment.

Short Courses

The Introduction to Optimisation and the Advanced Optimisation courses were created in 2015, to tackle concepts in problem formulation and solution method in optimisation, at basic and advanced levels. These two courses, taught by CPSE Academics and Researchers, have been growing in popularity with enrolments now at the highest level.

Dr Salvador Garcia-Munoz is teaching two courses on Introduction to Process Analytics using Multivariate Methods and Advanced Applications of Process Analytics using Multivariate Methods.

In the introductory course, participants are introduced to modern-day multivariate data analytics methods through lectures and hands-on workshops. The advanced course’s syllabus is geared towards topics such as the analysis of batch data, process and product design, multivariate image and texture analysis and chemometrics.

Summer School

In September 2018, CPSE held a Summer School on the topic of “Optimisation under Uncertainty”. This four-day event featured lectures from internationally leading speakers from North America, Europe and Asia on the topics of stochastic and robust optimisation, bi-level programming, model-predictive control, and multi-parametric programming. The event was attended by 60 doctoral students and professionals from 12 countries.
PSE@ResearchDayUK

On Tuesday 12th July 2016, CPSE hosted the Inaugural PSE@ResearchDayUK at Imperial College London. It was a great success with students participating from many universities. Professor Nilay Shah and Dr Benoit Chachuat launched the PSE@ResearchDayUK to bring together researchers from around the UK to explore the latest technological advances in core and emerging application areas in PSE and to build their personal networks for future collaborations. In 2017, a selection of papers presented during the second edition of PSE@ResearchDayUK were published in the special issue of Chemical Engineering Research and Design (ChERD). The third edition in 2018 was combined with the CPSE Summer School on Optimisation under Uncertainty.

The Professor Roger W. H. Sargent Lectures

CPSE has been organizing this annual lectureship since 1994 in celebration of CPSE’s Founding Director Professor Roger W. H. Sargent. These lectures are a tribute to Roger’s legacy in the field of Process Systems and aim at exploring the views from academics from around the world. Since the Lectures begun, we have had twenty-five distinguished speakers including:


2017 – Professor Frank Allgöwer, Universität Stuttgart. “Industry 4.0: Challenges and Opportunities for Model Predictive Control.”

2016 – Professor Jay H. Lee, Korea Advanced Institute of Science and Technology (KAIST). “Mathematical Programming and Dynamic Programming: How they have been used in control and can be combined for further use in planning, scheduling and control of multi-scale stochastic systems.”

CPSE Seminar Series

CPSE has been running a successful Seminar Series for many years. We invite distinguished national and international experts to the Centre each year. The seminars are free to attend and open to all.

2018 Seminar Series
Professor Jordi Bascompte
University of Zurich

2017 Seminar Series
Professor Ignacio E. Grossmann,
Carnegie Mellon University

2016 Seminar Series
Dr Thomas Vetter
University of Manchester

Dr Claudia D’Ambrosio
LIX École Polytechnique

Professor Sargent and his Academic Sons

L to R: Professor Claire Adjiman, Professor Anton Kiss, Dr Benoit Chachuat, Dr Gonzalo Guillén-Gosálbez and Dr Oleksiy Klymenko, during the 2018 PSE@ResearchDayUK

PSE@ResearchDayUK

On Tuesday 12th July 2016, CPSE hosted the Inaugural PSE@ResearchDayUK at Imperial College London. It was a great success with students participating from many universities. Professor Nilay Shah and Dr Benoit Chachuat launched the PSE@ResearchDayUK to bring together researchers from around the UK to explore the latest technological advances in core and emerging application areas in PSE and to build their personal networks for future collaborations. In 2017, a selection of papers presented during the second edition of PSE@ResearchDayUK were published in the special issue of Chemical Engineering Research and Design (ChERD). The third edition in 2018 was combined with the CPSE Summer School on Optimisation under Uncertainty.

The Professor Roger W. H. Sargent Lectures

CPSE has been organizing this annual lectureship since 1994 in celebration of CPSE’s Founding Director Professor Roger W. H. Sargent. These lectures are a tribute to Roger’s legacy in the field of Process Systems and aim at exploring the views from academics from around the world. Since the Lectures begun, we have had twenty-five distinguished speakers including:


2017 – Professor Frank Allgöwer, Universität Stuttgart. “Industry 4.0: Challenges and Opportunities for Model Predictive Control.”

2016 – Professor Jay H. Lee, Korea Advanced Institute of Science and Technology (KAIST). “Mathematical Programming and Dynamic Programming: How they have been used in control and can be combined for further use in planning, scheduling and control of multi-scale stochastic systems.”

CPSE Seminar Series

CPSE has been running a successful Seminar Series for many years. We invite distinguished national and international experts to the Centre each year. The seminars are free to attend and open to all.

2018 Seminar Series
Professor Jordi Bascompte
University of Zurich

2017 Seminar Series
Professor Ignacio E. Grossmann,
Carnegie Mellon University

2016 Seminar Series
Dr Thomas Vetter
University of Manchester

Dr Claudia D’Ambrosio
LIX École Polytechnique

Professor Sargent and his Academic Sons

L to R: Professor Claire Adjiman, Professor Anton Kiss, Dr Benoit Chachuat, Dr Gonzalo Guillén-Gosálbez and Dr Oleksiy Klymenko, during the 2018 PSE@ResearchDayUK

The Professor Roger W. H. Sargent Lectures

CPSE has been organizing this annual lectureship since 1994 in celebration of CPSE’s Founding Director Professor Roger W. H. Sargent. These lectures are a tribute to Roger’s legacy in the field of Process Systems and aim at exploring the views from academics from around the world. Since the Lectures begun, we have had twenty-five distinguished speakers including:


2017 – Professor Frank Allgöwer, Universität Stuttgart. “Industry 4.0: Challenges and Opportunities for Model Predictive Control.”

2016 – Professor Jay H. Lee, Korea Advanced Institute of Science and Technology (KAIST). “Mathematical Programming and Dynamic Programming: How they have been used in control and can be combined for further use in planning, scheduling and control of multi-scale stochastic systems.”

CPSE Seminar Series

CPSE has been running a successful Seminar Series for many years. We invite distinguished national and international experts to the Centre each year. The seminars are free to attend and open to all.

2018 Seminar Series
Professor Jordi Bascompte
University of Zurich

2017 Seminar Series
Professor Ignacio E. Grossmann,
Carnegie Mellon University

2016 Seminar Series
Dr Thomas Vetter
University of Manchester

Dr Claudia D’Ambrosio
LIX École Polytechnique

Professor Sargent and his Academic Sons

L to R: Professor Claire Adjiman, Professor Anton Kiss, Dr Benoit Chachuat, Dr Gonzalo Guillén-Gosálbez and Dr Oleksiy Klymenko, during the 2018 PSE@ResearchDayUK

The Professor Roger W. H. Sargent Lectures

CPSE has been organizing this annual lectureship since 1994 in celebration of CPSE’s Founding Director Professor Roger W. H. Sargent. These lectures are a tribute to Roger’s legacy in the field of Process Systems and aim at exploring the views from academics from around the world. Since the Lectures begun, we have had twenty-five distinguished speakers including:


2017 – Professor Frank Allgöwer, Universität Stuttgart. “Industry 4.0: Challenges and Opportunities for Model Predictive Control.”

2016 – Professor Jay H. Lee, Korea Advanced Institute of Science and Technology (KAIST). “Mathematical Programming and Dynamic Programming: How they have been used in control and can be combined for further use in planning, scheduling and control of multi-scale stochastic systems.”

CPSE Seminar Series

CPSE has been running a successful Seminar Series for many years. We invite distinguished national and international experts to the Centre each year. The seminars are free to attend and open to all.

2018 Seminar Series
Professor Jordi Bascompte
University of Zurich

2017 Seminar Series
Professor Ignacio E. Grossmann,
Carnegie Mellon University

2016 Seminar Series
Dr Thomas Vetter
University of Manchester

Dr Claudia D’Ambrosio
LIX École Polytechnique

Dr Pietro Belotti, FICO

Dr Carl Laird, Purdue University

Dr André Bardow, RWTH Aachen

Dr Mariano Martín
Universidad de Salamanca
Future Research Directions
– Concept Notes

Evolution of Concept Notes
It is essential for CPSE to continue to adjust and evolve to changes in technology and commercial needs. An internal CPSE review was held in 2016 of possible new research directions and this was shared with Industry Consortium members.

In 2017, Concept Notes were developed for ten areas again with input from Industrial member companies. The Notes cover the technical challenge in the area, what methodology will be used, potential outcomes and academic team members with a particular interest.

The ten areas identified were:

Core theme – modelling
• Accounting for and characterizing structural uncertainty
• Multiscale modelling – what is next?

Core theme – optimisation
• Integrating OR and PSE – what can we do?
• Machine learning and PSE – what are the opportunities?
• Global optimization – what next?

Core theme – design and operations
• PSE and Industry 4.0 – opportunities

Application areas
• Resource system engineering
• Structural products systems engineering
• Data systems engineering
• Pharma/healthcare systems engineering

Present Status and Way Forward
The areas identified are mainly evolutionary to the existing CPSE programme and so no major change in the overall programme direction is required. The work has, however, identified a range of future research possibilities for potential follow up either with individual or multiple companies.
Competence Area
Process and Product Design

Contributed by Suela Jonuzaj

Transforming trial-and-error practice into systematic methods and tools

The design of new materials and better processes are central to the well-being of modern societies but, at the same time, the negative impacts of most man-made chemicals and their manufacturing processes on the environment have increased dramatically over the last few years. The research directions of the CPSE community aim to address the constraints and objectives imposed by today’s market and to promote sustainable development in the area of Process and Product Design. In particular, researchers at CPSE focus on developing fundamental modelling and optimisation tools to design better materials, processes and products, taking into account economic, environmental, health and safety aspects. Our models are applied to specific problems of relevance to today’s industries, such as the selection of optimal processing materials (e.g., solvents); the design and manufacturing of high-performance products (e.g., polymers, drugs); the design of devices (e.g., fuel cells); the separation and purification of materials (e.g., purification of APIs); and carbon-capture technologies. The success of our methods relies on the use of (i) integrated designs that include decisions from different scales (from molecular to process scale), capturing the multi-faceted nature of such systems and (ii) state-of-the-art optimisation algorithms capable of solving large and difficult problems, yielding optimal solutions in a practically feasible computational time.

Integrating computer-aided methods into process and product design

In current practice, the molecules or materials required for processing and product formulations are often chosen first, before other design decisions are made. This is usually done from a limited set of choices because evaluating many options, computationally or experimentally, is costly and time-consuming. Once this choice is made, the product attributes, process topology and operating conditions are selected. Questions such as how many components in a chemical product and in what proportions, or what is the best solvent for a pharmaceutical manufacturing process cannot be answered in a sequential decision-making approach. These answers depend on physical/chemical properties, as well as on process properties such as temperature and pressure. By extending the boundary of computer-aided process/product design to include molecular or material-level decisions, real benefits can accrue: these include better process economics and lower environmental impact through increased material and energy efficiency. Further, by using optimisation to pose and solve extended design problems, the evaluation of every design is avoided, making it possible to consider large design spaces: countless molecules and mixtures, wide temperature/pressure ranges, and unusual process topologies. Several studies conducted within CPSE involve the development of systematic computer-aided methods and advanced optimisation algorithms for process and product design, which have the potential to enhance innovation and competitiveness.

Integrated molecular and mixture design: The design of chemicals and mixtures is an essential activity across a wide range of chemical-engineering applications, from separation processes to product design. In the process industry, for instance, suitable solvent mixtures are used in separation and purification processes, such as extraction and crystallization, to achieve better process efficiency and improved environmental and cost metrics. Mixtures are also critically important in the high-value manufacturing of chemical products, such as personal-care products, pharmaceuticals and agrochemicals. Jonuzaj et al.3 have developed a general systematic approach to molecular and mixture design, which integrates for the first time a logic-based methodology, Generalized Disjunctive Programming (GDP), within the computer-aided mixture/blend design (CAMbD) framework. In their model, the main design decisions of the mixture problem (how many compounds; which specific chemicals should be used; and in what proportions) are optimised simultaneously, rather than through “rules of thumb”. Solving the resulting problems can be challenging due to the complexity that arises from the nonlinear and nonconvex phase equilibrium and phase stability functions included in mixture problems, as well as dealing with a large combinatorial solution space. To address the difficulties arising from the complexity of the models and facilitate the problem solutions, Jonuzaj and Adjiman3 employed different relaxation techniques, including the big-M approach and Hull reformulations, to convert the disjunctive constraints into mixed-integer form. These solution strategies have been applied successfully to the design of optimal solvent mixtures for separation processes (crystallization and liquid-liquid extraction – Fig. 1).

![Figure 1: Solvent mixture design for separating acetic acid from water via liquid-liquid extraction.](image)
which eliminate infeasible regions of the molecular and process domain (see Fig. 2). Overall, the proposed framework prevents evaluations of infeasible primal problems, and enhances convergence to (locally) optimal solutions of challenging integrated material and process design and synthesis problems. The algorithm has been successfully applied to the separation of CO₂ from methane (Fig. 3) and of butanol from water⁴,⁵.

Expanding the boundaries of process modelling: In the process and chemical industry the most critical decisions are taken at early stages of process development and thus, advanced modelling and design are essential in improving the sustainability performance of the processes. Dr. Guillen's group highlights the importance of multi-criteria decision-making in process-design problems and develops models that integrate simulation and optimization techniques to solve complex superstructure flowsheets⁶–⁸.

Moreover, they employ multi-objective optimization techniques to formulate competing objectives, such as performance, economic and environmental metrics⁹–¹⁰ (e.g., improve process efficiency while reducing cost and environmental impact).

In working towards more-sustainable manufacturing processes and products in the chemical industry, Limleamthong et al.⁶ have developed a systematic methodology based on Data Envelopment Analysis (DEA) for the multi-criteria screening of chemicals taking into account thermodynamic, techno-economic and environmental metrics. The proposed approach was applied to the screening of 125 amine-based solvents and identified the most-efficient molecules for CO₂ capture. In later work, Calvo-Serrano et al.⁷ have investigated systematic methods that combine Life Cycle Assessment (LCA) and optimization to decrease the environmental impact of different chemicals in all stages of their life cycle. In particular, they have developed a multi-linear model that can be easily integrated into molecular-design software and/or readily incorporated into environmental databases, thereby facilitating the widespread application of sustainability principles at early stages of the design of new chemical products and processes.

The modelling of large-scale complex systems was addressed by Ibrahim et al.⁸, who proposed a coupled simulation-optimization approach for the design of a crude-oil distillation unit. The optimization of such systems is challenging due to the complex nature of the distillation units, their interactions with the associated heat-recovery network and the large number of degrees of freedom. Their methodology integrates rigorous tray-by-tray column simulation with an optimization algorithm, avoiding the use of restricted shortcut models that often cannot accurately predict the behavior of complex crude-oil distillation units. The proposed approach exploits the available physical property and thermodynamic models, as well as the crude-oil characterization and column hydraulic models, which can ultimately lead to more-accurate results.

**Molecular and process design for heat transfer fluids**

Increasing concerns over climate change and high energy prices have stimulated research on the utilization of heat sources of low thermal content for power generation. Organic Rankine Cycle (ORC) systems (see Fig. 4), which operate based on the vaporization of a working fluid to drive a turbine, constitute promising technologies to exploit available low-thermal resources and convert low-grade heat into useful power. However, the utilization of low-grade heat conversion technologies, such as ORC, to replace the conventional
fossil-fuel power plants may not always be economically viable due to their low thermal efficiency and high investment/capital cost. Therefore, it is essential to maximise the power output while reducing the cost of the system in order to improve the overall process performance/cost and aim towards a more sustainable energy future. Two important factors that affect the thermodynamic and economic cycle performance for a given heat source are the type of the working fluid(s) and the ORC system features. Prof. Markides’ group has conducted a number of studies\textsuperscript{11-14} for the development of improved ORC systems, from both technical and economic perspectives, where they have addressed several challenges in order to exploit the full potential of this technology.

In particular, Oyewunmi et al.\textsuperscript{11} have investigated the selection of optimal organic working-fluid mixtures for large ORC systems (applications with power outputs up to 30 MW). They employed SAFT-VR Mie, a molecular-based equation of state, to predict the thermodynamic properties of pure and mixed fluids, which was able to predict accurately the calorific properties of alkanes and perfluoroalkanes, including those for which experimental data are scarce. The property data obtained were then used in thermodynamic-cycle analyses in order to evaluate the performance and cost of a non-regenerative ORC system that recovers and converts waste heat from a refinery flue-gas stream. While this study considered large temperature-glide organic-fluid mixtures, it focused only on power output to select the optimal mixtures. In later work\textsuperscript{12}, the authors investigated the performance of working-fluid mixtures in ORC systems operating in combined heat-and-power (CHP) mode, capable of recovering and utilizing waste-heat from industrial processes. Within their proposed approach, optimal working fluids in ORC systems with optimal CHP heat-to-electricity ratio and heat-supply temperature settings were selected to match the seasonal variation in heat demand of different end-users.

White et al.\textsuperscript{13} developed an integrated framework that combines computer-aided molecular design of the working fluids with ORC system optimisation (CAMD-ORC). Their proposed CAMD-ORC approach used SAFT-$\gamma$ Mie, a group-contribution equation of state in which the working fluids are described by functional groups, to predict pure and mixture properties (Fig. 5) and it was applied to three industrial waste-heat recovery (WHR) applications. The simultaneous design avoids the use of common subjective screening criteria and paves the way towards the next generation of tailored working fluids and optimised systems for WHR applications. This work was further extended by coupling the CAMD-ORC framework with thermoeconomic system assessment.\textsuperscript{14}

Molecular and process design for carbon capture and storage (CCS)

Carbon capture and storage (CCS) is called upon to play a key role in meeting climate-change targets, delivering low-carbon heat and power, decarbonising industry and removing CO\textsubscript{2} from the atmosphere. A current research area within CPSE entails the development and analysis of CCS systems. Another research area involves the identification of suitable CO\textsubscript{2} capture solvents that lead to improved process performance and lower cost. The adoption of some well-established industrial technologies for CO\textsubscript{2} capture, such as chemical absorption processes, is proven challenging due to some major downsides that need to be overcome. These include the high energy input required for solvent regeneration and the negative environmental impacts associated with the extensive use of some conventional solvents, such as amine-based organic compounds. Therefore, significant efforts have been made to identify solvents that can enhance the economic and sustainability performance of chemisorption processes. Papadopoulos...
et al.15 developed a computer-aided molecular design methodology for identifying promising solvents that achieve high performance in terms of effective chemical absorption of CO2 and solvent regeneration. Their comprehensive approach considered the thermodynamic behaviour, reactivity and sustainability as performance criteria to select or design optimal solvent compounds. The model was employed to generate a ranked list of solvent molecules (including novel and existing compounds) using a massive design space with hundreds of thousands of possible compounds; this led to the identification of important candidate solvents for CO2 capture.

Mota-Martinez et al.16-17 proposed a systematic methodology to evaluate the suitability of chemical solvents for carbon capture based on economic, energetic and environmental metrics. In particular, they developed a novel solvent-screening tool that links the molecular characteristics of the sorbents to the carbon-capture process performance. It was shown that in addition to equilibrium-based indices, thermophysical (e.g., heat capacity) and transport (e.g., viscosity) properties have a significant impact on the overall performance of the process, and consequently on the capital and operating costs of this technology.

The proposed framework can be beneficial in selecting new solvents for carbon capture, as it identifies the minimum set of thermophysical and kinetic indicators required for choosing promising compounds that minimise the cost and maximise performance of CO2 capture.

The design of bio-based chemical products
The manufacturing of high-value chemicals and formulated products is essential for the sustainable development of the chemical and process industry. The use of biomass to produce valuable chemicals and fuels has emerged as a promising alternative to reduce our dependency on fossil fuels, which are used as the main feedstocks for the petrochemical industry. Several studies led by CPSE have focused on developing systematic methods and tools for the manufacturing of bio-based materials at reduced cost and environmental impact in order to improve product-process sustainability.

In the area of polymer design, Zhang et al.18 investigated the synthesis of biopolymers from biomass. Polymers are one of the most commonly used chemicals in both daily life and industry and thus, chemicals that can be easily extracted or synthesized from biomass are particularly explored for sustainable polymer production. The authors proposed a comprehensive reaction network to screen and narrow down a large number of biopolymer synthesis pathways in order to identify the most-promising sustainable polymers. The synthesis pathways were ranked with respect to different criteria, such as performance, cost and environmental impact, so that a small group of promising pathways can be identified for further research. An integrated superstructure reaction network that consists of a large number of reaction pathways from biomass to both commercialized and new polymers was developed by del Rio-Chanona et al.19.

The proposed approach integrated green chemistry and process profit metrics into a multi-objective optimization framework in order to optimise simultaneously both environmental impact and economic performance. Optimal biopolymer candidates and their best synthesis routes (from economic and environmental impact perspectives) were identified under different scenarios.

A wide variety of chemicals used in many aspects of human life can be produced from biomass via various chemical and biochemical processes. Among several biomass-to-fuel conversion processes, pyrolysis has gained increased attention as a sustainable option for the production of bio-oil and biochemicals, due to its low cost and its flexibility to convert any type of biomass feedstock to useful products (Fig. 7). While promising, the commercialization of the process has proved challenging because of the highly diverse biomass
resources and different pretreatment technologies, which lead to a wide range of intermediate and final product blends. The resulting mixed chemicals need to be characterized, purified and upgraded into viable market products. In working towards addressing these challenges, Jonuzaj et al. developed an optimization-based methodology within the computer-aided design framework for identifying optimal chemicals or chemical blends derived from biomass pyrolysis. Their proposed methodology was applied to the separation of different chemical blends (resulting from different biomass pretreatment methods) in order to obtain high-purity products at low cost.

**References**

17. Mota-Martínez, M.T., Hallett, J.P., Mac Dowell, N. (2017) Solvent selection and design for CO2 capture – How we might have been missing the point. Sustainable Energy Fuels 1, 2078–2090.
Competence Area

Operations and Control

Contributed by Vassilis M. Charitopoulos

**Process Operations** uses mathematical models that capture the underlying science of a process and adopts an optimization approach to give improved operation in terms of product quality, energy usage, environmental impact and sustainability. The research within the Centre covers optimization of the operations of existing plants, optimal designs for new plants that take account of dynamic operation at the design stage, management of supply chains and of batch processing.

**Process control** covers the theory and practice of advanced automation and control applied to a wide variety of processes including reaction, adsorption, granulation and polymerization carried out within a spectrum of manufacturing industries including oil & gas. Competencies feeding into applications include: integration of design; operation and decision making; multi-scale modelling; integrated monitoring of processes; electrical and mechanical equipment; and theoretical advances in parametric control.

A special feature of the programme is the ability to move new theory rapidly towards practical realization and thus to help the process control sector take early advantage of new developments.

Integration of control with process operations and design

Volatile global market environment, increasing competition and the need for reduction in cost and environmental impact are only a few of the reasons that have led the process industries to seek more-responsive and integrated operations. Some of the most important operational functionalities of the process industries comprise production planning, scheduling, real-time optimization and control. To this end, the process systems engineering (PSE) community has focused on the development of methods for their integration so as to exploit the inherent synergies and prevent suboptimal operations due to neglecting their underlying interdependence.

Nonetheless, if enhanced operations is the gift of integration, its price is quite high as it results in large-scale, typically non-convex, optimization problems and extensive computational times that prohibit its application to large-scale systems. Charitopoulos et al.\(^1\),\(^2\) studied the integration of planning, scheduling and control for continuous manufacturing processes and formulated the problem as a mixed integer linear program coupled with multi-parametric controllers within an outer feedback loop. Results from this work highlighted the importance of considering explicitly disturbances on the level of process dynamics as they have immediate impact on operational-level decisions. An economic MPC optimization index of which the intended use is to provide a procedure to compare different designs for a given process, assessing how well they can be controlled and optimized by a zone constrained MPC, was presented by Strutzel and Bogle\(^3\). The proposed index quantifies the economic benefits available and how well the plant performs under MPC control given the plant’s controllability properties, requirements and restrictions.

Advances in multi-parametric model predictive control and fault detection

Model predictive control (MPC) constitutes the most widely advanced control strategy within the process industry due to its ability to handle explicitly a variety of constraints, enhance process performance and account for economic considerations. In spite of its benefits, MPC requires the repetitive online solution of an optimization problem that, in many instances, is not computationally feasible and results in delays as well as reduced responsiveness in the face of dynamic disturbances. Multi-parametric model predictive control (mp-MPC) circumvents the aforementioned issue, by solving offline the related parametric program and thus substitutes the need for online re-optimization with point-set-membership evaluations which are computationally inexpensive.

![Figure 1: Interdependence of the different level of decision making in the process industries.](image)
Within the CPSE a number of researchers have presented new algorithms for the design of mp-MPC. Sun et al.\textsuperscript{8} presented a methodology for the design of robust mp-MPC for continuous-time linear dynamic systems based on the NCO tracking principles. In their approach, the dynamic system is immunized against the worst-case uncertainty realization by switching off the path and terminal state constraints. As illustrated by their earlier work for the deterministic case of linear continuous time dynamic systems, the mp-NCO strategy results in significantly less regions of optimality due to its analytic form. The computational efficiency and effectiveness of the proposed scheme was tested on a fluidized catalytic cracker case study. Charitopoulos and Dua\textsuperscript{a} presented an algorithm for the design of mp-MPC for hybrid polynomial dynamic systems and derived the exact explicit expressions of the control law and the related –not necessarily convex– regions of optimality through the symbolic solution of the underlying parametric program. Oberdieck et al.\textsuperscript{2} presented a connected graph approach for the solution of multi-parametric linear and quadratic problems which allows for decrease in computational times and the design of a combined heat and power system. Recently, Che Mid and Dua\textsuperscript{a} presented a multi-parametric approach for model-based fault detection of nonlinear chemical processes. In their work, the parameter estimates are obtained as an explicit function of the measurements while the diagnosis of fault is carried out by monitoring the changes in the residual of model parameters.

Robust tube-based model predictive control. Conventional model predictive control strategies assume that the dynamics of the underlying system are optimized as if neither external disturbances nor model mismatch were present. Although these uncertainties are the main reason why feedback is needed in the first place, the main advantage of certainty-equivalence in MPC is that the resulting optimization problems can often be solved efficiently, in real time. Moreover, this approach works well in many practical applications, and it often exhibits a certain robustness due its inherent ability to reject disturbances. However, the constraints may become violated when large disturbances occur, since uncertainty is not taken into account in optimizing the predicted state trajectories. In such cases, robust MPC schemes may be used to mitigate these optimistic predictions. Villanueva et al.\textsuperscript{3} proposed a robust tube-based scheme for linear and nonlinear control-affine continuous time systems which relied on a min–max differential inequality formulation. In their approach tubes with ellipsoidal cross-section were employed. A key advantage of this development is that it scales linearly with the length of the prediction horizon, and does not rely on a particular parameterization of the control law in comparison to existing robust tube based MPC schemes.

Control strategies for biochemical and biomedical process systems. The strategy of using synthetic small interfering RNA (siRNA) as a therapeutic agent has become a powerful tool for the post-transcriptional knockdown of defective genes in mammalian cells with the aim of treating severe diseases such as viral infection and cancer. While optimization of siRNA design along with chemical modifications can reduce off-target effects and improve the stability of siRNAs, safe and efficient delivery is still a key challenge in realizing the clinical potential of RNAi therapeutics. The optimal model based control of non-viral siRNA was investigated by Jamili and Dua\textsuperscript{10} and the authors investigated the optimal dosage injection rate so as to balance the trade-off between high efficacy and low toxicity of the therapeutic agents. The increasing market demand in the biopharmaceutical industry and the tight regulations in product quality necessitate efficient operating procedures that guarantee products of high purity.

In this direction, process intensification via continuous operation paves the way for the development of novel, eco-friendly processes, characterized by higher productivity and lower production costs. Paphanasiou et al.\textsuperscript{11} investigated advanced control strategies for a cell culture system in a bioreactor and a semi-continuous purification process and illustrated that their employment can efficiently manage to increase the system productivity, returning strategies that can lead to continuous, stable process operations.

**Synthesis and operation of water and energy process systems**

Efficient water-treatment design has progressively been growing in importance as the usage of water resources increases with population rise and industrial development. Their availability has been reduced with the more evident effects of climate change. Addressing this challenge necessitates more and efficient purification plants which can be realized by optimal design at conceptual stage. The water challenge has brought questions of how to most efficiently treat water resources to ensure good quality and safety of final products. Koleva et al.\textsuperscript{12} presented three mathematical models for the optimal synthesis of plants for seawater desalination and surface water treatment for the production of potable water (see the Water treatment section of Application Domain Environmental Systems Engineering). Lira-Barragán et al.\textsuperscript{13} presented a mathematical programming approach for the optimal water management for shale gas production. Apart from water, the use of energy at domestic and industrial levels is essential. The optimal management of electricity and heat generation and demand in microgrids from the residential sector was examined by Silvente and Papageorgiou\textsuperscript{14}. Alvarado et al.\textsuperscript{15} presented a Technology Selection and Operation (TSO) model that enables a new approach for the optimal...
selection and operation of energy system technologies that encompasses whole-life costing, carbon emissions as well as real-time energy prices and demands, thus providing a more comprehensive result than current methods. The TSO model framework is data-driven and therefore presents a high level of flexibility with respect to time granularity, period of analysis and the technology portfolio.

Optimization approaches for industrial process operations

The integrated optimization of upstream and downstream processing strategies of a monoclonal antibody (mAb) biopharmaceutical facility under uncertainty was studied by Liu et al. In the upstream processing (USP), the bioreactor sizing strategies are optimized, while in the downstream processing (DSP), the chromatography sequencing and column-sizing strategies, including the resin at each chromatography step, the number of columns, the column diameter and bed height, and the number of cycles per batch, were determined. Under the uncertainties of both upstream titter and chromatography resin yields, a stochastic mixed integer linear programming (MILP) model is developed, using chance constrained programming (CCP) techniques, to minimize the total cost of goods (COG). Aguirre et al. examined the integration of planning and scheduling for multiproduct multistage continuous plants and proposed a rolling horizon approach for the iterative solution of the problem which enabled faster solution times. A multi-period model for the optimal scheduling of an industrial cryogenic air separation process so as to maximize the net profit by minimizing energy consumption was studied by Fernández et al. Real variability in electricity prices from spot and future markets was also considered. In Liu et al., a mixed integer linear programming model for the optimal operation of a network of gas oil separation plants can be found.

References

Competence Area

Modelling and Model Solution tools

Contributed by Andrea Bernardi and Kamal Kuriyan

Multiscale models are at the core of the research conducted at CPSE. The development of such models and their use for decision-making are reported elsewhere, in the competence areas on Chemical Manufacturing Systems, Molecular Systems, Energy Systems, Biological Systems, Environmental systems, and Supply Chains.

The first part of this summary is devoted to CPSE’s contributions to the field of molecular dynamics, including intermolecular-potential models for use with equations of state, the prediction of thermophysical properties of fluids and interfaces, crystal-structure predictions, and the application of property predictions in multiscale process design. Some highlights of emerging applications in computational catalysis, coarse-grained molecular-dynamics simulations, multiscale molecular simulations and the integration of molecular dynamics and fluid dynamics models are presented herein. Then, the rest of the summary highlights methods and tools with broad application across domains, including global sensitivity analysis, model-based design of experiments, and parameter estimation.

Computational catalysis

Heterogeneous catalysts are important for many different applications in chemical and process engineering and it is crucial to have mathematical tools to analyse and assess their performances. Several phenomena are involved in the overall process, from adsorption/desorption of the reactants/products, to surface diffusion and chemical reactions. The aim of computational catalysis and surface science is to compute from ab initio simulations the rates of these elementary processes, thereby enabling the prediction of catalytic performance metrics (such as activity and selectivity) from first principles, and detailed validation of hypothesized kinetic mechanisms against experimental data.

Research in the Stamatakis group focuses on (i) the development of simulation methods that enable the fundamental understanding of how heterogeneous catalysts function, from the molecular level to the reactor; and (ii) the computational design of better catalysts for processes relevant to energy and sustainability, such as the upgrade of methane from natural/shale gas to liquid fuels, emissions control and biomass to biofuels conversion.

During this reporting period, the Stamatakis group has continued to develop software Zacros (www.zacros.org) for the kinetic simulation of catalytic reactions through the kinetic Monte Carlo (KMC) method. The software has been licensed to more than 360 users in academia and industry. In addition, they have recently introduced a new class of approximate kinetic simulations, which are computationally superior to KMC. Albeit still limited to relatively simple systems, they have been shown to exhibit several orders of magnitude lower computational cost than KMC at negligible loss of accuracy. The predictive capability of the software has been showcased in many relevant catalytic systems: catalytic reduction of CO, biomass conversion in biofuels, and methanol-to-liquids reactions.

The CO oxidation reaction on Pd is one of the main components of three-way catalytic converters for automotive exhausts. The KMC approach in Zacros has been used to investigate the effect of adsorbate-adsorbate lateral interactions among adsorbates in this reaction. This fundamental study explained the markedly different experimental kinetic orders under low versus high temperatures for this system; it was thus shown that adsorbate-adsorbate lateral interactions have a decisive effect on catalytic activity, challenging the status quo in the catalysis field, whereby such effects were attributed to other phenomena such as segregation of adsorbates into islands on the catalytic surface.

Liu et al. studied the conversion of biomass-derived oxygenates to biofuels (hydrocarbons). Quantum-chemistry calculations have been performed to elucidate the high activity of single Co atoms on MoS2 catalysts towards the hydro-de-oxygenation (HDO) reaction. In HDO, hydrogen reacts with the organic oxygenate and abstracts oxygen, which is subsequently removed as water. The calculations show that Co atoms promote the formation of sulphur vacancies on the Co/MoS2 material, which function as the active sites for this chemistry. Moreover, the presence of Co atoms has been computationally shown to prevent the degradation of the MoS2 catalyst via sulphur leaching and oxidation of the material. Experiments by Stamatakis’ collaborators at Oxford University showed that Co/MoS2 is indeed an active and stable catalyst for HDO.

Figure 1: (a) and (b) shows STM image of a 0.01 ML Pt/Cu(111) SAA surface. (c) Experimental TPR traces showing evolution of methane (solid lines) and ethene (dashed lines) from different catalysts surfaces following deposition of CH3. (d) Simulated TPR of methyl-covered Cu(111) (black), Pt/Cu(111) SAA (red) and Pt(111) (blue).
More recently, the activation of methane and its coupling towards higher hydrocarbons has been investigated. Breaking the C-H bonds of methane is difficult, which makes methane an extremely stable species. While there exist single-metal catalysts that can perform C-H activation (Ni or Pt), they tend to over-dehydrogenate methane and eventually suffer from deactivation via coking. In collaboration with experimentalists at Tufts University, highly dilute alloys of Pt and Cu have been investigated as potentially active and stable catalysts toward C-H activation and C-C coupling (cf. Figure 1). Using quantum chemistry methods and KMC simulation in Zacros it has been possible to understand the superior performance of the Pt/Cu “single atom alloy” (SAA), in which the dilution of Pt is so high that single-atoms of Pt exist on the surface. It has been shown that Pt/Cu can perform the first and second H-abstraction much more easily than Cu, but does not proceed up to coke, unlike Pt, thereby preventing its deactivation. Experiments have confirmed this result and shown that Pt/Cu can perform C-C coupling up to C3 species. This study paves the way towards future technologies that could efficiently convert methane to fuels with the use of such single atom alloy catalysts.

**Predictive models based on the SAFT EoS**

Currently, available computer power is allowing chemical engineers to explore modelling in ways that were only dreamt of a decade ago. Computer simulation based on molecular dynamics is rapidly changing the way the process industry thinks, and in a few years’ time empirical correlations and heuristic rules will most surely be displaced by ab-initio methods. Research in the Jackson and Müller groups has focused on the development of intermolecular force fields, which allow accurate determination of thermophysical properties of fluids (densities, pressures, etc.) through molecular-dynamic simulations. These force fields are based on the statistical associating fluid theory (SAFT) equation of state and provide the tools necessary to perform complex simulations in terms of scale and duration, that would otherwise be inaccessible to classical atomistic molecular-dynamics simulations. Highlights are presented here; further details may be found in the report on the Molecular Systems Engineering application domain.

Recent research has extended the SAFT-VR Mie equation of state (EoS), one of the latest versions of the SAFT family, in order to better connect experimental determinations, theoretical calculations, and molecular-simulation results. The main limitation is that SAFT-VR Mie restricts the model to chains of beads connected in a linear fashion. The extension by Muller and Mejia enables modelling phase equilibria for the case of planar ring compounds, too. The performance of this novel methodology was assessed for different families of molecules (aromatic hydrocarbons, heterocyclic molecules and polycyclic aromatic hydrocarbons), and a binary system of a chain fluid (hexane) with a ring fluid (tetrahydro-2H-pyran), showing a very good agreement between predictions and experimental measurements.

To setup and run a coarse-grained molecular-dynamics simulation requires a lot of expertise and a tool to assist the user in this task was not available in the literature. This motivated the development of the Python code raaSAFT, a tool to assist the setup and execution of coarse-grained dynamic simulations in a computationally efficient way. The package builds on the HOOMD-blue code, and as such it can exploit the computational power of GPUs. The user can obtain the required coarse-grained parameters for performing simulations from Bottled SAFT (www.bottledsaft.org), an online interactive database of over 6000 chemical compounds. The package has been extensively tested for different systems, showing a speedup of more than three orders of magnitude compared with atomistically-detailed simulations, while retaining an excellent agreement with experimental data.

The potential applications of CG dynamic models span different sectors of the process industry from petrochemicals to pharmaceuticals. Jimenez-Serratos et al. employ a coarse-grained (CG) model within large-scale simulations that describe the temperature-composition fluid-phase behaviour of binary mixtures of polystyrene in aliphatic solvents (exemplified by n-hexane and n-heptane). The interactions between the CG segments are described by Mie potentials, with parameters obtained from a top-down approach using the SAFT-γ methodology. Using only one temperature-independent unlike interaction energy parameter the model captures the experimental solubility behaviour and gives quantitative predictions of both upper and lower critical solution points and the transition to the characteristic “hourglass” phase behaviour for these systems.

Another important class of predictions are the interfacial properties of complex fluids, which is particularly relevant in the petrochemical sector, as in crude oil there are very large molecules that are far from ideal. An example of such non-ideal behaviour is in the “crumpling drop” experiments, where the interface of a drop covered by large molecules such as asphaltenes being deflated becomes non-smooth at some point (cf. Figure 2). In the

---

**Figure 2:** Left: Image of a deflated asphaltene-stabilised water drop in oil from Pauchard et al. Langmuir 30 (2014) 12795–12803. Right: Raytrace of the drop profile from simulations, revolved around the symmetry axis and with crumples inserted into the region where \( T_{\phi} = 0 \).
literature several hypotheses have been made on possible physical explanations but none of them had a solid theoretical background. A multiscale approach is proposed to explain this experimental evidence from a theoretical point of view. At the nanoscale the interfacial properties are predicted using a CG dynamic simulation of asphaltene molecules. These properties have then been applied in macroscale simulations considering a novel level-set/ghost-fluid/immersed-boundary method for taking the complex interface behaviour into account. The nanoscale model correctly predicts the interfacial orientation of the asphaltene molecules, a result never previously achieved by a molecular simulation in the literature. Moreover, the macroscale simulations can reproduce the crumpling drop experiment with a striking accuracy and provide new insight on the physical explanation, while highlighting the shortcomings of the previous hypotheses.

Interfacial polymerisation is a widely used technique in the process industry, used for instance to produce polyamide membranes for reverse osmosis. The availability of accurate predictive mathematical models can be of great help in optimising the process and producing better membranes. However, atomistic models are often too computationally demanding to be used in practice. CG simulations are used by Muscatello et al. and the modelled membranes share the general characteristics (e.g. dry and hydrated densities, average transport properties) with atomistic models built on ad-hoc procedures. Moreover, a comparison of the simulations with experimental data from the literature confirmed a good agreement of predicted and measured thickness and roughness.

There is a growing interest in carbon-capture technologies, and amine-based absorption is one of the most employed methods to capture CO₂ from concentrated sources, such as power plants, which are among the main contributors to the overall world's CO₂ emissions. However, carbon capture incurs a significant economic penalty arising from the high energy requirement of the solvent regeneration stage. Selecting the “right” solvent is crucial to the economic viability of the overall process, but there is a lack of predictive approaches that can be used to estimate the properties of potential solvents and solvent mixtures in the absence of experimental data. The modelling of aqueous mixtures of alkanolamines and CO₂ presents several challenges. The first difficulty arises from the complex chemical nature of alkanolamines, which feature at least two highly polarizable functional groups, a hydroxyl and an amino group. A second challenge arises from the reactive nature of mixtures of alkanolamines with H₂O and CO₂. In particular, alkyl-functional primary and secondary amines react (reversibly) with CO₂ to form carbamates. Chremos et al. propose a novel approach based on the SAFT-γ SW group-contribution approach to provide a predictive thermodynamic description of solvents and their mixtures with CO₂, enabling the computer-aided design of optimal solvents and solvent blends to separate CO₂ from the flue gas. The proposed predictive approach offers a robust platform for the identification of new solvents and mixtures that are viable candidates for CO₂ absorption, thereby guiding experimental studies.

Molecular dynamics for fluid dynamics simulations

Most modelling tools for engineering fluid dynamics rely on a continuum hypothesis.

For the description of droplets on a surface, these continuum-scale models require boundary conditions at solid–liquid, liquid–vapour and vapour–solid interfaces. The meeting of these three interfaces at the moving contact line represents the greatest challenge in selecting these boundary conditions. And the common assumption of no-slip results in a non-integrable stress singularity at the contact line. But this paradox can be avoided in a number of ways, including the assumption of a precursor film, some form of slip, a diffuse interface or evaporation and condensation. The complexity of the contact line has resulted in a number of models for the dynamics being applied at the continuum scale, such as hydro-dynamic models including Tanner’s law, Cox’s law, kinetic models such as molecular kinetic theory (MKT) and kinematic models. Smith et al. propose a novel approach based on a Langevin-style equation parameterised to be representative of a full molecular-dynamics (MD) simulation (cf. Figure 3). MD simulations have the potential to explicitly model the diffuse and complex nature of the inner region at the molecular scale but simulation of molecular droplets are limited, by computational constraints, to nanometer length and pico-second time scales, neither of which are realistic for most

![Graphical representation of the parameterised Langevin model proposed by Smith et al.](image-url)
Global Sensitivity Analysis (GSA) and metamodelling

Sensitivity analysis (SA) aims at quantifying the relative importance of each input parameter in determining the value and variance of model output. Global SA (GSA) estimates the effect of varying a given input (or set of inputs) while all other inputs are varied as well, thus providing a measure of interactions among them. GSA is used to identify key inputs whose uncertainty most affects the output and the results are used to rank inputs, fix unessential inputs and decrease problem dimensionality. For computationally expensive models and models which need to be run repeatedly, for example, in the global optimisation of the design space and for online optimisation, control and real-time fault detection, the replacement of a full model by a (series of) significantly less computationally expensive metamodels, or reduced-order models (ROMs), is a practical way of making computations tractable. A series of methods has been developed for the generation of ROMs from large, complex models using various derivatives of the High Dimensional Model Representation (HDMR) family of metamodelling methods, which exploit the fact that for many practical problems only low-order interactions of the inputs are important. These have been incorporated into general-purpose software tools for GSA and metamodelling and used in the development of novel methods for global optimization. GSA and metamodelling have been applied to complexity reduction of biological models for antibody-producing mammalian cell cultures and lignocellulosic bioconversion to ethanol, and enhancements to GSA methods are facilitating new applications. The combination of GSA with automatic differentiation methods has been applied to probabilistic seismic-hazard analysis \(^\text{13}\) and the pricing of multi-asset options \(^\text{14}\). Recent developments in extending and enhancing GSA methods are discussed below.

Lambert et al. \(^\text{15}\) used the group method of data handling (GMDH), an inductive modelling method (i.e. one that does not a priori postulate the structure of expressions), to efficiently calculate a sparse HDMR expansion. A key feature of GMDH is a self-organization property so that model complexity increases in an adaptive fashion. The model self-organization stops when the optimal model complexity has been found. A stepwise method is defined for using GDMH to compute an HDMR expansion. Examples are given of the application of the GDMH-HDMR approximation to benchmark functions including the Ishigami function, the Sobol’ g-200 function, the K-function and the Rosenbrock function. A key advantage of the method lies in its ability to deal with high dimensions and under-determined systems with a limited number of function evaluations, coupled with the convenience of optimal selection of parameters and polynomial orders in the HDMR expansion.

Kucherenko and Song \(^\text{16}\) proposed four different direct formulas and a double-loop reordering (DLR) method to improve the computational efficiency in estimation of Sobol’ main effect indices which are widely used in GSA. Test cases showed that these new direct formulas are much more efficient than the original Sobol’ formula for models with independent inputs, especially for small values of the Sobol’ indices. DLR is found to outperform direct formulas when the values of the Sobol’ indices are not very small and is also much easier to implement for models with dependent inputs.

Figure 4: Complex domains created by an output constraint, which cannot be evaluated independently from the model function itself. \(^\text{17}\)

Kucherenko et al. \(^\text{17}\) developed a framework for estimating sensitivity indices in non-rectangular domains in the presence of inequality constraints. The framework extends existing approaches to estimating Sobol’ indices in models with correlated variables. For the case of correlated variables, the main effect and total sensitivity indices are derived as generalizations of Sobol’ sensitivity indices. Inequality constraints impose additional structural dependencies between model variables. A common example of an inequality constraint is when the output of a model is constrained by a minimum or maximum threshold. With the imposition of inequality constraints the parameter space is no longer a hypercube, but may assume an arbitrary shape depending on the number and nature of constraints. Formulas are developed for main effect and total sensitivity indices. Two numerical methods are proposed for the estimation of the sensitivity indices. The first is a quadrature integration method and the second an acceptance-rejection method which avoids sampling from conditional distributions. Several test cases are developed for the proposed methods in domains of different shapes (cf. Figure 4). The results show that grid quadrature competes with Monte Carlo estimators for low-dimensional models but its convergence rate degrades with increasing model dimensionality. Some initial analysis on decomposing the variance contributions into correlated and structural contributions is also provided, but further work is required to develop a clear interpretation.

Parameter estimation and design of experiments

The efficiency of the experimental design in conventional model-based design of experiments (MBDOE) is affected by the initial estimates of parameter values. To remedy this, intermediate parameter estimations may be carried out at pre-specified updating times while the experiment is running to redesign the remaining measurements. However, this still requires the redesign strategy to be determined in advance. With information-driven procedures, redesign is based on the maximisation of a target profile which guarantees a reliable increase in the information content before estimating intermediate parameters, making it
possible to determine when to redesign the experiments\textsuperscript{18}. The information-driven redesign optimisation has been tested with two simulated case studies for a fermentation bioreactor and a physiological model for diabetes. The results show the higher efficiency of the technique, which is able to exploit the information from the running experiment.

Galvanin et al.\textsuperscript{19} proposed a joint model-based design of experiments approach to simultaneously discriminate among competitive kinetic models and obtain improved estimates of the model parameters. With conventional model-building procedures, experiments are designed first to discriminate between model structures, and then to improve the precision of parameter estimates once a suitable model structure is determined. However, the design for model discrimination may be ineffective at the beginning of this procedure when both model structure and parameters are unknown, the discriminating experiments could provide a low level of information for estimation of kinetic parameters, and the sequential procedure may lead to a large number of experiments being required to obtain reliable kinetics. In contrast, the joint method is able to discriminate between proposed models, while at the same time providing statistically sound estimates of all required parameters.

An application of optimal design of experiments to identify parameters in electrodialysis was presented by Galvanin et al.\textsuperscript{20}. Due to the complexity of the proposed model, extensive experimentation may be required to obtain statistically sound estimates of the model parameters and a model-based design of experiments approach is used to minimise the effort in development of the model. Thanks to the model-based approach, a single informative batch experiment can be designed for the efficient estimation of the parameters of the electrodialysis model. A comparison of standard batch experiments based on a factorial design with a single experiment designed with the MBDOE approach shows that both approaches produce statistically valid parameter estimates. However, the MBDOE approach shows a dramatic reduction in the overall experiment time, from 1080 minutes for the series of traditional batch experiments, down to 60 minutes or even less for a single MBDOE experiment.

The joint MBDOE method by Galvanin et al.\textsuperscript{19} was applied for the development of a model describing the oxidative dehydrogenation of methanol to formaldehyde over silver catalyst (cf. Figure 5), and compared with a sequential method with the same number of experiments. The sequential method performs adequately for model discrimination, but it fails to provide sufficient information for some of the kinetic parameters. In contrast, the joint method is able to discriminate between proposed models, while at the same time providing statistically sound estimates of all required parameters.

An application of optimal design of experiments to identify parameters in electrodialysis was presented by Galvanin et al.\textsuperscript{20}. Due to the complexity of the proposed model, extensive experimentation may be required to obtain statistically sound estimates of the model parameters and a model-based design of experiments approach is used to minimise the effort in development of the model. Thanks to the model-based approach, a single informative batch experiment can be designed for the efficient estimation of the parameters of the electrodialysis model. A comparison of standard batch experiments based on a factorial design with a single experiment designed with the MBDOE approach shows that both approaches produce statistically valid parameter estimates. However, the MBDOE approach shows a dramatic reduction in the overall experiment time, from 1080 minutes for the series of traditional batch experiments, down to 60 minutes or even less for a single MBDOE experiment.

An application of parameter estimation to model the kinetics of pyrolysis oil (PO) hydrothermal upgrading was presented by Sharifzadeh et al.\textsuperscript{21}. The compounds in PO are classified in terms of hydroxy groups since the dynamics of deoxygenation reactions strongly depend on the strength of hydroxy groups bonded to organic compounds. Trial reaction networks are formed with the minimum and maximum degrees of freedom. The results from these models are analysed to identify the significant components. The parameter estimation is performed using a genetic algorithm implemented in MATLAB to minimize the model mismatch. A new network model is then formed based on an understanding of the underlying chemical assumptions and by eliminating the least significant links in the maximum network. This leads to a reduction in the number of estimated parameters, which helps address issues in over-fitting physically insignificant pathways with limited experimental data. The results demonstrate that it is possible to model the main underlying kinetic pathways in deoxygenating PO by using lumped kinetic data.

Another application of systematic parameter estimation and MBDOE using gPROMS was reported by Bernardi et al.\textsuperscript{22} for the calibration (and subsequent verification) of a microalgae growth model under light-limited conditions. A combination of fluorometry and respirometry experiments was used for the calibration, and the optimally designed experiments were finally realized in order to verify the estimability of all of the model parameters.
References


Competence Area

Computational Optimisation and Machine Learning

Contributed by Benoît Chachuat

Enabling decision-making in Process Systems Engineering

As the economies around the world are becoming more inter-connected, the amount of scientific and engineering data generated is skyrocketing, and society demands ever more energy, a cleaner physical environment and better healthcare. Therefore, we are ending up with very complex models to solve and analyse. The complexity continues to grow in size on one hand and in terms of non-linearity, non-convexity, combinatorial nature and uncertain parameters on the other. We are not only expected to be able to solve these models fast (speed) but also to have to ensure that the solution obtained is reliable (reliability); speed and reliability often conflict each other.

Multiple groups within CPSE have strands of research in computational optimisation and machine learning, including the Computational Optimisation Group (COG) and the Statistical Machine Learning Group. Current interests include large-scale convex optimisation (Parpas), mixed-integer and nonconvex global optimisation (Adjiman, Chachuat, Misener), derivative-free and surrogate-based optimisation (Fraga, Kucherenko), parametric optimisation (Dua), dynamic optimisation and optimal control (Bogle, Chachuat, Deisenroth, Parpas), Gaussian processes (Deisenroth), reinforcement learning (Deisenroth), and Bayesian optimisation (Deisenroth, Misener). CPSE also has a strong track-record in software development (Adjiman, Chachuat, Fraga, Kucherenko, Misener). The summary and highlights below aim to illustrate recent developments in this competence area.

Large-scale optimisation

It is often possible to exploit the structure of a large-scale optimisation model in order to develop algorithms with lower computational complexity. Luong et al.¹ focus on large-scale nonsmooth convex optimisation, a common problem for a range of computational areas including machine learning and computer vision, and develop an improved Mirror Descent method with a special choice of distance function. Problems where the fidelity by which the optimisation model captures the underlying application can be controlled, are also common in the fields of optimal control, machine learning, computer vision, and inverse problems. Hovhannisyan et al.² develop and analyse a large-scale optimisation algorithm to minimize the sum of a convex function with Lipschitz-continuous gradient and a nonsmooth term by exploiting such a model hierarchy. This algorithm has a better convergence rate than any other existing multilevel method for convex problems. In a related work, Parpas² develops an algorithm to minimize the sum of a smooth, not necessarily convex function and a nonsmooth convex function, and analyse its convergence speed (see Fig. 1).

Large-scale mixed-integer nonlinear programming (MINLP) and generalized disjunctive programming (GDP) problems are common ground in PSE applications, for instance in computer-aided molecular and process design (CAMPD). Gopinath et al.⁴ propose a modified outer-approximation algorithm for the direct solution of CAMPD problems, with applications to separation systems. Multiple tests are developed to prune infeasible regions from both the process and molecular domains, and thereby enhance convergence. Jonuzaj & Adjiman⁴ compare the big-M and convex-hull approaches to GDP for solving mixture design problems, including cases where the number of mixture components itself is optimised.

Nonconvex and mixed-integer nonlinear optimisation

The paper by Boukouvala et al.⁸ reviews recent advances in global optimisation for both MINLP and constrained derivative-free optimisation (CDO), and highlights possible synergies between these two areas.

Pooling problems are an important class of global optimisation problems, encountered in operation and scheduling of important industrial processes such as petroleum refineries, where the key objective is to mix various intermediates to achieve desired properties and quantities of products. The paper by Baltean-Lugojan & Misener⁹ presents an analysis of the piecewise parametric structure of such pooling problems and its links with computational tractability. Further, Cecon et al.⁹ use functional programming to recognize named structure in optimisation problems, with applications to pooling.

Many complete search methods for problems in global optimisation and constraint satisfaction hinge on the ability to compute enclosures for the range of nonconvex functions as well as sets defined by multiple equalities and/or inequalities. The paper by Rajyaguru et al.⁹ presents an arithmetic for the computation of Chebyshev models for factorable functions and an analysis of their convergence properties. Chebyshev models consist of a pair of a multivariate polynomial approximating the factorable function and an interval remainder term bounding the actual gap with this polynomial.
approximant (see Fig. 2), and they perform better than their Taylor model counterparts. Nerantzis & Adjiman\textsuperscript{10} develop a tailored branch-and-bound algorithm for bounding individual eigenvalues of a symmetric interval matrix at an arbitrary precision. Unlike other existing methods, tight bounds for a specific eigenvalue can be obtained even when its range overlaps with those of other eigenvalues. In a related work, Subramanyam et al.\textsuperscript{14} study two-stage robust optimisation problems with mixed discrete-continuous decisions in both stages. These algorithms have been demonstrated on benchmark problems originating from multiple application areas, including the shortest path and vertex packing problems in graph theory, as well as capital budgeting and project management problems.

In the area of chance-constrained programming, Hanasusanto et al.\textsuperscript{15} consider joint chance constraints where the distribution of the uncertain parameters is only known to belong to an ambiguity set characterized by the mean and support of the uncertainties and by an upper bound on their dispersion. They present conditions under which such constraints are computationally tractable (conic representable). Rujeerapaiboon et al.\textsuperscript{16} develop the first polynomial-time constant-factor approximations for both discrete and continuous scenario reduction, where the goal is to approximate a given discrete distribution with another discrete distribution that has fewer atoms.

On the topic of parametric programming finally, Charitopoulos & Dua\textsuperscript{17} develop an algorithm for exact mapping of the solutions of linear programs with simultaneous variations in the cost, constraint right-hand side, and constraint left-hand side parameters (see Fig. 3).

**Stochastic, robust and parametric optimisation**

Dynamic decision-making under uncertainty, where actions need to be taken both in anticipation of and in response to the realization of a priori uncertain problem parameters, is among the most challenging areas in operations research and optimisation theory. The paper by Hanasusanto et al.\textsuperscript{12} investigates the complexity of linear two-stage stochastic programs with fixed recourse, and shows that even approximating the solution of such problems with a sufficiently high accuracy is intractable (#P hard) in general. Hanasusanto et al.\textsuperscript{13} consider the approximation of two-stage distributionally robust programs with binary recourse decisions by their associated $K$-adaptability problems, which pre-select $K$ candidate second-stage policies here-and-now and implement the best of these policies once the uncertain parameters have been observed. In a related work, Subramanyam et al.\textsuperscript{14} study two-stage robust optimisation problems with mixed discrete-continuous decisions in both stages. These algorithms have been demonstrated on benchmark problems originating from multiple application areas, including the shortest path and vertex packing problems in graph theory, as well as capital budgeting and project management problems.

Dynamic optimisation and optimal control

Set-valued integration methods for uncertain or parameter-dependent dynamic systems find applications in many research areas, including reachability and invariance analysis for control systems, robust optimisation and control, set-membership estimation, and global optimisation. Peric et al.\textsuperscript{18} present an extension of set-valued integration to enable efficient sensitivity analysis of parameter-dependent ordinary differential equation (ODE) systems, using both the forward and adjoint methods. Their approach enables uncertainty propagation by building on the sensitivity analysis capabilities of state-of-the-art solvers, e.g., the SUNDIALS suite. Bogle & Perez-Galvan\textsuperscript{19} use such set-valued integration combined with interval contractors (see Fig. 4) within a branch-and-bound algorithm to solve parametric dynamic optimisation problems to guaranteed global optimality.

In a similar vein, Paulen et al.\textsuperscript{20} use set-valued integration based on Taylor models within a branch-and-prune algorithm to enclose the set of parameters for which the response of the dynamic system is within a given bounded set. Applications of this technique are in the fields of set-membership estimation and regression under uncertainty. In the area of optimal control, and more generally for optimisation problems in infinite-dimensional Hilbert space, Houska & Chachuat\textsuperscript{21} propose a new complete search algorithm, called branch-and-lift, whereby the degree of a
control parameterization is progressively lifted and the approximation error is rigorously bounded.

**Financial engineering and risk management**

The work by Baltean-Lugojan & Parpas is concerned with the calibration of sophisticated volatility models based on fine-grained higher-order expansions, in order to better balance parameter stability with quality of fit over market data. In the field of portfolio selection, Kapsos et al. propose a computationally efficient formulation for the risk budgeting problem and introduce the robust risk budgeting framework that accounts for uncertainty in the input parameters. Rujeerapaiboon et al. use methods from distributionally robust optimisation to design fixed-mix strategies that offer similar performance guarantees as the growth-optimal portfolio, but for a finite investment horizon.

**Machine Learning**

Reinforcement learning provides a principled mathematical framework for experience-driven autonomous learning. Currently deep learning is enabling reinforcement learning to scale to problems that were previously intractable, such as learning to play video or learning control policies for robots directly from camera inputs. A survey of the fast developing field of deep reinforcement learning is presented in the paper by Arulkumaran et al.

Gaussian Processes (GPs) are a powerful state-of-the-art nonparametric Bayesian regression method, which relies on high-level assumptions about the underlying process to be modeled, such as smoothness or periodicity. Calandra et al. develop a novel supervised method that jointly learns a transformation of the data into a feature space and a GP regression from the feature space to observed space, in order to deal with complex and non-differentiable processes. They demonstrate their approach on complex non-smooth functions where standard GPs perform poorly, such as robotics tasks with contacts. Gaussian process state-space models (GPSSM) are essentially non-linear dynamical systems, whereby unknown transition and/or measurement mappings are described by GPs. They provide a competitive way of learning from time series due to their ability to identify complex systems, with potential applications across engineering, physics and economics. The paper by Eleftheriadis et al. addresses the difficult problem of learning a GPSSM model, not merely computing the posterior for a given GPSSM.

Bayesian Optimisation is a data-efficient, global black-box optimisation method optimising an expensive-to-evaluate fitness function. It uses GPs to describe a posterior distribution over fitness functions from available experiments. The paper by Calandra et al. demonstrates that Bayesian optimisation is particularly suited for robotic applications, where it is crucial to find a good set of gait parameters in a small number of experiments. Ulmasov et al. develop an improved Bayesian optimisation algorithm (DSA) to address problem with higher dimensionality, and apply it to a case study in parameter estimation for biological systems (see Fig. 5).

![Figure 5: Average computation time of DSA vs. BO in various parameter estimation problems.](image)

**References**


Application Domain

Chemical Manufacturing Systems

Contributed by Qingyuan Kong

Chemical Manufacturing Systems, being the fundamental application domain in chemical engineering, explores the need for new technologies, more effective use of new tools of analysis, and improved integration of all elements of manufacturing operations, including machines, information and humans. Recent advances in Process Systems Engineering address key issues involved in the design and operation of Chemical Manufacturing Systems. Computer-aided modelling tools, which are designed to assist in the decision-making process, target various scales of Chemical Manufacturing Systems from molecular-level modelling to the optimisation of plant-wide planning and operation. In CPSE, multiple groups focus on the development of models and their applications at different scales: Modelling of Thermodynamics (Adjiman, Galindo, Jackson), Modelling of Reaction Kinetics (Adjiman, Galindo, Galvanin), Product Design (Adjiman, Galindo, Jackson), Optimisation-based Process Synthesis and Process Analysis (Adjiman, Fraga, Guillén-Gosálbez, Papageorgiou, Shah), and Planning and Operation of Chemical Manufacturing Systems (Dua, Papageorgiou, Guillén-Gosálbez).

Modelling of Thermodynamic Interactions

One key challenge in modelling advanced chemical manufacturing processes is the simulation of complex interactions between chemical substances, which could significantly affect the performance of the entire plant. To model such interactions, thermodynamic models are routinely employed in the design and optimisation of separation and production processes. In CPSE, the statistical associating fluid theory (SAFT), developed by the Molecular Systems Engineering Group, has been applied to several industries. Papaioannou, et al.1 present a study that investigates the application of the SAFT-γ Mie group-contribution approach to the study of a range of mixture systems in the oil and gas industry. The model is shown to provide an excellent prediction of the properties for the systems of interest, exhibiting excellent agreement with experimental data.

Hutacharoen, et al.2 develop novel models within the SAFT-γ Mie group-contribution framework for the accurate description of the fluid-phase equilibria

Figure 1: Comparison between the model-predicted solubility (lines) and experimental data (circles). Reproduced from Reference 3.
Over a broad range of compositions of the mixtures. The models’ predictive capability is validated by calculating partition coefficients and solubilities of a number of highly multifunctional compounds of importance in the pharmaceutical industry (Figure 1).

Modelling of Reaction Kinetics

One of the expertise areas of CPSE is the kinetic modelling of chemical reactions to find the optimal reaction conditions and provide a benchmark for the future development of the reactions. Diamanti, et al.\(^3\) combine quantum-mechanical (QM) calculations and experimental data to provide a useful strategy for kinetic model development, which is applied to simulate a hydrogen abstraction reaction (See Figure 2).

Galvanin, et al.\(^4\) conduct a kinetic modelling study on the gas-liquid methoxycarbonylation of ethylene using a homogenous catalyst in a continuous flow Hastelloy capillary microreactor. The kinetic experiments show that carbon monoxide and methanol have a positive effect on the reaction rate in the operating design space, while ethylene presents an insignificant effect on the reaction rate.

**Product Design**

Another aspect that can significantly improve the performance of a chemical manufacturing plant is the choice of chemicals used in the process, such as the catalyst, solvent and even the reactant. In CPSE, especially in the Molecular Systems Engineering group, researchers are constantly developing modelling tools to design the most suitable substances for specific functions.

Chremos, et al.\(^5\) demonstrate for the first time that the SAFT model based on transferable intermolecular square-well (SW) potentials (SAFT- SW) can be used for the modelling of complex reacting systems that take place in mixtures of water (H\(_2\)O), carbon dioxide (CO\(_2\)), and alkanolamines (Figure 3). As a result, the predictive model can serve as a tool for the identification of new solvents and mixtures that are viable candidates for various purposes, e.g., CO\(_2\) absorption. Jonuzaj, et al.\(^6\) propose a generalised disjunctive programming approach, which is integrated into a novel computer-aided mixture/blend design framework for the systematic design of mixtures. The method is applied to a case study to find an optimal solvent mixture that maximises the solubility of ibuprofen, and the findings provide evidence of the usefulness and versatility of the proposed approach to optimal mixture design.

![Figure 2: Illustration of the hybrid model combining the QM calculation and the experimental data.](image)

**Figure 2: Illustration of the hybrid model combining the QM calculation and the experimental data.**

Struebing, et al.\(^7\) combine the quantum-mechanical (QM) method with a computer-aided molecular design (CAMD) model to examine the impacts of different solvent choices on reaction rates and selectivity. The results highlight the trade-offs between different chemical and physical properties such as reaction rate constant, solvent density and solid reactant solubility and lead to the identification of several promising solvents to enhance reaction performance.

![Figure 3: Vapour pressure in a pressure–temperature PT representation. The symbols correspond to experimental data, and the curves represent the SAFT-γ SW calculations. Reproduced from Reference 5](image)

**Figure 3: Vapour pressure in a pressure–temperature PT representation. The symbols correspond to experimental data, and the curves represent the SAFT-γ SW calculations. Reproduced from Reference 5**

**Process Analysis and Optimisation-based Process Synthesis**

Prior to building a chemical manufacturing plant, all process alternatives must be thoroughly assessed and systematically compared against each other to yield the optimal process design schematic.

**Detailed Process Assessment**

CPSE has leading-edge experts in conducting a thorough and accurate model-based economic and environmental assessment, which plays a crucial role in the development of a feasible chemical manufacturing plant.
manufacturing processes. Gonzalez-Garay, et al.\textsuperscript{8} compare the economic and environmental performance of the conventional industrial process for propylene glycol production against three different hydrogenolysis routes based on biodiesel glycerol using process modelling and optimisation tools along with life cycle assessment (Figure 4).

Figure 4: Production of biobased propylene glycol using glycerol waste from biodiesel production.

The comparison reveals that there are bio-based process alternatives that outperform the current propylene glycol production scheme simultaneously in profit and environmental impact. Hankin and Shah\textsuperscript{9} investigate whether it is possible to inject CO\textsubscript{2} directly to methanol/DME synthesis systems without upstream conversion to CO by evaluating and comparing the performance of four systems in terms of energy efficiency and CO\textsubscript{2} conversion. It is concluded from the assessment that CO\textsubscript{2} can be utilised directly in the direct DME synthesis route, whereas upstream conversion to CO is found necessary to achieve significant yields and increased overall CO\textsubscript{2} conversion with the methanol/two-step DME systems. Giarola, et al.\textsuperscript{10} report the first techno-economic assessment of a conceptual process design for the production of phthalic anhydride from an agricultural residue (i.e. corn stover), which includes the assessment of energy integration alternatives, water consumption and greenhouse-gas emissions. The study provides crucial insights into the feasibility of using biorenewable resources for the production of phthalic anhydride. Lin, et al.\textsuperscript{11} conduct a model-based economic and environmental evaluation for three alternative nitrogen removal and recovery methods integrated into wastewater treatment systems. The assessment points out that although the well-developed conventional route is still favoured, emerging technologies such as ion exchange and Anammox have the potential to surpass the current route to achieve economically and environmentally optimal performance.

Process Synthesis

High-level process synthesis screens potential process alternatives in manufacturing to determine the optimal production plan and the process flowsheet as benchmarks.

Kong and Shah\textsuperscript{12} develop an optimisation-based framework (framework I in Figure 5) for the conceptual design of reaction-separation processes. Heat integration is also implemented to examine its effect on the entire process.\textsuperscript{13}

Figure 5: Implementation of simultaneous heat integration with process synthesis.

The resulting model linearises the energy balances constraints through the discretisation of the temperature variable (framework II in Figure 5), and is the first process synthesis model that accounts for the simultaneous synthesis of reaction pathways, separation sequences, and heat integration cascades.

Zhang, et al.\textsuperscript{14} propose the first optimisation model to examine more than 100 synthesis pathways leading to 20 different polymers based on their carbon efficiency and economic potential. Koleva, et al.\textsuperscript{15} utilise the concept of superstructure optimisation and present a methodology that compares the combination of various water treatment technologies based on their water net cost (WNC) for the design of an economically favourable water treatment plants. The model’s solutions of two industrial case studies show good agreement with the existing practices.

Design of Separation Processes

Distillation, being the traditional and commonly used separation technology, is still among the most investigated topics in CPSE. The study by Leeson, et al.\textsuperscript{16} presents a novel optimisation-based model for the preliminary design of heat-integrated multicomponent distillation sequences. The model is tested on a mixed alkane feed
stream and is found to have the potential for significant cost reductions compared to a heuristic design (given in Figure 6).

Ibrahim, et al.\textsuperscript{17} propose a rigorous simulation-optimisation approach for the design of a complex crude-oil distillation unit. The proposed approach is illustrated by its application to a specific distillation unit, in which numerical results demonstrate that the new approach is capable of identifying appealing design options while accounting for industrially relevant constraints.

The design and optimisation of other separation technologies have also been addressed by CPSE researchers. For instance, Gopinath, et al.\textsuperscript{18} propose a modified outer-approximation (OA) algorithm for dealing with the strong and nonlinear interactions between solvent and process that arise in the design of complicated separation systems, such as the adsorption system, based on computer-aided molecular and process design (CAMPD). The algorithm makes it possible to tackle highly nonlinear CAMPD problems without resorting to problem decomposition. Liu, et al.\textsuperscript{19} develop an optimisation-based framework for the selection of resin used in chromatographic separations for the pharmaceutical industry. The results show that the proposed method can process a considerable amount of experimental data, and identify the best resins within a few minutes of computational time. The optimisation-based concept is also applied on the design of desalination systems for shale gas produced water\textsuperscript{20} and the treatment system for the flowback water from shale gas production\textsuperscript{21}. Both models show their abilities towards the synthesis of more cost-effective separation systems.

**Operation and Planning of Chemical Manufacturing Processes**

Aside from the design and modelling of chemical manufacturing systems, optimisation-based framework for the optimal process planning and operations is also a focus of CPSE. Charitopoulos, et al.\textsuperscript{22} formulate a Traveling Salesman Problem (TSP)-Based model to deal with the computational complexity arising from the large-scale integrated planning, scheduling and optimal control (iPSC) problem of continuous manufacturing processes (see Figure 7).

Aguirre, et al.\textsuperscript{23} develop a computationally efficient mixed integer linear programming (MILP) model, which also features the TSP formulation, and a solution approach involving a rolling horizon and iterative-improvement algorithm for solving medium-term planning and scheduling in multiproduct multistage continuous plants.

Vieira, et al.\textsuperscript{24} propose a novel mixed integer linear programming (MILP) model, based on a resource task network (RTN) continuous time single-grid formulation, to address issues arising in the optimal planning and scheduling of biopharmaceutical manufacturing processes, such as the campaign schedule of batch and/or continuous process steps and sequence-dependent changeovers operations.

Some of the mature frameworks have already been applied to industrial cases to boost their performances. Fernández, et al.\textsuperscript{25} present a multiperiod mixed-integer linear programming (MILP) model to determine the optimal production schedule of an existing industrial cryogenic air separation process to increase its profitability. Through the implementation of the model, significant improvement is attained. Liu, et al.\textsuperscript{26} develop a tailor-made mixed integer linear programming (MILP) model to optimise the crude transfer through swing pipelines and equipment utilisation in an existing network of gas oil separation plants in the Ghawar field. Compared to the current rule-based practice, an average 12.8% cost saving is realised by the developed model.
References


Application Domain
Molecular Systems Engineering

Contributed by Silvia Di Lecce and Suela Jonuzaj

Thermophysical methodologies are continuously being developed and improved due to the high demand to accurately predict the thermophysical properties of complex fluids in a wide range of industrial applications. In this context, the Molecular Systems Engineering group aims to offer a direct link between theory, simulations and experiments allowing multiscale modelling of the system from the sub-atomic (quantum) to the macroscopic scale. Multiple groups within CPSE have strands of research in the application domain of molecular systems engineering, publishing papers which are relevant in several industrial applications, such as pharmaceutical, fine chemical and petrochemical. A summary of recent research work and key developments and achievements in this area is presented below. A visual representation of the split between different subareas is shown in Figure 1.

Developing intermolecular-potential models for use with the SAFT-γ Mie Equation of State

Theoretical approaches based on statistical mechanics allow accurate understanding and prediction of the macroscopic behaviour of complex aqueous mixtures. The predictions of thermophysical properties of complex multifunctional molecules are often the primary goal, which can be achieved by first developing a model for simpler systems. This is shown in Hutacharoen et al.1, where group-interaction models developed to accurately describe the thermophysical properties of alkanes and alcohols in aqueous solutions are then used to predict the solubility and the octanol-water partitioning for a range of organic and pharmaceutically relevant compounds. The model provides a very meticulous platform that reproduces the fluid phase equilibria over a broad range of compositions of the mixtures and for different thermodynamic states (see Figure 2). The predictions of solubilities for active pharmaceutical ingredients (i.e. azelaic acid, ibuprofen, and ketoprofen) in different solvents find remarkable agreement with the experimental data, making the SAFT-γ Mie approach a promising tool in modeling complex molecules of relevance to pharmaceutical systems.

Figure 1: Percentages of recent research works published in the application areas indicated in the legend.

Figure 2: Prediction of solid-liquid equilibria of active pharmaceutical ingredients (APIs) in different solvents as a function of temperature at ambient pressure (p = 0.101MPa). The symbols represents the experimental data and the continuous and dashed curves the description with the SAFT-γ-Mie approach: (a) azelaic acid in water; (b) ibuprofen and ketoprofen in water; (c) ibuprofen in n-butanol-1-ol; and (d) ibuprofen and ketoprofen in acetone.
Solvents with the ability to solubilize a large number of substances are often hydrogen-bonding compounds characterized by high polarity. Water, acetone and carboxylic acid are examples of these solvents that are widely used in the pharmaceutical industry as pure or mixtures, for example in counter-current chromatography, solvent extraction and solution crystallization. Theoretical predictions of the macroscopic behaviour of these compounds and their mixtures is challenging from a theoretical perspective. The SAFT-γ Mie equation of state (EoS) exploits highly versatile association-site schemes to model mixtures in which short-range association interactions occur. The recent paper by Sadeqzadeh et al. develops highly transferable SAFT-γ Mie models that accurately describe the fluid-phase behaviour and excess properties of binary and ternary mixtures containing acetone and carboxylic acid with water and non-polar compounds.

The SAFT-γ Mie group-contribution approach can also provide a good representation of a wide set of properties relevant to the oil and gas sector over a broad range of conditions. The work by Papaioannou et al. considers mixtures of n-alkanes (methane and alkanes) and carbon dioxide (CO₂). The former are prevalent components in crude oil and natural gas, while the latter is naturally present in fluid reservoirs or injected to enhance the oil recovery or carbon storage. Exceptional theoretical predictions of experimental liquid–liquid and vapour–liquid-equilibria data, calorific properties (i.e. excess enthalpy and heat capacities) and of a variety of properties that are important for fluid-flow calculations from equations of state (i.e. densities, speeds of sound and excess properties of mixing), are demonstrated for an extensive set of mixtures.

Thermodynamic and transport properties of electrolyte solutions play a significant role in many scientific and industrial applications. Although the description of these properties is a challenging task, Eriksen et al. demonstrate the ability of the SAFT EoS to represent the thermodynamic behaviour of strong electrolyte aqueous solutions, including salts of monovalent and divalent ions.

Carbon dioxide is extremely important in the context of climate change and particularly global warming. Fossil-fuel power plants are major sources of CO₂ emissions. Many works have focused on CO₂ absorption using amines, especially monoethanolamine (MEA), in order to minimize the energy consumption of the process and the CO₂ emissions. Predictive models play a significant role in the design of carbon-capture systems because of their ability to accurately describe the phase and chemical behaviour of CO₂. Furthermore, they can identify new solvents or highlight the best operating conditions and mixtures that lead to optimal performance without excessive reliance on experimental data. In this context, Brand et al. adopt a physical approach to model the chemical equilibria inherent to the reactive capture of CO₂ using aqueous MEA. The model developed ensures an accurate description of the system and allows one to obtain the best-case performance of the solvent considered.

### Force-Field parameters from the SAFT equation of state for use in coarse-grained molecular simulations

The SAFT EoS provides an excellent description of the fluid phase equilibria for many systems. An important aspect of the theory is that the force-field parameters based on the underlying intermolecular potential can be then employed in molecular-dynamics simulation to obtain a wide range of information, such as thermodynamic, structural, interfacial and dynamical properties, which are inaccessible from the EoS. A large body of work within CPSE focuses on the description of the phase behaviour and prediction of these properties, which are crucial in many petrochemical applications.

Lobanova et al. developed a SAFT-γ coarse-grained force field for aqueous mixtures of carbon dioxide and linear alkanes, including the ternary system, for use in direct molecular-dynamics simulation. An accurate description of the anomalously miscibility of CO₂ in water is reproduced, as is the extreme immiscibility of the hydrocarbon. The predictions of the interfacial tension are in excellent agreement with the available experimental data. Another key paper in this area has extended the SAFT approach to polymer-solvent systems successfully, predicting by coarse-grained simulations the liquid–liquid phase diagrams. The SAFT approach and molecular-dynamics simulation were further used to accurately predict fluid phase behaviour of elastin-like polypeptide sequences in aqueous solutions, including the lower critical solution temperature.

Elastin-like polypeptides (ELPs) such as VPGVG are simple prototypical models of proteins which exhibit interesting lower critical solution behaviour in aqueous solution. A coarse-grained SAFT-VR square-well model was developed with the aid of detailed atomistic simulation of the system. The SAFT model was used to explore the global features of the phase behaviour of the system. An interesting novel type of closed-loop liquid–liquid immiscibility was predicted for the system. The theory provides a good description of the limited experimental data available.

The increasing interest in the design of materials at the molecular scale results in an urgent need for improving the capabilities of molecular-simulation methods and force fields to accurately predict the adsorption in porous media for systems of relevant practical interest, and the interfacial tension of mixtures. Papers by Herdes et al. are related to the 8th and 9th Industrial Fluid Properties Simulation Challenges. The former challenge focused on predicting adsorption isotherms of n-perfluorohexane in the certified reference material BAM-P109 standard activated carbon. The state-of-the-art version of the statistical associating fluid theory (SAFT) for potentials of variable range as reformulated in the Mie group contribution incarnation (SAFT-γ Mie) was used to develop coarse-grained intermolecular models from the vapour pressure and saturated liquid density data of the pure fluids using the EoS, and further validated by molecular-dynamic simulations. Coarse-grained intermolecular potential models were then used to obtain the adsorption isotherm kernels for argon, carbon dioxide, and n-perfluorohexane in graphite slit pores of various widths using Grand Canonical Monte Carlo simulations. The second challenge was set with the aim of assessing...
the capability of molecular-simulation methods and force fields to accurately predict the interfacial tension of oil–water mixtures at high temperatures and pressures. The focus was on predicting the liquid–liquid interfacial tension of binary mixtures of dodecane–water, toluene–water and a 50:50 (wt%) mixture of dodecane:toluene–water at 1.825 MPa (250 psig) and temperatures from 110 to 170°C.

Coarse-grained molecular-dynamics simulations based on the SAFT-γ Mie force field allow one to analyse structural properties at the interface, as mentioned above. Morgado et al.11 explored the conformation of the perfluoroalkylalanes in the air–liquid interfacial region, showing its implications in the surface tension. The paper by Garrido et al.12 merges the SAFT EoS and density gradient theory to produce a theory for interfacial tensions of fluids.

Parameters for SAFT force field can also be derived from Bottled SAFT, an interactive web page (www.bottledsaft.org) that allows users to access a database of over 6000 chemical compounds and find the coarse-grained parameters for performing simulations. This data set is easily searchable by CAS number, name or chemical formula. Alternatively, the application allows the user to calculate parameters for components not present in the database. Once the intermolecular potential has been found through Bottled SAFT, code snippets are provided for simulating the desired substance using the “raaSAFT” framework, which leverages established molecular-dynamics codes to run the simulations, as shown by Ervik et al.13

**Prediction of Thermophysical Properties of Complex Fluids and Interfaces using Molecular Simulations**

The description of transport and interface properties of complex systems using molecular simulation finds applications in the design of membranes for desalination of water, the flow of gases and crude oils through reservoirs and the efficient separation of gases16–20. The paper by Brumby et al.21 studied the structural properties and interfacial tension of a fluid of rodlike hard-spherocylinder particles in contact with hard structureless flat walls by means of Monte Carlo simulation. This study represents the first calculations of the fluid–wall surface tension between a nematic liquid crystal and a solid substrate. A surface-ordering scenario is confirmed by the simulations: the local orientational order close to the wall changes from uniaxial to biaxial nematic when the bulk concentration reaches about 85% of the value at the onset of the isotropic–nematic phase transition. The surface ordering coincides with a wetting transition whereby the hard wall is wetted by a nematic film. Braga et al.22 have used the nonequilibrium path-integral formulation of Crooks fluctuation theorem and the intrinsic sampling method to calculate the atomistically detailed free-energy profile for the liquid–vapour interface of the Lennard-Jones fluid. Free-energy barriers are found corresponding to the atomic layering in the liquid phase as well as a barrier associated with the presence of an adsorbed layer as revealed by the intrinsic density profile.

Classical atomistic molecular-dynamics simulations of four structurally diverse model asphaltenes, a model resin, and their respective mixtures in toluene or heptane under ambient conditions have been carried out. Relatively large systems (~50000 atoms) and long time scales (>80 ns) were explored by Headen et al.23. Where possible, comparisons were made with available experimental observations asserting the validity of the models. When the asphaltenes are dissolved in toluene, the fluid–wall surface tension between a nematic liquid crystal and a solid substrate.

Materials comprising porous structures, often in the form of interconnected concave cavities, are typically assembled from convex molecular building blocks. The use of nanoparticles with a characteristic nonconvex shape provides a promising strategy to create new porous materials, an approach that has been recently used with cage-like molecules to form remarkable liquids with “scrabbled” porous cavities. Avendaño et al.24 have proposed the design of highly open liquid-crystalline structures from rigid nanorings with ellipsoidal and polygonal geometry. By exploiting the entropic ordering characteristics of athermal colloidal particles, they demonstrate that high-symmetry nonconvex rings with large internal cavities with the formation of distinctive liquid-crystalline smectic phases.

**From property predictions to molecular and process design**

Over the last decades there has been growing interest in the development of systematic methods, within the Computer-Aided Molecular Design (CAMD) framework, for the determination of optimal chemicals and their properties for various chemical-engineering applications, spanning from chemical reactions to separations. In organic reactions for instance, the choice of solvent often has a large impact on reaction rates and selectivity. Struebing et al.25 developed a systematic methodology for the design of optimal solvents for improving reaction rates. The design approach integrates quantum mechanical (QM) information for the reaction rate constant in different
solvents within a CAMD model. The multiscale formulation combines electronic-structure methods with bulk thermodynamic property prediction and reactor design. The QM-CAMD approach they proposed provides a valuable framework to link reactor design and solvent design prior to any experimental investigations. Understanding and modeling reaction kinetics are integral parts of process development, and the importance of developing accurate modeling tools for predicting reaction kinetics is undisputed. Diamanti et al.\textsuperscript{26} presented a thorough investigation of the suitability of QM calculations to predict the effect of temperature on the rate constant of one hydrogen abstraction reaction. They further developed a novel hybrid approach to build better correlative kinetic models that combine a limited number of QM calculations and experimental data. The method provides valuable insights for combustion and atmospheric chemistry, where hydrogen abstraction reactions are of specific interest and the modeling of chemical kinetics requires the specification of a large number of rate constants over wide temperature ranges.

The selection of suitable processing materials has a significant impact on process performance, as material and process decisions (properties of molecules, process flow sheet, unit sizes, operating conditions) are in fact interdependent. Choosing a processing material based on a few desirable physicochemical properties, in isolation from process performance considerations, can thus lead to poor decisions. Instead, a process-wide evaluation of the chemical is essential to identify choices that lead to better (or even optimal) process performance metrics such as reduced cost and environmental impact. Gopinath et al.\textsuperscript{27} have developed an integrated computer-aided molecular and process design (CAMPD) methodology which is applied to separation systems. The proposed approach enables the simultaneous optimization of solvent and process variables, yielding optimal solvent structure and process conditions. The results highlight the extent to which optimal solvent and process conditions are interrelated and dependent on process specifications and constraints.

Despite the importance of designing optimal chemicals, pure compounds cannot always achieve specific property targets or meet the desired performance criteria (e.g., better cost environmental measures). Thus, there is a pressing need for identifying mixtures that can achieve better performance than pure compounds while being more environmentally benign. However, the design of optimal mixtures, which entails the design and/or selection of appropriate components and of their composition, remains challenging. The choice of the desired components is often based on database searches or expensive and time-consuming experiments and usually binary mixtures are used for various applications, which may lead to suboptimal solutions. In order to exploit the full potential of a truly general mixture design approach and avoid the use of restricted datasets, the work by Jonuzaj et al.\textsuperscript{28} bridges the computer-aided molecular and mixture design concepts by developing a general methodology, where the number, identity and compositions of mixture ingredients are optimised simultaneously. In this general formulation, the molecules are designed (built) from an extensive set of atom groups, leading to the design of countless new and/or existing molecules and mixtures. For instance, more than 1000 pure compounds can be generated from a set of 49 atom groups, which lead to the design of almost 0.5 million binary and 200 million ternary mixtures. This general methodology is applied to the design of optimal solvent and antisolvent mixtures for the cooling and antisolvent crystallization of ibuprofen (see Figure 4), as well as to the design of optimal solvent mixtures for separating acetic acid from water with liquid—liquid extraction. The overall proposed mixture design approach paves the way for identifying innovative solutions (e.g., new molecular structures, mixtures, property functions) which play an integral role in the development of process and chemical technologies.

**Systematic methodologies for crystal structure predictions**

The crystal structure of a molecule plays a key role in determining solid-state properties such as, colour, solubility, bioavailability and hygroscopicity. In the pharmaceutical and fine-chemical industries, the formation of unexpected crystal forms, such as polymorphs or solvates, could lead to both legal and economical risks. In this context, the prediction of all the crystal structures that a specific molecule or set of molecules can form becomes very useful.

The CrystalPredictor and CrystalOptimizer codes have been used to explore the space of crystal structures successfully in several crystal structure prediction (CSP) investigations in recent years, including in the series of blind tests organised by the Cambridge Crystallographic Data Centre and in the prediction of the crystal structures of pharmaceutically-relevant molecules. One of the key research challenges in developing CSP capabilities is to enable the investigation of increasingly flexible compounds within tractable computational times, competitive with experimental polymorph screens. A major improvement towards the accurate description of a molecule’s intramolecular variation as a function of conformational flexibility has been achieved in the paper by Habgoo et al.\textsuperscript{29}, where the Local Approximate Model (LAM) method developed in CrystalOptimizer is incorporated into CrystalPredictor. The CSP of large and flexible molecules of particular
interest in many industrial applications can result in a larger computational cost. The paper by Sugden et al. describes the adaptive Local Approximate Model (LAM) algorithm that achieves greater accuracy in the initial ranking of potential crystal structures, while managing computational cost, so that a thorough exploration of the search space is possible, for ever larger and more flexible molecules. The LAM method is found to be effective in the CSP of several molecules and pharmaceutical compounds (see Fig. 5).

Figure 5: Intramolecular energy variation in β-D-glucose, as a function of two of the flexible torsions.

References


Application Domain

Biological Systems Engineering

Contributed by José Morais and António Lima Grilo

Biological Systems Engineering brings together several core competence areas of CPSE to study, understand, optimise and control biological systems at the cellular, tissue and organ levels through the integration of experimentation, mathematical modelling, model analysis and process design tools. The work CPSE researchers are developing has a direct impact in Biotechnology, Biomedical Engineering, Systems and Synthetic Biology.

Addressing the needs of modern, personalized healthcare

At Imperial College, Dr. Susana Santos, Dr. Mark Allenby, Dr. Ruth Misener, Dr. Nicki Panoskalsis and Professor Mantalaris are developing strategies for the production of autologous red blood cells, an urgent need of all healthcare systems (Allenby et al., 2017; Brito dos Santos et al., 2016). In the same group, Joana Santos, José Morais and Dr. Sophie Zemenides are studying the metabolism of cells of different types of leukaemia and related diseases and developing 3D culture systems to culture these cells (Pefani et al., 2017; Santos et al., 2017; Velliou et al., 2017a). For this purpose, Dr. Asma Tahlawi is developing suitable biomaterials for cell culture and testing them for culturing different cell types. Symeon Savvopoulos, Dr. Ana Quiroga are developing mathematical models of leukaemia chemotherapy treatment (Quiroga-Campano et al., 2017; Savvopoulos et al., 2016). Tamador Alsobaie is studying the tissue engineering of the lung while Dr. Robert MacFarlane and Dr. Michail Klontzas are studying the tissue engineering of the bone through the production of cells of those tissues from different sources of stem cells to enable the development of cellular therapies (E. Klontzas et al., 2016). Dr. Spyridon Vernardis and Dr. Klontzas are conducting metabolism analysis of different stem cells and differentiated cells, a promising strategy to distinguish cell types in the era of cell therapies (Győrgy et al., 2017a; Győrgy et al., 2017b; Klontzas et al., 2017; Vernardis et al., 2017). These researchers collaborate with academic partners in the UK, across Europe and South Korea.

Developing tools to enable faster bioprocess development

Antonio Grilo, Dr. Ana Quiroga and Professor Mantalaris are investigating bioprocesses for the production of high value biologics. The researchers are studying different aspects of the biology of the cells involved in the manufacturing of such drugs and developing multi-scale, predictive, experimentally validated mathematical models to enable accelerated process development and optimisation.
Bioprocess optimization studies are being conducted by Dr. Ruth Misener whose group is developing algorithms for bioprocess optimization under uncertainty. Robust optimization and Bayesian optimisation methods are being developed and applied to different biological systems domains including stem-cell differentiation, red-blood-cells production, and leukaemia disease trajectories. Simon Olofsson has developed multi-objective optimisation methods for optimising bone neotissue growth and has merged data-driven and analytical approaches to design of experiments for model discrimination.

Dr. Cleo Kontoravdi and co-workers are developing process models to enable the implementation of Quality by Design in bioprocessing (Goey et al., 2017; Sou et al., 2017). Together with Dr. Oleksiy Klymenko (University of Surrey), they have built a modelling framework to design optimal cell culture conditions for desired antibody glycosylation, a key quality attribute of biopharmaceutical products. They applied a new computational method called constrained global sensitivity analysis to design cell-culture experiments that are anticipated to give rise to higher-quality antibody without being detrimental on production targets. The findings were confirmed experimentally, demonstrating that this computational approach can help identify the appropriate Design Space with a minimum amount of experimentation. The proposed concept can reduce the resources and the time needed for research and development of new biopharmaceutical products or already existing therapeutics (Goers et al., 2017; Klymenko et al., 2016; del Val et al., 2016).

The group of Dr. Kiparissides, at UCL, is working towards the development of comprehensive dynamic models of cellular growth that incorporate the impact of key process parameters (nutrient concentration, feed composition, pH, pCO2, etc) on cellular growth and product yields.

From a different perspective, Dr. Kontoravdi is collaborating with Dr. Karen Polizzi and Prof. Oscar Ces on the design and fabrication of a synthetic platform for producing and modifying proteins ex vivo in a fully controlled manner (Figure 1). Working with these living cells has a considerable downside, as protein synthesis is always strongly dependent on host cell metabolism in determining the product yield and quality. Cell-free systems have evolved from an analytical tool into a powerful complementary approach to cell-based production systems. Cell-free methods show several unique advantages over traditional cell-based platforms because of the direct access to the reaction network and avoidance of mechanisms that have evolved for preserving homeostasis. They are also potentially not subject to product limitations as cytotoxic, unstable, or insoluble proteins, such as membrane proteins, can all be expressed by such systems. At the moment this production platform is not financially attractive for the production of standard biopharmaceuticals on an industrial level due to the high cost of reagents, but it is clear that the potential to create a new class of smart micromachines that can be engineered for functional purposes is attractive for challenging products.

Mathematical tools underpin the development of microalgae-based products

Microalgae have long been identified as promising candidates for biofuel production. In comparison to conventional oil crops, they are independent from arable land and fresh water and can accumulate an array of useful by-products for the food, cosmetics or pharmaceutical industry. Lab- and pilot-scale experiments have shown that many microalgae species can grow orders of magnitude faster than conventional oil crops. The main commercial applications of microalgae so far have been concerned with high-value products, including carotenoids and polyunsaturated fatty acids. In contrast, the commercial viability of using microalgae for biofuel production is still uncertain and calls for the development of large-scale outdoor raceway ponds to reduce production costs. Scaling up microalgae production systems is particularly challenging due to the presence of light- and nutrient-dependent processes that are competing for growth. In comparison to lab-scale experiments, full-scale production systems can exhibit a dramatic loss of productivity.
due to imperfect mixing or light distribution, contamination or lack of adequate monitoring and control.

The group of Dr. Kiparissides is working on the development of stochastic parameter-estimation algorithms able to deal with highly non-linear models and large numbers of parameters. Primary application areas include: (a) the production of recombinant proteins from mammalian cell cultures and (b) the production of high-value chemicals and/or recombinant proteins from microalgae.

This is also the scope of research headed by Dr. Benoît Chachuat whose group is working on mathematical models capable of capturing the processes governing light-limited growth in microalgae, in order provide reliable predictions in large-scale production systems and a means for improving their design and operation (Bernard et al., 2015). Special emphasis has been on developing a high-fidelity model of light-dependent photosynthetic production (Bernardi et al., 2016). This model accounts for the processes of photoproduction, photoregulation and photoinhibition, which act on time-scales ranging from seconds to hours – see Figure 2 comparing measured and predicted fluorescence profiles in *N. gaditana*. It has been shown that, despite comprising many parameters, a full calibration and validation of such a model is possible using a combination of fluorometry and respirometry experiments, together with optimal experimental design techniques. Several follow-up works have investigated extensions of the model in order to encompass the slower time-scale process of photoacclimation, which can play an important role in outdoor production systems (Bernardi et al., 2017; Nikolaou et al., 2016b).

Finally, a multiphysics model of large-scale, microalgae raceway ponds, where the previous light-limited growth model is combined with CFD (Figure 3) and light-attenuation models describing the flow conditions and the light gradient, has also been developed through this research (Nikolaou et al., 2016a). This raceway pond simulator provides a way of assessing various scale-up effects (e.g. mixing) and how key design and operating parameters (e.g. extraction rate, water depth, paddle wheel position) may affect microalgae productivity.

**Figure 2:** PAM fluorescence profiles (points with error bars) compared with fluorescence flux predictions (red line) for an experiment with fast and slow changing light irradiance levels (gray-shaded area).

**Figure 3:** Coupling methodology of photosynthesis kinetics, hydrodynamics and light attenuation in a multiphysics simulator of microalgae culture in raceway ponds.

**Systems and synthetic biology: tools to understand disease mechanisms and support bioprocess development**

Professor David Bogle’s group, at UCL, continues to develop systems engineering of the liver. The zonated (distributed) liver model that William Ashworth developed with the UCL Institute for Liver and Digestive Health was used to assess the impact of pharmacologically targeting various processes in the model to clear steatosis (build-up of lipids) in patients with non-alcoholic fatty liver disease (NAFLD). This disease is present in one third of US and UK adults. A number of hepatic processes were targeted both individually and in combination: glycolysis, pyruvate oxidation, lipogenesis, b-oxidation, and triglyceride synthesis. Some preliminary experimental results were also obtained particularly with reference to free fatty acids. Current work is extending the model to include the fructose pathway as there is evidence that excess fructose is strongly associated with the development of NAFLD.
Together with the UCL Cancer Institute and with support from the CRUK/UCL Centre Development Fund Prof. Bogle, Lazaros Papagerogiou and colleagues have developed a new approach for determining the dynamic behaviour of cells over an extended period. The approach is used to explore the behavior of erythroid cells over a period of twenty-four hours using microarray gene expression profiles. The initial network structure is determined using a mathematical programming approach. The dynamic behavior of the state transitions of the gene regulatory network is determined using best fit to a Boolean network. This is part of a longer-term effort to explore the network behavior of differentiating stem cells.

A major challenge currently facing a clinical translation of gene-based therapy is the lack of an optimal gene delivery vector for nucleic acids. A novel gene delivery technology based on a multidisciplinary approach involving mathematical analysis, control theory, biological science, and engineering technology can play a crucial role to provide a platform to help evaluate translation of developments in the area of gene therapy into clinical practice. While a number of computational works provided insights into the process of gene delivery, most modelling works in the literature only partially describe the process and so biological effects such as toxicity and cell-division events had been largely ignored. This research work by Vivek Dua and colleagues presents an innovative approach based on the optimal control strategy, and aims at incorporating the dynamics of the gene-delivery process while simultaneously considering the key pharmacological issues. An integrated pharmacokinetic/pharmacodynamic (PK/PD) model-based control algorithm was developed for non-viral siRNA delivery to take into account the main multi-objective optimisation issues such as efficacy and toxicity, as well as the effect of uncertainty in cell division time. The structure of the pharmacokinetic model is shown in Figure 5.

The methodology developed in this research study provides an effective model-based tool for making decisions under uncertainty, which is lacking for gene delivery systems. A conceptual block diagram representing a closed-loop model-based control scheme is shown in Figure 6.
Information processing in cells and tissues/cell populations combining is also being conducted in Dr Krishnan’s group whose research focusses on mathematical modelling, theoretical work, systems approaches and collaborations in both systems and synthetic biology. These include a range of levels, from the level of basic chemical kinetics of multisite modification, to pathways and networks, through to cells and populations. Both temporal and spatial aspects of information processing are focal points of interest.

The work focusses on the behaviour of cell-cycle regulatory systems in dynamic environments, developing a methodology to understand how the cell cycle (exemplified by budding yeast) and growth transitions are perturbed by dynamic changes in the environment. While there have been many studies of cell-cycle behaviour in a range of systems, how this and associated growth landmarks are dynamically controlled by the environment is much less studied.

Biochemical information processing systems (in cell signalling and elsewhere) contain a number of building blocks and modules which perform specific information processing tasks: eg covalent modification cycles, monostable and bistable switches, oscillators, adaptive/homeostatic modules, which have been the focus of many studies. However, these studies typically focus on the behaviour of the module in isolation without any detailed consideration of the network within which the module is present. The behaviour of modules in networks and the extent to which modularity may be preserved, and when it may be compromised is fundamental to both systems and synthetic biology. The researchers have formulated a systems framework to address this in detail. This reveals many different aspects of how the network environment affects a module, and how a module affects a network, and also reveals what key features of a module (biochemical, network structure, dynamical systems characteristics) are responsible for this (Menon and Krishnan, 2016).

Compartmentalization is a ubiquitous feature of natural biochemical pathways and a key emerging tool in synthetic biology. A widely used approach to analysing compartmental systems is through compartmental ODE models. Compartmental models have been assessed by comparing them to detailed reaction transport models and establishing a correspondence between them. This is done for various building-block reactions in signalling and metabolism. Through a detailed analysis, researchers can reveal exactly when and how compartmental models may be inaccurate, the consequences for both natural and engineered biological analysis and how this can be used to improve their predictive power (Menon et al., 2017).

Multisite modification is a basic ingredient of cell signalling networks and a basic way of encoding substrate function. The gap between the behaviour of multisite modification in isolation (intrinsics kinetics) and that as part of a pathway has been bridged. CPSE researchers have shown a range of effects the pathway can have on the qualitative behaviour of these systems, including behaviour that cannot be observed by the system in isolation. This reveals many basic systems aspects of the coupling of a pathway and a kinetic module, with applications in systems biology, synthetic biology and more generally in chemical information processing.

Researchers in the group of Dr. Peter DiMaggio, at Imperial College, have discovered a novel enzyme expressed in malaria, PSE7T, that methylates histones to control processes involved in evading the host immune response (Chen et al., 2016). Specifically, the mass spectrometry platform developed in Dr. DiMaggio’s group revealed that PSE7T methylates lysines 4 and 9 on histone variant H3. Methylation of these specific lysines was previous linked to antigenic variation, a process by which the parasite changes expression of its surface proteins to avoid recognition and clearance by the host. Discovery of the enzymes that regulate these evasion mechanisms, such as PSE7T, provide important therapeutic opportunities for targeting malaria.

Systems biology is also being studied as a means to improve bioprocess development. Dr. Kiparissides and coworkers are investigating the use of systems engineering methodologies combined with wet-lab experiments to elucidate the impact of bioprocessing conditions both macroscopically (biomass/product titre) and metabolically (pathway up/down regulation, product yields). The group has developed and/or adapted a number of Monte Carlo based techniques that allow representative sampling of large solution spaces in underdetermined LP problems commonly met in Systems Biology. Subsequent use of Multivariate Analysis (MVA) techniques enables the analysis of distinct cellular physiologies (or cell lines) from a metabolic perspective and the identification of key metabolic nodes or pathways that present significantly divergent behaviour.

References


Application Domain

Energy Systems Engineering

Contributed by Gbemi Oluleye

Energy Systems Engineering is receiving increasing attention as we transition to a Low-to-Zero carbon society. New advances in Process Systems Engineering address the development of efficient, sustainable and environmentally friendly energy systems at different scales, and sub-application areas like Carbon Capture and Storage (CCS), renewables and Energy Storage. Computational modelling represents a powerful approach to support provision of possible, and plausible futures for the fuel and technology mix in energy systems, and how these systems will transition from their current state to future low-carbon or even net carbon-negative states. Energy Systems modelling also determines the impact of technology and resource costs and availabilities, and emissions constraints on the costs and feasibilities of achieving these transitions. Modelling occurs at various energy system scales from individual commercial and industrial buildings (i.e. single-user systems) through to communities (Distributed Energy Systems and Micro-grids), cities (Urban Energy Systems), national and global scales. Multiple groups within CPSE have strands of research in all the aforementioned scales. Single-user energy systems (Fraga, Mac Dowell, Thornhill, Papageorgiou, Sharifzadeh, and Brandon), Distributed Energy Systems and Micro-grids (Fraga, Shah, Markides, Papageorgiou), Urban Energy Systems (Shah, Mac Dowell), National Energy Systems (Hawkes, Guillén-Gosálbez, Mac Dowell, Shah, Sharifzadeh), to Global Energy Systems (Hawkes). Sub-application domains with strands of research by CPSE academics are Energy Storage, Renewables, Carbon Capture and Storage, Bioenergy and Hydrogen.

Single-User Systems

The variability challenge inherent in the sizing of complex renewables-based energy systems in a mining operation is addressed in Amusat et al. Their proposed energy system for this single-user is shown in Fig. 1. Soltani et al. evaluated the performance of post-combustion CO₂ capture using Monoethanolamine (MEA) retrofitted to a 600MW Combined Cycle Gas Turbine (CCGT-CCS). They discovered that the reboiler energy consumption (for LP steam at 140 – 160 °C) is reduced with an increase in MEA concentration, leading to a reduction in solvent flow rates (Fig. 2).

In Xenos et al. the flexibility of an air-separation plant is assessed through a novel multi-period Mixed Integer Linear Programming (MILP) optimisation framework, which integrates production scheduling with Demand Response (DR) programs. The objective is to determine optimal decisions for the operating conditions within the plant while safely providing services to the electricity grid. Considering an electrical power plant, an MILP model is developed in Zhang et al. for the fair design of integrated carbon capture, transport and storage infrastructure in a power plant. The model determines the emission capture locations and the capture amount of the power plant with CCS. Sharifzadeh et al. use a steady-state multi-objective optimisation framework to integrate solid-oxide fuel cells to improve the overall efficiency of a thermal power plant. The Pareto optimal solutions demonstrated a strong trade-off between the profitability and the range of safe operating window. Xenos et al. proposes an MILP framework which integrates optimal operation and maintenance applied to a network of compressors of large compressors of chemical plants.

![Figure 1: Proposed integrated energy system for mining operation. The solid black lines show the possible electricity network while the broken red lines represent heat.](image1.png)

![Figure 2: Effect of MEA concentration in lean solvent on the reboiler energy efficiency (90% CO₂ capture, rich loading:0.5, 0.20 lean loading).](image2.png)

![Figure 3: Schematic diagram of SOFC-CCHP and conventional system.](image3.png)
Moving from the industrial sector to buildings, a multi-criteria assessment (by combination of an improved Gray Relational Analysis (GRA) approach and an entropy-weighting method) is applied in Jing et al.\textsuperscript{7} to rank the performance of SOFC-based combined heating and cooling power system for public buildings in China. A Mixed Integer Non-Linear Programming (MINLP) model is proposed Jing et al.\textsuperscript{8} for an SOFC based CCHP system for a hospital (Fig. 3).

**Distributed Energy Systems and Micro-grids**

Future energy systems scenarios feature distributed energy systems because conventional energy systems face challenges with regard to growing global energy needs, emissions and the need for alternative energy resources. Wouters et al.\textsuperscript{9} formulated an MILP model to design a neighbourhood-based energy system, considering the trade-off between total annualised costs and electricity system unavailability. In Alvarado et al.\textsuperscript{10} a Technology Selection and Operation (TSO) model is proposed for the design of distributed energy systems. The model is formulated as an MILP. The TSO model is unique because decisions are influenced by real-time price models of electricity thereby providing meaningful insights that allow stakeholders to make technology investment decisions with greater assurance. Delangle et al.\textsuperscript{11} develop an MILP model to select and operate the best mix of technologies to run a district heating network, including optimisation of the pipe layout. The methodology considers spatial expansion features.

Micro-grids are decentralised networks that integrate electricity and heat generation systems close to the consumption points. Silvente and Papageorgiou\textsuperscript{12} propose an MILP formulation to optimally manage energy and heat generation, storage and demand for micro-grids (Fig. 4). Their MILP formulation is capable of dealing with the operational scheduling problem of a micro-grid to exploit the benefits of the flexibility in the energy demand. Zhang et al.\textsuperscript{13} applies an MILP model for energy consumption scheduling among smart homes using a micro-grid system. The daily power consumption tasks are scheduled by coupling environmental and economic sustainability in a multi-objective optimisation with \( \varepsilon \)-constraint method. The model is demonstrated on a case study of 30 smart homes with the same living habits under three price schemes.

**Urban Energy Systems**

Urban Energy Systems modelling comprises a series of processes such as the production, transportation, storage, conversion and distribution of energy, with the ultimate objective of satisfying the energy demand of end-users. Their design requires making complex decisions about technology choice, location and fuels. Zheng et al.\textsuperscript{14} perform a real world case study in urban China to quantify the potential savings from retrofit design of Urban Energy Systems (flow diagram in Fig. 5). A robust MINLP model is developed, which rigorously optimizes the configuration, sizing and operation of the system from both demand and supply side perspectives, accounting for the time-dependant demand profiles as well as the equipment sizing and part load operations for various technologies.
National Energy Systems

Decarbonising electricity systems on a national scale is essential to mitigating climate change. Vijay et al. present two novel methods for estimating the interrelated changes in wholesale electricity and reserve prices for the UK electricity system: (1) a unit-commitment model to simulate the short-run marginal cost of generation; and (2) a new reserve price model that mimics actual operation of the electricity market. They considered the overall energy mix rather than just a change in renewable capacity. A multi-objective optimisation framework is applied by Limleamthong et al. to redesign the UK electricity mix. The method considers economics, environmental, and social aspects simultaneously and combines multi-objective optimization and bi-level optimization to explore Pareto fronts in a systematic manner. Still on electricity systems Heuberger et al. apply a new electricity-systems model (formulated as MILP) based on a hybrid between generation expansion and a unit commitment model to quantify and qualify the role and value of CCS, energy storage and renewable energy on a national scale. An output of the model is shown in Fig. 6.

Global Energy Systems

Modelling of global energy systems is appropriate for evaluating the impact of novel technologies and fuels. The scenarios generated by energy-systems models on a global scale provide a picture of the range of possible and plausible pathways to a low-carbon future and achieving a limit to global warming of below 2 °C by 2100. In Bosch et al. the first temporally explicit Geospatial Information System (GIS) methodology to characterise the global onshore wind energy potential with respect to topographical features, land use and environmental constraints is developed. It builds up from highly spatially and temporally resolved raw data to capacity potentials for almost every country in the world. A representative output of this model is shown in Fig. 7.

Chavez-Rodriguez et al. present an energy-system model for natural gas in the Southern Cone region. The model uses the TIMES_ConoSur gas and power optimisation model from 2012 to 2030 and has two distinctive model features: (1) a relatively high level of spatial disaggregation in order to capture the diversity of energy landscapes within the region, and (2) a new and more credible approach to characterising upstream resource extraction and processing. Gambhir et al. combine an integrated assessment model (TIAM-Grantham) representing CO2 emissions (and their mitigation) from the fossil-fuel combustion and industrial sectors, coupled with a model covering non-CO2 emissions (GAINS) to analyse the emissions and cost impacts of mitigation of non-CO2 greenhouse gases at a global level, in scenarios aimed at meeting a range of long-term temperature goals.

Few et al. use a multi-region energy system model, TIAM (TIMES integrated assessment model), to assess the impact of a range of conventional and shale-gas cost and availability assessments on mitigation scenarios aimed at maintaining global warming below 2 °C by 2100, with a 50% likelihood (Fig. 8).

The critical notion of how feasible it is to achieve long-term mitigation goals to limit global temperature change is explored in Gambhir et al., using a model inter-comparison of three integrated assessment models (TIAM-Grantham, MESSAGE-GLOBIOM and WITCH) harmonized for
socio-economic growth drivers using one of the new shared socio-economic pathways (SSP2), to analyse multiple mitigation scenarios aimed at different temperature changes in 2100. The schematics of the process used is in Fig. 9. In Napp et al., lessons from historical energy transitions were used to create a set of diagnostic tests to assess the feasibility of an example 2°C scenario (generated using the least-cost optimization model, TIAM-Grantham). The key assessment criteria included the rate of deployment of low-carbon technologies and the rate of transition between primary energy resources. The rates of deployment of key low-carbon technologies were found to exceed the maximum historically observed rate of deployment of 20% per annum.

Figure 8: Share of global primary energy supplied by (solid lines) all natural gas, and (dashed lines) shale gas in 2 °C consistent energy systems in a range of cost scenarios for conventional and shale gas. High-cost conventional, low-cost shale (HC_LS); medium-cost conventional, medium-cost shale (MC_MS); and low-cost conventional, high-cost shale (LC_HS).

Figure 9: Schematic illustrating the process used to derive emissions scenarios from CO₂ budgets and iterate for target temperature levels where appropriate. RCP:Representative Concentration Pathway; GHG:greenhouse gas; FF:fossil fuels and industry; MAC:marginal abatement cost; MOHC:Met Office Hadley Centre; NMVOC:non-methane volatile organic compounds; and MAGICC:Model for Greenhouse-gas-Induced Climate Change.

Sub-application Domain: Energy Storage
The integration of Energy Storage makes low carbon technologies dispatchable and increase their energy conversion efficiency and flexibility. Heuberger et al. apply a new electricity systems model (formulated as an MILP model) based on a hybrid between generation expansion and a unit commitment model to quantify and qualify the role and value of grid-level energy storage. The model is able to provide insights on the total system costs and available storage capacity (Fig. 10).

Figure 10: Optimal capacity mix (right y-axis), and total system cost (left y-axis) under 2035 conditions depending on the level of grid-level energy-storage capacity availability.

Mariaud et al. propose an optimal TSO model for photovoltaic and battery storage. The model schematic is shown in Fig. 11. A steady-state MILP approach is employed to formulate the optimisation problem. Patsios et al. propose an integrated electro–thermo–chemical modelling methodology that integrates reduced-order models of battery-cell chemistry, power electronic circuits and grid operation into a computationally efficient framework. Thermal energy storage is considered in Pantaleo et al. 26.

Figure 11: Schematic description of the data inputs and output components of the TSO model.

Sub-application Domain: Renewables
Renewable energy technologies play a crucial role in most climate-change-mitigation scenarios because of their ability to significantly reduce carbon emissions in the electricity and heat sectors (the largest carbon dioxide emitting activities globally). Energy-system modelling in this sub-domain serves as a decision support framework for assessing technology investments. Amusat et al. developed a framework for bi-criteria sizing of standalone hybrid energy systems. Their methodology combines stochastic modelling of renewables with chronological simulation for performance evaluation. Bosch et al. characterise the technical and economic potential of global onshore wind energy based on a temporally-explicit Geospatial Information System (GIS). Pantaleo et al. perform a techno-economic assessment of a hybrid solar-biomass combined heat and power
systems composed of a gas turbine, and bottoming Organic Rankine cycle as shown in Fig. 12.

Mariaud et al. present a TSO model to optimise photovoltaic (PV) and battery systems. Herrando and Markides perform a techno-economic assessment of a hybrid PV/solar-thermal (PVT) system for distributed electricity and hot-water provision in a typical house in London, UK. Sharifzadeh et al. develop a comprehensive framework where design and operation of the electricity grid are considered simultaneously and the uncertainties in the wind and solar generation as well as demand are systematically taken into account. The case of retrofitting the current UK electricity grid to include 50% renewable power generation by 2030 is used as a case study.

Sub-application Domain: Carbon Capture and Storage (CCS)

CCS will be a critical component of a portfolio of low-carbon energy technologies required to combat climate change. Its contribution to timely and cost-effective decarbonisation of the energy system is widely recognised. Soltani et al. simulate an MEA-based post-combustion CO₂ capture process applied to a 600 MW natural-gas-fired power plant with exhaust-gas recycle. Their results indicate that whilst gas CCS will require more energy, or will be more costly, per tonne of CO₂ captured, than coal CCS, it will require appreciably less energy, or be much less costly, per MWh of low-carbon power produced, which is after all, the point. Addressing the intensive capital-cost challenge of CCS, Cabral et al. apply process integration and intensification approaches to increase the net efficiency (by 3%) of oxy-combustion processes, and this reduces the £/MWh of electricity by 13%. Bio-energy with Carbon Capture and Storage (BECCS) is an important greenhouse-gas removal (GGR) technology with the potential to provide significant reductions in atmospheric CO₂ concentration. Bui et al. assess the influence of solvent selection and biomass co-firing proportion on recoverable heat, energy efficiency and carbon intensity of a 500 MW pulverized fuel BECCS system. The results of the Techno-Economic Study of Biomass to Power with CO₂ capture (TESBiC) project, that entailed desk-based review and analysis, process engineering, optimisation as well as primary data collection from some of the leading pilot demonstration plants is presented in Bhave et al. They considered eight options with a wide range of Technology Readiness Level (TRL) from 4 (bench-scale test rig) to TRL 6-7 (demonstration) as shown in Fig. 13.

Sub-application Domain: Bioenergy

Biomass grown and harvested sustainably is considered an appropriate substitute for fossil fuels. Bio-energy with carbon capture and sequestration, or BECCS can achieve an overall negative CO₂ balance when carefully deployed. Bui et al. address gap in efficiency improvement in biomass-fired plants via waste-heat recovery from the boiler system. Pantaleo et al. propose a novel hybrid biomass-CSP combined CHP system and a thermo-economic methodology suitable for the thermodynamic, thermal and financial appraisal of such a plant in different energy-demand segments. The methodology adopts a combination of a solar-energy yield assessment, combined-cycle thermodynamic modelling and energy-efficiency analysis, a simplified representation of the energy demand, a cost assessment, and a discounted cash-flow analysis.

Sub-application Domain: Hydrogen

Hydrogen has been widely discussed as a notable future alternative to replace oil and natural gas delivering high-quality and clean energy in transport and heat
sectors. The relevance of hydrogen as an energy carrier is that it can be generated from a variety of primary energy sources, renewable and non-renewable, and hence it can span the several phases of a transition towards energy futures that meet sustainable goals. Based on a logistic diffusion model, future hydrogen demand is expected to reach 50% of the market share by 2070\textsuperscript{34}. Moreno-Benito,\textsuperscript{36} proposed a multi-period spatial-explicit MILP model for the development of hydrogen supply-chain infrastructures. The framework is able to perform simultaneous optimisation of the range of production technologies, scales, transportation modes and CCS systems across time and space is addressed as shown in Fig. 14.

**Final Thoughts**
The use of optimization models for improved decision-making at preliminary stages of design allows better insight into the synergies between different energy sources. Energy-system models are nonetheless subject to a number of limitations. Firstly, these models rely on the availability of data of sufficiently high quality when in reality there are multiple uncertainties around key inputs such as socio-economic trends, technology innovations and fossil-fuel resources. Secondly, these models are often based upon single optimal decisions, considering near-optimal solutions can provide rational decision options that account for practical considerations, and decision makers are likely to favour such an approach over the analysis of a single optimal solution. Thirdly, political, social and behavioural factors are challenging to include within the framework of an energy-systems model. Fourthly, these models typically assume perfect foresight of future energy needs, technology costs and fossil-fuel supply costs, which will not be the case in practice. The future direction of research in Energy Systems Engineering will address these limitations.

![Figure 14: Hydrogen and CO_2 pathways included in the optimisation framework. LH2 is liquid hydrogen, GH2 is gas hydrogen, SMR is steam methane reforming, BG is biomass gasification, WE is water electrolysis.](image-url)

References


Application Domain

Environmental Systems Engineering

Contributed by Miao Guo

Environmental Systems Engineering involves the management and planning of water, air and land resources, which underpin multiple functional ecosystem services to provide benefits for wellbeing. Driven by a range of environmental challenges, e.g., climate change, energy and resource insecurity, decision making in Environmental Engineering has evolved from cost optimal design to problems featured by conflicting environmental, engineering and economic objectives and constraints. In addition, the environmental system complexity, e.g., interdependency of land and water, interaction of environmental resources with economic sectors requires analyses, planning and operation from a whole-system perspective. PSE research in Environmental Systems Engineering involves the development and applications of mathematical models to improve design, operation and control of environmental processes and develop emerging environmental systems.

Multiple groups within CPSE are conducting research in areas such as mathematical modelling, optimisation, process design, and life-cycle assessment (LCA) to address open research challenges and inform decision-making on planning and operation of environmental processes and systems. The summary below gives an overview of recent advances by these groups.

Multi-scale modelling of microalgae culture

Algae referring to eukaryotic organisms either unicellular (microalgae) or multicellular (macroalgae), along with cyanobacteria have been regarded as third or fourth-generation (3G or 4G) feedstock for biorefinery. The desirable traits of algal strains compared with terrestrial plants include high CO₂ sequestration capacity, tolerance to a wide range of conditions and seasonal variations, rapid production cycle and high photosynthesis efficiency. To advance understanding of the underlying photosynthetic mechanisms, CPSE researchers have developed mathematical models to project the microalgae growth and photosynthetic process in response to environmental variables e.g. light conditions. Bernardi, Nikolaou and co-authors have developed a state model to describe the dynamics of photoproduction and photoregulation, which is validated using experimental data. This represents a step forward in capturing microalgae growth in response to variable light conditions notably critical in large-scale industrial culturing systems. The predictive capability and applicability of the state model was further improved by introducing photoacclimation process rules, which act at a slower time scale compared to processes of photoproduction, photoinhibition and photoregulation. Such a semi-empirical modelling approach balancing simplicity and reliability enables applications in monitoring, control and optimisation of microalgae production systems. In contrast to kinetic modelling, del Rio-Chanona et al., developed a robust artificial neutral network (ANN) model that is capable of simulating the microalgal lutein photoproduction dynamic process. The experimental verification demonstrated the predictive power of this ANN model, which could facilitate future investigation of lutein bioproduction process control and optimization.

Landscape optimisation for terrestrial plants

In contrast to 3G/4G aquatic biomass, terrestrial biomass refers to higher plant species underpinned by different photosynthesis pathways (e.g. Calvin-Benson-Bassham and Hatch-Slack cycles). Such terrestrial plants are reliant on land and water resources, which form the landscape generating multiple functional ecosystems services for human society (e.g. food, and energy supply). Land use change due to increasing food...
demands and expanding bio-sectors occur against a backdrop of ongoing global degradation of environmental systems and ecosystem services. This emerging area has attracted increasing research attention, where mathematical optimisation has been applied to inform landscape design and land-use planning. Galán-Martín et al.\(^6\) presented a multi-objective linear-programing (LP) model to optimise sustainable agricultural systems, where the rainfed and irrigated arable lands were allocated to meet food demands and water, land-capacity constraints. The land competition between food and non-food (e.g. bioenergy) systems has been addressed in the optimisation research presented by Guo et al.\(^7\), where a mixed integer linear programming (MILP) model was formulated to account for land allocation for different plants (including food and non-food crops) to deliver multiple ecosystem services.

**Multi-criteria design of sustainable bio-refineries**

Aquatic and terrestrial biomass can be used as feedstock for bio-refining where a wide range of biomass organic molecules can be converted into a plethora of bio-products. Such biorefinery is interdependent with land, air and water resources, which underpin the biomass provisioning. Multi-decision criteria are involved in decision-making on refinery sustainability, e.g., climate change, water use, acidification, eutrophication in addition to economic feasibility. Research efforts were made to reduce the dimensionality of key performance indicators (KPI). An enhanced $\epsilon$-constraint algorithm was proposed by Copado-Mendez et al.\(^8\), which integrated dimensionality reduction techniques with pseudo/quasi-random sequences. In addition, multivariate statistical analyses were applied to identify the correlations between LCA decision criteria metrics.\(^9\) The results suggested that despite most LCA metrics being correlated, there is no single LCA indicator capable of representing overall environmental performances.

In addition, modelling has been applied to inform the design and operation of biorefinery. The research carried out at CPSE includes design, economic and environmental evaluation\(^10\), kinetic modelling and optimisation\(^11\) in different applications ranging from single-site technology\(^12\) to multi-site network/supply chain design\(^13,14\). The modelled biomass feedstock focused on lignocellulosic\(^15,16\) and 3G algae\(^17\); technologies range from thermochemical\(^18\) to biochemical routes\(^19\). Below we will take several examples to give an overview of the sustainability design of biorefinery. At single-technology level, a numerical model was proposed by Niu et al.\(^20\) to understand the enzymatic hydrolysis of cellulose, where the operating conditions (e.g. cellulase composition and loading) were modelled. At network-design level, Zhang et al.\(^21\) applied a reaction network flux balance method to screen over 100 synthesis pathways to identify the most promising low-carbon biopolymers. Limleamthong et al.\(^22\) presented a systems approach based on Data Envelopment Analysis (DEA) and LP to screen the 125 amine-based solvents for CO$_2$ capture, where LCA KPIs and technical performances (e.g. CO$_2$ solubility, surface tension) were considered. At supply-chain level, biorefinery planning under uncertainties was modelled\(^23\) by extending the state task network (STN) formulation in order to reduce the computational time for solving large-scale supply chain design problems.

Carbon capture and storage/utilisation as part of biorefining future has been highlighted as negative-emission technologies and shown as a promising pathway to mitigate climate change\(^24\). The techno-economic evaluation was applied as a screening tool to highlight the potential roles of bio-power CCS (biomass-derived power generation and carbon capture and storage) in meeting 2050 carbon reduction targets\(^25\). A whole-systems model (shown in Fig 2) was developed\(^26\) to analyse the bioenergy with CCS (BECCS) network and value chains and examine whether BECCS deliver sustainable negative emissions. This study concluded that carbon positive or negative are dependent on BECCS deployment conditions. BECCS along with other carbon-capture technologies were further analysed under food-energy-water nexus context and were concluded as decarbonisation routes to enhance the environmental profiles of food production\(^27\).

![Figure 2: Sub-model overview\(^28\). Biomass water, carbon, energy and land footprints were calculated using region specific data. The power plant modelled by IECM BECCS hydro, energy and carbon efficiencies were derived from supply chain and power plant models. The time-dependent carbon efficiency of BECCS was derived from GHG balance over a 50-year time horizon.](image)

### Biorefining for waste recovery

Another biorefinery feedstock is waste, which has the potential to realise the resource-circular economy. Systems analyses and evaluation have been adopted to understand the waste recovery potential, where the carbon-containing and nutrient-rich organic waste in solid, liquid and gas phases represents promising resources. Anaerobic digestion (AD) is one of the most widespread resource-recovery technologies in the wastewater treatment and bio-solids sector. The generated biogas is often used for onsite combined-
heat-and-power (CHP) generation, but can also be upgraded and injected into the natural-gas grid, compressed as transport fuels or for wider applications. AD in conjunction with separation and recovery technologies (e.g. ion exchange) was studied to understand the trade-offs between economic and environmental sustainability. AD coupling with fuel-cell technologies have been investigated to estimate its techno-economic feasibility and emission reduction potential in the UK, where diverse waste sources have been considered (e.g. municipal solid waste, agricultural waste and energy corps). This research confirmed the significance of AD as a profitable technology to generate biogas, which has a theoretical potential to meet 5.5% UK primary energy demands by 2030; AD was also suggested as an environmentally desirable technology for fuel-cell adoption, which can further enhance the AD environmental benefits by reducing over 50% CO₂ release and other pollutant emissions. Research has also been conducted on organic solid waste treatment, e.g., the integrative DEA and LCA method to assess food management problems.

### Water treatment

The world water baseline scenario for year 2050 estimates that 5500 km³ of freshwater will be required to meet the water demand for manufacturing, electricity production and domestic use, which represents an increase of 55% from current global demand. As given in Fig 3, water systems entail sources (e.g., groundwater and surface water), water-treatment (e.g. purification) and use, where water treatment and desalination play a dominant role in the water supply chain. To address the research challenges on how to efficiently treat water resources and wastewater, to ensure sustainable supply of safe quality water, CPSE researchers have explored process synthesis and network planning of water-treatment processes. Koleva et al. presented a superstructure optimisation model to synthesise water-treatment technologies. The methodology was demonstrated in seawater desalination and surface-water-treatment optimisation problems.

The water-energy nexus has also been investigated. Take shale gas as an example. Shale gas is a promising energy source to address increasing global energy demands. One of the main challenges for promoting cleaner production of shale gas lies in the management of flowback water, i.e., the large quantity of high-salinity wastewater generated from shale-gas extraction. Thereby, optimisation models have been developed to design flowback water treatment systems, which are of particular interest for reducing water footprint and enhancing overall sustainability of the shale-gas process. The resulting MINLP superstructure optimisation model considered alternative technologies (direct on-site reuse, pretreatment before desalination, indirect reuse and proposal) for managing shale-gas flowback water. Desalination of shale-gas flowback water was optimised by enhancing water recovery and reducing brine disposal in order to maximise system energy efficiencies. However, uncertainties in well data (e.g. flow rates, salinities) can hamper the process design tasks. Onishi et al. further developed a mathematical optimisation model to design a desalination process treating shale-gas flowback wastewater under uncertainty. Uncertainty was also considered in the scenario-based optimisation study by Lira-Barragán et al., where water network synthesis was formulated as an MILP model to optimise the annual costs for treating flowback water. The management of flowback wastewater was optimised from the whole shale-gas system and supply-chain perspective, by considering the wastewater quality and spatial–temporal variations as part of the optimisation framework.

### Low-carbon and sustainable energy systems

The energy supply and demand sectors not only interact with water and land resources but they are also major GHGs contributors. They have been included within the national and regional decarbonisation agenda. A large body of research has been conducted within CPSE in response to the energy sustainability design challenge. Overall, modelling research advances have considered decision spaces across energy supply and demand sides, addressing sustainability design under long-term strategic planning and mid/short-term operational decisions. Another research challenge is dealing with uncertainty in the energy system. Recent progress in these areas is exemplified below.

Amusat et al. optimised renewable-energy supply planning (e.g. sizing, solar and hydraulic power technology options) under deterministic decision-making. They pointed out the limitations of deterministic optimisation in addressing the variability in renewable inputs. Charitopoulos and Dua proposed a multi-parametric optimisation tool adopting DEA and LP modelling to compare and rank electrical generation technologies in the order of efficiency and sustainability. An approach was also presented by Limleamthong to combine bi-level programming and multi-objective optimisation under uncertainty. The derived optimal solutions for electrical power systems that address the cost and environmental objectives simultaneously. Galán-Martín et al. proposed a decision-making tool adopting DEA and LP modelling to compare and rank electrical generation technologies in the order of efficiency and sustainability. The emerging role of fuel cells and hydrogen in energy decarbonisation has been highlighted. Hydrogen as a low-carbon fuel is expected to play key roles to meet energy demands in the transport, residential and commercial sectors.
Brandon and Kurban analysed the role of fuel cells in three hydrogen-production pathways namely power-to-gas, power-to-power and gas-to-gas (Fig 4).

Figure 4: Schematic diagram of main energy conversion pathways (power-to-gas, power-to-power and gas-to-gas) in a renewable energy integrated energy system. FC=fuel cell.

Jing et al. developed a multi-criteria decision-making approach to evaluate the technical, economic and environmental perspectives of solid-oxide fuel cells in conjunction with cooling heating and power (SOFC-CCHP) and their applications in different building categories. Jing et al. formulated an MINLP model to optimise the SOFC-CCHP design to achieve cost-optimal and minimised greenhouse gases (GHGs). Overall, SOFC-CCHP demonstrated higher efficiency compared with benchmark combustion CHP system. Socio-economic and environmental variables (e.g. climate, energy price) were also identified as influencing factors using multi-criteria decision-making systems.

Sustainability of built environment and multiple sectors

Interdependent from natural resources and environment, built environment refers to the human-made surroundings. Thus, it is important to address natural resources and sustainability in planning and operation of built environment. CPSE has carried out research to improve the eco-profiles of built environments by modelling and optimising design, operation and control of the processes and networks involved. Our research ranges from individual building to building clusters e.g. industrial park. Carreras et al. presented a surrogate-based optimisation model to design the thermal insulation in a building, where decision spaces (environmental and economic objectives) were reduced by dimensionality-reduction techniques.

They reduced computational complexity by constructing surrogate models based on input-output data derived from a commercial simulator (EnergyPlus). An MILP model was formulated to optimise the technology and operation of photovoltaic and battery storage systems and their integration in UK commercial building selection, which resulted in cost and environmental benefits.

Research has also been conducted on building clusters, where different functional buildings are considered simultaneously. An optimisation model was developed to design an integration strategy for urban power and thermal energy under regional industrial park context. A mathematical modelling framework was also proposed to evaluate and optimise the life-cycle environmental impacts of mega-event project. A single objective optimisation was formulated to minimise the greenhouse gas (GHG) over the project life cycle, covering project construction, staging and post-event site development and operations. Parkes et al. used the London Olympic Park as case study to demonstrate the model functionality and applications in decision-making support, where the construction materials have been highlighted as the main contributors to greenhouse gases (GHGs). The results also suggested that the post-event site redevelopment could play a significant role in GHG profile minimisation. These studies demonstrated how a systems approach and mathematical programming can be used to inform the planning and decision-making of large-scale built environment problems.

In addition to the above research overview, researchers within CPSE have also explored cross-sector interactions and addressed decarbonisation pathways from a macro-system perspective. This has been achieved via a bottom-up approach in conjunction with top-down modelling (e.g. input-output models). Multi-objective optimisation was combined with environmentally extended input–output tables to explore the GHG-minimised pathways for different economic sectors to meet the US national decarbonisation goals (see Fig 5).


Application Domain

Supply Chains of the Future

Contributed by Di Zhang

Supply chains of the future will have to deal with a host of new challenges facing us in the 21st century.

The activities in the supply-chain area essentially address enterprise-wide and supply-chain optimisation mainly for process industries. Supply chains of the future will have to deal with new challenges from the following aspects, both conceptual (i.e. new methods and numerical algorithms) and practical (novel applications and case studies): incorporating sustainability aspects as additional objectives rather than as constraints on design and operation strategies; handling multiple sources of uncertainty in an efficient manner; customisation of products and services closer to the point of use; commercialising innovation; optimising the various uses of biomass for energy and materials production; designing infrastructure for carbon dioxide capture and utilisation; and decarbonising supply chains in an optimal manner.

Owing to their temporal and spatial scales, supply-chain problems are often decomposed into a three-level hierarchy: strategic level, planning level and operational level. Our model-based approaches use abstraction and high-fidelity mathematical modelling together with powerful numerical methods to answer particular questions at different hierarchical levels, from the design of supply chains, to the detailed scheduling of batch plants, and to the solution of the vehicle routing problem.

Multiple groups within CPSE have strands of research in the application domain of future supply chains. Supply-chain problems have been mainly studied by the following CPSE academic research groups: Brandon; Guillén-Gosálbez; Hawkes; Mac Dowell; Markides; Papageorgiou; Shah; and Wiesemann. Indicative recent research works in this application domain, covering different aspects by following a similar conceptual approach, are summarised below.

Process industry. Process-industry supply-chain optimisation is a critical aspect to modern enterprises and a flourishing research area. It enhances decision-making towards the development of optimal infrastructures (assets and network) and the optimisation of planning decisions. Medina-González et al. propose a systematic methodology to support risk management in optimisation under uncertainty, with applications to strategic planning of chemical supply chains. The methodology can handle several risk metrics simultaneously, facilitate decision-making and avoid subjectivity when selecting the final solution. The objective of the work from Cadavid-Giraldo et al. is to take advantage of technological advances for improving the economic and environmental performance of the cement industry (see Fig. 1). A mathematical approach based on multi-objective mixed integer linear programming (MILP) is applied to decide whether technological updating projects should be undertaken at a given manufacturing stage, in order to meet both environmental and economic objectives.

Gas supply chain. Spatially-explicit multi-period MILP models are commonly used in the strategic design of gas supply chains, including natural gas, shale gas and hydrogen. Calderón et al. propose an MILP model for the strategic design of Bio synthetic natural-gas (BioSNG) supply chains, which determines procurement of feedstock, plantation of energy crops and different models for transportation of feedstock and final products. Cogeneration of power and heat from the gasification process is considered. It is suggested that government schemes are essential for the economics of future BioSNG projects. Guerra et al. propose an optimisation framework for shale-gas supply-chain design from the shale formation to final product demand centres, and from fresh water supply for hydraulic fracturing to water injection and/or disposal. It integrates water management with the design and planning of the shale-gas supply chain. Another work related to shale gas is provided by Mahdi et al., which addresses the question of interactions between design and operational decisions in shale-gas networks. Sensitivity analysis of important decisions is conducted, including well length, well arrangement, number of fractures, fracture distance, CO2 injection rate and shut-in scheduling. The results indicate that the interactions between design and operational decisions...
are significant and that they should be optimised simultaneously. Balcombe et al. present a comprehensive compilation of estimated CO$_2$ and methane emissions across the global natural-gas supply chain, with the aim of providing a balanced insight for academia, industry, and policy makers. This work finds large variations across facilities, regions and gas-well types. The majority of emission estimates are low across the supply chain but there are a select few larger emitters that disproportionately contribute to total emissions: the appearance of super-emitters. Moreno-Benito et al. formulate an MILP model for the development of hydrogen supply-chain infrastructures. A hierarchical solution procedure is applied for solving the computationally intense problem, which decides the range of production technologies, scales, transportation modes and CCS systems across time and space (see Fig. 2).

Biofuels. Optimal-design biofuel supply-chain networks enhance economic, environmental and social performance. MILP modelling is deployed for the biofuel supply-chain design and applied to different country case studies. Panteli et al. develop an MILP model to maximise profits and assess the systematic design and planning of a spatially explicit, multi-feedstock, multi-period and multi-echelon lignocellulosic biomass-to-bio-based products supply chain. Biomass yield uncertainty is considered in a follow-up work. Delval et al. present a biocombustion system modelling toolkit, soft-linking an agent-based model with an optimisation model to support the development of advanced biofuels towards a more sustainable energy market. An approach based on the Analytic Hierarchy Process (AHP) is introduced by Wheeler et al., where a single-objective model is constructed to provide a unique Pareto solution of the original MOO model. The AHP is combined with a mixed-integer non-linear programming (MINLP) formulation that simplifies its application. The proposed approach is applied to a sustainable sugar/ethanol supply-chain design in Argentina. Based on a State Task Network formulation, Medina-González et al. propose a methodology, which considers biomass quality in the management of energy supply chains. The approach is capable of optimisation under uncertainties, considering multiple selection criteria and accounting for the material quality effect. Santibañez-Aguilar et al. present a mathematical programming model for the optimal planning of a distributed system of biorefineries (see Fig. 3) that considers explicitly the uncertainty associated with the supply-chain operation as well as the associated risk. The potential of the proposed approach is demonstrated through its application to the production of biofuels in Mexico, considering multiple raw materials and products.

Figure 2: Evolution of the hydrogen supply chain infrastructure over time.

Food. For food supply chains, Georgiou et al. present a preliminary high-level approach to holistic modelling and benchmarking of large-scale supply-chain systems involving multiple technologies, processes and stages. The modelling framework discussed offers the option of improvement for both the operational system efficiency and technological performance of the supply chain. Through this approach technological models as well as supply-chain optimisation models can be used for the characterisation of the processes within the supply-chain system.

Figure 3: Super structure of the proposed methodology.
References


Dr Salvador Acha Izquierdo
salvador.acha06@imperial.ac.uk

Dr Jesus Algaba Fernandez
j.algaba16@imperial.ac.uk

Dr Praveen K Bains
p.bains@imperial.ac.uk

Dr Andrea Bernardi
a.bernardi13@imperial.ac.uk

Dr Thomas Bernet
t.bernet@imperial.ac.uk

Dr Jasmin Cooper
jasmin.cooper@imperial.ac.uk

Dr Nathaniel Cooper
nathaniel.cooper@imperial.ac.uk

Dr John Crawshaw
j.crawshaw@imperial.ac.uk

Dr Antonio del Rio Chanona
a.del-rio-chanona@imperial.ac.uk

Dr Silvia Di Leccce
silvia.di-leccce@imperial.ac.uk

Dr Dimitra Gialama
dimitra.gialama07@imperial.ac.uk

Dr Sara Giarola
s.giarola10@imperial.ac.uk

Dr Miao Guo
miao.guo@imperial.ac.uk

Dr Andrew Haslam
a.haslam@imperial.ac.uk

Dr Gan Huang
g.huang@imperial.ac.uk

Dr Dauda Ibrahim
d.ibrahim@imperial.ac.uk

Dr Diana Iruretagoyena Ferrer
d.iruretagoyena09@imperial.ac.uk

Dr Franciska Jalil Vega
franciska.jalil12@imperial.ac.uk

Dr Maria Guadalupe Serratos Jimenez
m.jimenez-serratos@imperial.ac.uk

Dr Suela Jonuzaj
s.jonuzaj13@imperial.ac.uk

Dr Zoltan Kis
z.kis10@imperial.ac.uk

Dr Sergei Kucherenko
s.kucherenko@ic.ac.uk

Dr Kamal Kurian
kkuriyan@ic.ac.uk

Dr Niccolo Le Brun
niccolo.le-brun11@imperial.ac.uk

Dr Dimitrios Letsios
d.letsios@imperial.ac.uk

Dr Ryan Luong
vu.luong05@imperial.ac.uk

Dr Matthias Mersch
matthias.mersch1@imperial.ac.uk

Dr Ignacio Moya Ramirez
i.moya-ramirez@imperial.ac.uk

Dr Edward O’Dwyer
e.odwyer@imperial.ac.uk

Dr Gbemi Oluleye
o.oluleye@imperial.ac.uk

Dr Oluwagbemisola Oluleye
o.oluleye@imperial.ac.uk

Dr Oyeniyi Oyewunmi
oyeniyi.oyewunmi12@imperial.ac.uk

Dr Antonio Marco Pantaleo
a.pantaleo@imperial.ac.uk

Dr Maria Papathanasiou
maria.papathanasiou11@imperial.ac.uk

Dr Felipe Antonio Perdomo Hurtado
f.perdomo-hurtado@imperial.ac.uk

Dr Miguel Pineda Rodriguez
m.pineda@ucl.ac.uk

Dr Carlos Pozo Fernandez
c.pozo-fernandez@imperial.ac.uk

Dr Srikanth Ravipati
s.ravipati@ucl.ac.uk

Dr Sara Riera Curt
s.riera-curt@imperial.ac.uk

Dr Romain Réocreux
r.reocreux@ucl.ac.uk

Dr Paul Sapin
p.sapin@imperial.ac.uk

Dr Julia Schumann
j.schumann@ucl.ac.uk

Dr Jian Song
jian.song@imperial.ac.uk

Dr Jamie Speirs
jamie.speirs@imperial.ac.uk

Dr Isaac Sugden
i.sugden@imperial.ac.uk

Dr Kyungjae Tak
k.tak@imperial.ac.uk

Dr Marcus Tillotson
m.tillotson@imperial.ac.uk

Dr Koen Van Dam
k.van-dam@imperial.ac.uk

Dr Viktor Voulgaropoulos
v.voulgaropoulos@imperial.ac.uk

Dr Kai Wang
kai.wang@imperial.ac.uk

Dr Tao Wen
t.wen@imperial.ac.uk

Dr Ioannis Zacharoudiou
i.zacharoudiou@imperial.ac.uk
CPSE Staff Contacts

Academic Staff
Imperial College London

Department of Chemical Engineering

Professor Claire S. Adjiman
c.adjiman@imperial.ac.uk

Dr Cleo Kontoravdi
cleo.kontoravdi08@imperial.ac.uk

Dr J Krishnan
j.krishnan@imperial.ac.uk

Professor Amparo Galindo
a.galindo@imperial.ac.uk

Professor Geoffrey C. Maitland
g.maitland@imperial.ac.uk

Professor Christos Markides
c.markides@imperial.ac.uk

Professor Erich Müller
e.muller@imperial.ac.uk

Professor George Jackson
g.jackson@imperial.ac.uk

Professor Constantinos C. Pantelides
c.pantelides@imperial.ac.uk

Dr Benoit Chachuat
b.chachuat@imperial.ac.uk

Professor Nialay Shah
n.shah@imperial.ac.uk

Professor Nina F. Thornhill
n.thornhill@imperial.ac.uk

Dr Dr Panos Parpas
p.parpas@imperial.ac.uk

Department of Earth Science and Engineering

Professor Nigel Brandon
n.brandon@imperial.ac.uk

Business School

Professor Wolfram Wiesemann
ww@imperial.ac.uk

Emeritus and Honorary Academics

Dr Graham Elkes
graham.elkes@imperial.ac.uk

Professor Michael Georgiadis
mgeorg@auth.gr

Dr Gonzalo Guillén-Gosálbez
gonzalo.guillen.gosalbez@chem.ethz.ch

Department of Computing

Dr Ruth Misener
r.misener@imperial.ac.uk

...continued
Emeritus and Honorary Academics

...continued

Professor John Perkins
john.perkins@imperial.ac.uk

Professor Efstratios (Stratos) Pistikopoulos
e.pistikopoulos@imperial.ac.uk

Professor Berc Rustem
b.rustem@imperial.ac.uk

Professor Paul Rutter
p.rutter@imperial.ac.uk

Dr Salvador Garcia Muñoz
s.garcia-munoz@imperial.ac.uk

Dr Paul Oram
p.oram@imperial.ac.uk

Emeritus and Honorary Academics

UCL (University College London)

UCL Department of Chemical Engineering

Professor I. David Bogle
d.bogle@ucl.ac.uk

Dr Vivek Dua
v.dua@ucl.ac.uk

Professor Eric S. Fraga
e.fraga@ucl.ac.uk

Dr Federico Galvanin
f.galvanin@ucl.ac.uk

Dr Luca Mazzei
l.mazzei@ucl.ac.uk

Professor Lazaros Papageorgiou
l.papageorgiou@ucl.ac.uk

UCL Department of Biochemical Engineering

Dr Matteo Salvalaglio
m.salvalaglio@ucl.ac.uk

Professor Eva Sørensen
e.sorensen@ucl.ac.uk

Dr Michail Stamatakis
m.stamatakis@ucl.ac.uk

UCL Department of Electronic and Electrical Engineering

Dr Mahdi Sharifzadeh
m.sharifzadeh@ucl.ac.uk

Support Staff

Miss Senait Selassie
s.selassie@imperial.ac.uk

UCL Department of Biochemical Engineering

Dr Alexandros Kiparissides
alex.kiparissides@ucl.ac.uk

UCL Centre for Artificial Intelligence

Professor Marc Deisenroth
m.deisenroth@ucl.ac.uk
**PhD Projects 2018**

**Katie Addison**  
*Chemical Biology of histone methyltransferases*  
Supervisor: Dr Peter DiMaggio  
Start date: October 2014

**Zainab Ahmed**  
*Chemical Biology*  
Supervisor: Dr Jawahar Krishnan  
Start date: October 2017

**Abdullah Al kindi**  
*Hybrid-Flexible Nuclear-Solar Power*  
Supervisor: Prof Christos Markides  
Start date: October 2018

**Ibrahim M. Algunaibet**  
*Contribution to the Optimisation of Energy Systems Considering Life Cycle Sustainability Criteria*  
Supervisor: Dr Gonzalo Guillén-Gosálbez  
Start date: March 2018

**Sakhr Alhuthali**  
*Understanding the Interplay between Upstream and Downstream Bioprocessing by a Sequence of Mathematical Models*  
Supervisor: Dr Cleo Kontoravdi  
Start date: October 2015

**Deemah Aljuhani**  
*Supply Chain Optimisation-Based Approaches Using Mathematical Programming Techniques*  
Supervisor: Prof Lazaros Papageorgiou  
Start date: September 2016

**Amjad Saeed Al-Qahtani**  
*Optimisation of Life Cycle Assessments of Carbon Management Technologies*  
Supervisor: Dr Gonzalo Guillén-Gosálbez  
Start date: November 2016

**Juman Al-Saqlawi**  
*Residential Roof-Top Solar PV Systems: Techno-Economic Feasibility and Enviro-Economic Impacts*  
Supervisor: Dr Niall Mac Dowell  
Start date: October 2015

**Tamador Alsobaie**  
*Generation of Lung Epithelium from hIPS Cells in 3D Dynamic Culture*  
Supervisor: Prof Athanasios Mantalaris  
Start date: May 2012

**Jae Sik An**  
*Investigation of Liquid-Film Characteristics in Downwards Co-Current Gas–Liquid Annular Flows with Laser-Induced Fluorescence Techniques*  
Supervisor: Prof Christos Markides  
Start date: February 2014

**Humera Ansari**  
*CO₂ Enhanced Shale Gas Recovery*  
Supervisor: Prof Geoffrey Maitland  
Start date: November 2016

**Athanasios Antonakoudis**  
*Model-Driven Optimisation of Bioprocess Design*  
Supervisor: Dr Cleo Kontoravdi  
Start date: January 2018

**Sara Antunes Febra**  
*Ring Formation in a Statistical Associating Fluid Theory Framework*  
Supervisors: Prof Claire Adjiman, Prof George Jackson and Prof Amparo Galindo  
Start date: March 2014

**Robert Arnold**  
*Integrated Assessment of Alternative UK Energy Scenarios*  
Supervisor: Prof Niall Shah  
Start date: October 2018

**Husain Baqael**  
*Sustainability-Based Assessment and Optimization of Ionic Liquid Systems using Life Cycle Thinking*  
Supervisors: Prof Jason Hall and Dr Benoît Chachuat  
Start date: October 2018

**Radu Baltean-Lugojan**  
*Structure Exploitation in Large Scale Non-Convex Optimization*  
Supervisor: Dr Ruth Misener  
Start date: April 2015

**Rodrigo Barbosa**  
*Developing a Numerical Platform for the Prediction of Anti-Cancer Quality Attributes in Biotherapeutics*  
Supervisor: Dr Cleo Kontoravdi  
Start date: October 2016

**Davide Bascone**  
*Modelling and Optimisation of the Nuclear Fuel Cycle*  
Supervisor: Prof Eric Fraga  
Start date: March 2015

**Moiz Bohra**  
*Optimising Qatar’s Transition to Renewable Energy through Model-Based Analysis*  
Supervisor: Prof Nilay Shah  
Start date: April 2016

**Matthew Booth**  
*Development of a Turbidostat Platform to Improve Algal Growth Kinetics*  
Supervisor: Dr Alexandros Kiparissides  
Start date: September 2017

**Francesco Borghesan**  
*Assessment and Optimization of Site Utilities*  
Supervisor: Prof Nina Thornhill  
Start date: November 2016

**Jonathan Bosch**  
*Temporally-Explicit and Spatially-Resolved Global Wind Energy Potentials as Inputs to Energy Systems Models*  
Supervisor: Dr Adam Hawkes  
Start date: October 2014

**David Bowskill**  
*Improving Lattice Energy Models for Utilisation in Crystal Structure Prediction Techniques*  
Supervisors: Prof Claire Adjiman and Prof Constantinos Pantelides  
Start date: October 2017

**Patrick Brandl**  
*Techno-Economic Multi-scale Screening of CO₂ Capture Technologies*  
Supervisor: Dr Niall Mac Dowell  
Start date: November 2017
Pantelis Broukos  
**Urban Energy Systems**  
Supervisors: Prof Nilay Shah and Dr James Keirstead  
Start date: September 2012

Renato Cabral  
**A Quantification of the Value Provided by Flexible Oxy-Combustion CCS to the UK Energy System**  
Supervisor: Dr Niall Mac Dowell  
Start date: October 2015

Junjun Cai  
**Elucidation and Control of Signal Transduction, Metabolism and Gene Regulation in Cellular Systems**  
Supervisor: Dr Jawahar Krishnan  
Start date: July 2016

Raúl Calvo Serrano  
**Process Optimisation and Sustainability Analysis**  
Supervisor: Dr Gonzalo Guillén Gosalbez  
Start date: April 2016

Juan Sebastian Campos Salazar  
**A Multigrid Approach to SDP Relaxations of Sparse Polynomial Optimization Problems**  
Supervisor: Dr Panos Parpas  
Start date: October 2013

Harry Cardenas Mansilla  
**Theory and Molecular Modelling of Gas Adsorption in Nanopores**  
Supervisors: Prof George Jackson and Prof Erich Müller  
Start date: November 2015

Francesco Ceccon  
**Special Structure Detection in MINLP**  
Supervisor: Dr Ruth Misener  
Start date: October 2016

Benjamin Paul Chamberlain  
**Machine Learning**  
Supervisor: Prof Marc Deisenroth  
Start date: October 2014

Artemis-Danae Charalambidou  
**A Combined Mathematical and Experimental Investigation of Multiphase Flow, Nutrient Transport and Mammalian Cell Metabolism in Continuous Bioreactors**  
Supervisor: Dr Alexandros Kiparissides  
Start date: September 2018

Maria Anna Chatzopoulou  
**Optimisation of High-Efficiency Combined Heat and Power Systems for Distributed Generation**  
Supervisor: Prof Christos Markides  
Start date: October 2014

Jingyi Chen  
**Materials Science and Engineering**  
Supervisor: Prof Nigel Brandon  
Start date: November 2015

Andres Chico  
**Optimisation Model for the Implementation of Second Generation Biorefineries with Economic, Environmental and Social Objectives**  
Supervisor: Prof Eric Fraga  
Start date: June 2018

Solène Marine Chiquier  
**Deployment of Negative Emissions Technologies around the World**  
Supervisor: Dr Niall Mac Dowell  
Start date: September 2018

Ridwanur Chowdhury  
**Electrochemical Science and Engineering**  
Supervisor: Prof Nigel Brandon  
Start date: September 2017

Charalampos Christodoulou  
**Modelling and Optimization of Absorption during Coating of Pharmaceutical Tablets**  
Supervisors: Dr Luca Mazzei and Prof Eva Sorensen  
Start date: October 2015

Cheng-Ta Chu  
**Global Electricity Sector Decarbonisation Modelling**  
Supervisor: Dr Adam Hawkes  
Start date: October 2015

Constanza Cunicheo Melgarejo  
**The Combination of Bioenergy, Natural Gas and CCS for Negative Emissions**  
Supervisors: Dr Niall Mac Dowell and Prof Nilay Shah  
Start date: November 2015

Habiba Ahut Daggash  
**Quantifying the Value of Negative Emissions Technologies for Climate Change Mitigation in Energy Systems**  
Supervisor: Dr Niall Mac Dowell  
Start date: October 2016

Matthew Thomas Darby  
**First-Principles Simulations of Molecular Phenomena on Bimetallic Hydrogenation Catalysts**  
Supervisor: Dr Michail Stamatakis  
Start date: October 2013

Nat Dilokthanakul  
**Cognitive Integration and Collective Synchronization in Self-organizing Spiking Neural Network**  
Supervisor: Prof Marc Deisenroth  
Start date: October 2014

David Dorantes Romero  
**Capture and Analysis of Process Connectivity and Topology**  
Supervisor: Prof Nina Thornhill  
Start date: October 2012

Michael Ehrenstein  
**Optimisation of Supply Chains Threatened by Extreme Events**  
Supervisor: Dr Gonzalo Guillén Gosalbez  
Start date: September 2016

Jude Ejeh  
**An Optimization Framework for the Oil and Gas Supply Chain**  
Supervisor: Prof Lazaros Papageorgiou  
Start date: September 2016

Melis Ekinci  
**CLICK-seq: A Novel Proteomic Tool to Map the Epigenome of Disease**  
Supervisor: Dr Peter DiMaggio  
Start date: October 2014

Karl Fairhurst  
**Molecular Simulation of Associating Fluids, Using a Combination of Molecular Dynamics (MD) and Monte Carlo (MC) Simulations, with Coarse-Grained Models**  
Supervisors: Prof Erich Müller and Prof George Jackson  
Start date: October 2015
Mathilde Fajardy  
Can Bioenergy with Carbon Capture and Storage Deliver Sustainable and Resource Efficient Negative Emissions?  
Supervisor: Dr Niall Mac Dowell  
Start date: October 2016

Maziar Fayaz Torshizi  
Modelling and Coarse-Grained Simulation of Polymers and Liquid Crystals  
Supervisor: Prof Erich Müller  
Start date: October 2015

Mohammed Fazel  
Near-Wall and Interfacial Studies of Gas–Liquid Horizontal Stratified Flows  
Supervisor: Prof Christos Markides  
Start date: November 2017

José Morais  
An in Silico-In Vitro Approach to Leukaemia  
Supervisors: Prof Athanasios Mantalaris and Dr Nicki Panoskaltsis  
Start date: October 2016

Pedro de Oliveira Filho  
Development, Implementation and Application of a Language for Modelling Uncertainty in Design and Process Optimisation  
Supervisor: Prof Eric Fraga  
Start date: October 2015

Joana Filipa Salgado Soares dos Santos  
Towards Personalised Medicine: Developing a 3D leukaemia biomimicry  
Supervisors: Prof Athanasios Mantalaris and Dr Nicki Panoskaltsis  
Start date: July 2015

Anton Firth  
Novel Process to Remediate Land and Water Contaminated by Acid Mine Drainate, with a Focus on South Africa  
Supervisor: Dr Niall Mac Dowell  
Start date: September 2017

Nicholas Francesco Francia  
Towards a Finite-Temperature Screening of Crystal-Energy Landscapes  
Supervisor: Dr Matteo Salvalaglio  
Start date: March 2018

Andrea Gayon Lombardo  
Electrochemical Science and Engineering  
Supervisor: Prof Nigel Brandon  
Start date: November 2017

Caroline Ganzer  
Pathways for the Integrated Decarbonisation of the UK Energy System and Industry  
Supervisor: Dr Niall Mac Dowell  
Start date: October 2018

Solomos Georgiou  
Operational and Technological Energy Efficiency and Decarbonisation Potential of Supply Chains  
Supervisors: Prof Nilay Shah and Prof Christos Markides  
Start date: October 2015

Shubhechhya Ghosal  
Distributionally Robust Capacitated Vehicle Routing  
Supervisor: Prof Wolfram Wiesemann  
Start date: September 2017

Ilaria Gimondi  
Molecular Modelling of Nucleation and Polymorphic Transformations of Organic Crystals  
Supervisor: Dr Matteo Salvalaglio  
Start date: November 2015

Victoria Gkoutzioupa  
A Framework for the Development, Analysis and Validation of Mathematical Models of Upstream Unit Operations Used in the Production of Recombinant Proteins as Part of an Integrated Whole Bioprocess Modelling Platform  
Supervisor: Dr Alexandros Kiparissides  
Start date: September 2017

Andrés González Garay  
Multi-Scale Modelling and Optimisation of Sustainable Chemical Processes  
Supervisor: Dr Gonzalo Guillén Gosálbez  
Start date: October 2016

Lucian Gomoescu  
Advanced Techniques for Formal Validation of Complex Mathematical Models  
Supervisors: Prof Constantinos Pantelides and Dr Benoît Chachuat  
Start date: April 2016

Edward Graham  
The Integrated Molecular and Process Modelling of Carbon Dioxide Capture in Amine Solvents  
Supervisors: Prof Claire Adjiman, Prof George Jackson and Prof Amparo Galindo  
Start date: December 2014

Eliana Grant  
Solvent Effects on an SNAr Reaction; Mechanism, Kinetics, Solvent Design  
Supervisors: Prof Claire Adjiman, Prof Amparo Galindo and Prof Alan Armstrong  
Start date: April 2015

Yingjian Guo  
Modelling the Role of Gas T&D Infrastructure in Future Low Carbon Energy Systems  
Supervisor: Dr Adam Hawkes  
Start date: October 2015

James Wilford Hamilton  
Long Term Development of the Investment Supply Chain in Energy  
Supervisor: Dr Adam Hawkes  
Start date: March 2017

Asmaa Harraz  
Computer-Aided Molecular and System Design of Solar-Cooling Technologies using Absorption Processes  
Supervisors: Prof Christos Markides and Dr Niall Mac Dowell  
Start date: September 2017

Chiara Heide  
Cell-Free Protein Synthesis inside Compartmentalized Vesicle-Based Artificial Cells  
Supervisor: Dr Cleo Kontoravdi  
Start date: December 2015

Clara Heuberger  
Electricity Systems Modelling for Optimal Design and Technology Valuation  
Supervisors: Dr Niall Mac Dowell, Prof Nilay Shah and Dr Iain Staffell  
Start date: January 2015
<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>Supervisor/Supervisors</th>
<th>Start Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pooya Hoseinpoori</td>
<td>Decarbonisation of Heat in the UK</td>
<td>Dr Niall Mac Dowell</td>
<td>August 2017</td>
</tr>
<tr>
<td>Chunbing Huang</td>
<td>Stochastic Collisional Exchange Processes: Theoretical Investigation and Numerical Platform Development</td>
<td>Dr Federico Galvanin</td>
<td>September 2017</td>
</tr>
<tr>
<td>Khairul Aminin Ibrahim</td>
<td>Fuel Cells</td>
<td>Prof Nigel Brandon</td>
<td>January 2015</td>
</tr>
<tr>
<td>Frederike Jaeger</td>
<td>Flow of Fluids through Porous Media with Application to Membranes: from the Molecular to the Continuum Scale</td>
<td>Prof Erich Müller and Prof Omar Matar</td>
<td>October 2014</td>
</tr>
<tr>
<td>Elnaz Jamili</td>
<td>Model-Based Optimal Control of Non-Viral Gene Delivery</td>
<td>Dr Vivek Dua and Dr Michail Stamatakis</td>
<td>November 2012</td>
</tr>
<tr>
<td>Caroline Jones</td>
<td>Quantification and Monitoring of Fluid Phase Behaviour and Trapping in Geological Carbon Sequestration Sites</td>
<td>Prof Geoffrey Maitland</td>
<td>October 2016</td>
</tr>
<tr>
<td>Sanket Sayaji Kamthe</td>
<td>Reinforcement Learning for Robotics and Control</td>
<td>Prof Marc Deisenroth</td>
<td>October 2016</td>
</tr>
<tr>
<td>Ashkan Kavei</td>
<td>Fuel Cells</td>
<td>Prof Nigel Brandon</td>
<td>September 2015</td>
</tr>
<tr>
<td>Siti Khalit</td>
<td>Thermodynamic Modelling of Acid Gas Absorption</td>
<td>Prof Claire Adjiman, Prof George Jackson and Prof Amparo Galindo</td>
<td>May 2015</td>
</tr>
<tr>
<td>Christoph Kirmse</td>
<td>Waste-Heat Recovery and Power Generation with Reciprocating Motion</td>
<td>Prof Christos Markides</td>
<td>December 2014</td>
</tr>
<tr>
<td>Michail Klontzas</td>
<td>Bone Tissue Engineering</td>
<td>Prof Athanasis Muntalakis</td>
<td>October 2014</td>
</tr>
<tr>
<td>Esma Koca</td>
<td>Global Launch Decisions and Product Rollover Strategies for SMEs</td>
<td>Prof Wolfram Wiesemann</td>
<td>September 2013</td>
</tr>
<tr>
<td>Mariya Koleva</td>
<td>Optimisation of Wastewater Systems</td>
<td>Prof Lazaros Papageorgiou</td>
<td>March 2013</td>
</tr>
<tr>
<td>Lukmaan Ebrahim Kolia</td>
<td>Development of a Kinetic Model for Green Microalgae Using Genetic Programming and Optimisation Techniques</td>
<td>Dr Alexandros Kiparissides and Dr Frank Baganz</td>
<td>September 2016</td>
</tr>
<tr>
<td>Loukas Kollias</td>
<td>Molecular Modelling of the Templated Growth of Hierarchical Materials</td>
<td>Dr Matteo Salvalaglio</td>
<td>September 2016</td>
</tr>
<tr>
<td>Clea Kolster</td>
<td>Evaluation of dynamic CO₂ Injection in the North Sea</td>
<td>Dr Niall Mac Dowell</td>
<td>October 2014</td>
</tr>
<tr>
<td>Scott Qingyuan Kong</td>
<td>Optimisation-Based Process Synthesis of Emerging Reaction Pathways for Bio-Based Polymers and Monomers: An effective Mixed Integer Linear Programming Approach</td>
<td>Prof Nilay Shah</td>
<td>October 2014</td>
</tr>
<tr>
<td>Stefanos Konstantinopoulos</td>
<td>Free Energy Calculations for Crystal Structure Prediction</td>
<td>Prof Constantinos Pantelides</td>
<td>December 2017</td>
</tr>
<tr>
<td>Pavlos Kotidis</td>
<td>Model-Driven Optimization of Bioprocess Design</td>
<td>Dr Cleo Kontoravdi</td>
<td>October 2017</td>
</tr>
<tr>
<td>Spyridon Kournopoulos</td>
<td>State-of-the-Art Thermodynamic Models for Mixtures Containing Water, Carbon Dioxide, Salts and Hydrocarbons in Bulk and in Confinement</td>
<td>Prof George Jackson and Prof Amparo Galindo</td>
<td>September 2016</td>
</tr>
<tr>
<td>Georgia Kouyialis</td>
<td>Symmetry and Degeneracy in Nonconvex Optimisation Problems: Application to Heat Recovery Networks</td>
<td>Dr Ruth Misener</td>
<td>October 2014</td>
</tr>
<tr>
<td>Elnaz Jamili</td>
<td>Exploiting Symmetry in Mixed Integer Non-Linear Optimisation</td>
<td>Dr Ruth Misener</td>
<td>January 2018</td>
</tr>
<tr>
<td>Ye Seol (Lauren) Lee</td>
<td>Integrated Computer-Aided Molecular and Process Design: Optimal Solvent Design for CO₂ Chemical Absorption Process</td>
<td>Prof Claire Adjiman, Prof George Jackson and Prof Amparo Galindo</td>
<td>October 2017</td>
</tr>
<tr>
<td>Duncan Leeson</td>
<td>Development of a Modelling Framework for Energy-Efficient Oil Refining</td>
<td>Prof Niall Mac Dowell, Dr Niall Mac Dowell</td>
<td>October 2014</td>
</tr>
</tbody>
</table>
David Leng  
**Fault Propagation, Detection and Analysis in Process Systems**  
Supervisor: Prof Nina Thornhill  
Start date: October 2013 (Part-time)

Emily Leonidou  
**Small Molecule-Mediated Knockdown of DOT1L as a New Epigenetic Therapeutic Approach for Leukaemia**  
Supervisor: Dr Peter DiMaggio  
Start date: September 2017

Yunjie Liao  
**Development and Validation of a Model of Energy Differential Production across the Liver Sinusoid**  
Supervisors: Prof David Bogle and Dr Nathan Davies (UCL Division of Medicine)  
Start date: October 2015

António Lima Grilo  
**An Integrated Mathematical Model of Cell Cycle, Metabolism and Apoptosis of mAB-Producing GS-NS0 cells**  
Supervisor: Prof Athanasios Mantalaris  
Start date: June 2016

Phantisa Limleamthong  
**Systematic Computer Aided Process Engineering Tools for the Optimal Design and Planning of Sustainable Chemical Processes**  
Supervisor: Dr Gonzalo Guillén-Gosálbez  
Start date: April 2016

Tom Lindeboom  
**Molecular Origins of the Thermodynamic Properties, Phase Separation Behaviour and Structure of Biomolecules in Aqueous Solutions**  
Supervisors: Prof Amparo Galindo and Prof George Jackson  
Start date: October 2015

Ely sia Lucas  
**Modelling of the Water-Energy-Food Nexus via Environmentally Extended Input-Output Tables Coupled with Optimisation**  
Supervisor: Dr Gonzalo Guillán-Gosálbez  
Start date: October 2018

Matthieu Lucek  
**Abnormal Event Management for the Process Industries using Heterogeneous Data from Disparate Sources**  
Supervisor: Prof Nina Thornhill  
Start date: October 2016

Saulius Lukauskas  
**Mining of Next Generation Sequencing (NGS) and Affinity-Purification Mass Spectrometry (AP-MS) data to identify chromatin targets of epigenetic regulators**  
Supervisor: Dr Peter DiMaggio  
Start date: October 2014

Maximilian Lularevic  
**A Combined Multi-Scale Modelling and Experimental Investigation of the Effects of Lactate Metabolism on Mammalian Cell Bioprocessing**  
Supervisors: Dr Alexandros Kiparissides, Dr Cleo Kontoravdi and Dr Colin Jaques  
Start date: September 2015

Teng Martin Ma  
**Elucidating the Strong Interactions Between Pt-Pd Nanoalloys and TiO2 Support with Neural Network Potentials**  
Supervisor: Dr Michail Stamatakis  
Start date: October 2018

Robert MacFarlane  
**The Generation of 3D Mineralised Implants using Human Induced Pluripotent Stem Cells for Bone Tissue Engineering Applications**  
Supervisor: Prof Athanasios Mantalaris  
Start date: October 2013

Elli Makrydaki  
**Design and Fabrication of an Artificial Golgi Reactor**  
Supervisor: Dr Cleo Kontoravdi  
Start date: October 2016

Amit M. Manthanwar  
**Multiscale Design, Robust Optimisation and Robust Model Predictive Control of Fuel Cell Energy Systems**  
Supervisor: Prof Efstratios Pistikopoulos  
Start date: February 2012

Veselina Marinova  
**Crystal Growth of Active Pharmaceutical Ingredients**  
Supervisor: Dr Matteo Salavaglio  
Start date: June 2016

Calum J McIntosh  
**Controlling the Quality of Novel Glycoprotein Therapeutics**  
Supervisor: Dr Cleo Kontoravdi  
Start date: November 2015

Govind Menon  
**Elucidating Temporal and Spatial Aspects of Cellular Information Processing**  
Supervisor: Dr J Krishnan  
Start date: October 2014

Adrian Millea  
**Information Geometry and Deep Learning**  
Supervisor: Prof Marc Deisenroth  
Start date: November 2015

Miten Mistry  
**Integrating Mixed Integer Nonlinear Programming and Satisfiability Modulo Theories for Next-Generation Optimisation Algorithms**  
Supervisor: Dr Ruth Misener  
Start date: October 2015

Luciana Miu  
**A Socio-Technical Framework to Drive the Introduction of Energy Efficiency Measures for Private Households in the UK**  
Supervisor: Dr Adam Hawkes  
Start date: October 2016

Maher Morsi Hassan Mohamed  
**Experiments of Phase-Change Transport Processes**  
Supervisor: Prof Christos Markides  
Start date: July 2018

Hannah Moran  
**Experiments and Simulations of Direct Steam Generation for Concentrating Solar Power**  
Supervisor: Prof Christos Markides  
Start date: September 2017

Riccardo Moriconi  
**Gaussian Processes, Reinforcement Learning**  
Supervisor: Prof Marc Deisenroth  
Start date: October 2016
Diego Armando Moya Pinta
Development and Application of Global Energy Systems Modelling with the MUSE Framework
Supervisor: Dr Adam Hawkes
Start date: October 2017

Mohamad Muhieddine
A Computer-Aided Framework for the Design of Solvents and Processes
Supervisors: Prof Claire Adjiman, Prof Amparo Galindo and Prof Alan Armstrong
Start date: October 2018

Ahmad Najjaran Kheirabadi
Advanced Solar-Cooling Technologies using Absorption Processes
Supervisor: Prof Christos Markides
Start date: October 2016

Peter Keene North
Urban Energy Systems
Supervisor: Prof Nilay Shah
Start date: May 2014

Nur Redzuan Nur Jazlan
The Design of Optimal Solvents in Reactive Systems
Supervisors: Prof Amparo Galindo and Prof Claire Adjiman
Start date: October 2016

Funmilayo Olabode
Parameter Estimation Using Neural Networks
Supervisor: Dr Vivek Dua
Start date: January 2014

Simon C W Olofsson
Advanced Optimisation and Control for Bioreactors
Supervisors: Dr Ruth Misener and Dr Marc Deisenroth
Start date: May 2016

Andreas Olympios
Multifidelity Techno-Economic and Whole-Energy-System Modelling of Heat Sector Decarbonisation
Supervisor: Prof Christos Markides
Start date: October 2018

Mengzheng Ouyang
Catalytic Chemistry and Electrochemistry of Solid Oxide Fuel Cells
Supervisor: Prof Nigel Brandon
Start date: April 2015

Samata Pandey
Antibody Engineering
Supervisor: Dr Cleo Kontoravdi
Start date: November 2016

Arun Pankajakshan
Optimal Design of Experiments in Microreactor Platform for the Automated Identification of Reaction Kinetics
Supervisors: Dr Federico Galvanin and Prof Asterios Gavrilidis
Start date: January 2017

Konstantinos Papanikolaou
First-Principles Kinetic Monte Carlo Simulations of Hydrogenation Reactions on Alloy Catalysts
Supervisor: Michail Stamatakis
Start date: November 2017

Janith Petangoda
Model-Based Reinforcement Learning for Robotics
Supervisor: Prof Marc Deisenroth
Start date: September 2017

Catalina A. Pino-Muñoz
Mathematical Modelling of Vanadium-Based Redox Flow Batteries
Supervisor: Prof Nigel Brandon
Start date: October 2015

Yoga Wienda Pratama
Modelling and Optimization of Energy Systems for Net Zero Emissions
Supervisor: Dr Niall Mac Dowell
Start date: April 2018

Andres Chico Proanio
Optimization in Biorefineries from Wastes
Supervisor: Prof Eric Fraga
Start date: September 2016

Marco Quaglio
Embracing Uncertainty in the Deterministic Modelling of Kinetic Phenomena
Supervisor: Dr Federico Galvanin
Start date: September 2016

Edouard Querel
3D Interfaces for High Energy Density Na-Batteries
Supervisor: Prof Nigel Brandon
Start date: October 2017

Ussama Javed Rai
Developing Energy Storage and Demand Response Aggregation Models for Smart Energy Grid Applications in Context of Energy Transitions
Supervisor: Dr Adam Hawkes
Start date: March 2017 (Part-Time)

Shakeel Ramjanee
Towards Production Wide Optimization for Upstream Field Recovery
Supervisors: Dr Benoît Chachuat, Prof Ann Muggeridge and Prof Nilay Shah
Start date: November 2015 (Part-Time)

Hunnan Rajput
Closing the Knowledge Gap by Combining Empirical and Fundamental Models
Supervisor: Dr Benoît Chachuat
Start date: November 2018

Emma Richards
Rheology and Phase Boundary Predictions of Non-Ionic Surfactants Through Coarse Grained Molecular Modelling Using SAFT-y Mie
Supervisors: Prof Erich Müller and Prof George Jackson
Start date: October 2018

Daniel Rodriguez Vallejo
Development of a Computational Framework for the Optimisation of Chemical Processes under Uncertainty
Supervisors: Dr Benoît Chachuat and Dr Gonzalo Guillén-Gosálbez
Start date: January 2017

Andrew Russell
Non-Newtonian Fluid Selection and Stirred Vessel Design for Matched Rheology and Transport Process Similarity
Supervisor: Prof Christos Markides
Start date: October 2015

Raymond Elliott Sacks
Liquid-Water Compression of Air for Energy Storage Applications
Supervisor: Prof Christos Markides
Start date: March 2018
Steindor Saemundsson
Deep Generative Models
Supervisor: Prof Marc Deisenroth  
Start date: October 2016

Joana Salgado Soares Dos Santos
Three-Dimensional Human Leukaemia Cell Cultures
Supervisor: Prof Athanasios Mantalaris  
Start date: July 2017

Hugh Richard Raffello Salimbeni
Multi-Task Reinforcement Learning
Supervisor: Prof Marc Deisenroth  
Start date: October 2015

Manfredi Giovanni San Martino
Biomedical Engineering and Tissue Engineering
Supervisor: Dr Jawahar Krishnan  
Start date: September 2017

Victor Sanchez Tarre
A Combined Multi-Scale Modelling and Experimental Approach to Optimize Algal Culture Efficiency at the Metabolic, Process and Reactor Design Level
Supervisors: Dr Alexandros Kiparissides and Dr Gary Lye  
Start date: September 2015

Giannis Savva
Development of Novel Methods for Accelerating Kinetic Monte Carlo Simulations of Reactive Systems
Supervisor: Dr Michail Stamatakis  
Start date: October 2018

Symeon Savopoulos
Mathematical Modelling of Chronic Lymphocytic Leukaemia
Supervisors: Prof Athanasios Mantalaris and Dr Nicki Panoskaltsis  
Start date: March 2014

Oliver Schmidt
Supervisor: Dr Adam Hawkes  
Start date: October 2015

Marzia Sesini
Gas Storage and its Strategic Coordination within the EU Market: A Qualitative and Quantitative Approach
Supervisor: Dr Adam Hawkes  
Start date: October 2015

Sara Shahruddin
Detailed Understanding and Development of Wax Control Chemical (P50521): Chemical Synthesis
Supervisor: Prof Erich Müller  
Start date: September 2014

Benedict Simon
Hybrid Flow Batteries
Supervisor: Prof Nigel Brandon  
Start date: February 2018

Michael Simpson
High-Performance Positive Displacement Compression and Expansion Machines
Supervisor: Prof Christos Markides  
Start date: November 2016

Olivia Sloan
Combined CO₂ Storage and Enhanced Oil Recovery in the North Sea. Rock Heterogeneity and Flow in Geologic Systems with Low Flow Potential – Applications to Subsurface CO₂ Injection
Supervisors: Dr Sam Krevor, Dr Niall McDowell and Dr Jerome Neufeld  
Start date: October 2015

Qiao Yan Soh
Optimal Analysis, Design and Operation of Smart Estate Equipment and Systems for the Built Environment
Supervisor: Prof Nilay Shah  
Start date: October 2018

Bowen Song
Solid Oxide Fuel Cell
Supervisor: Prof Nigel Brandon  
Start date: October 2015

Graham Stevenson
Engineering Ceramic Scaffold Electrodes for Solid Oxide Fuel Cells and Solid Oxide Electrolyzer Cells
Supervisor: Prof Nigel Brandon  
Start date: September 2015

Carlos Ricardo Suarez Heredia
Development of a Combined Mathematical and Experimental Platform for the Design and Optimisation of Metabolically Balanced Nutrient Supplementation Strategies in Semi-Continuous Mammalian Cell Cultures
Supervisor: Dr Alexandros Kiparissides  
Start date: April 2016

Nixon Sunny
Development of a Modelling Framework to Support a H2-CCS Chain Network for the Decarbonisation of Cities and Industrial Clusters
Supervisors: Prof Nilay Shah and Dr Niall Mac Dowell  
Start date: October, 2017

Akara Supratak
Computing
Supervisor: Prof Marc Deisenroth  
Start date: October 2013

Rui Tan
Advanced Redox Flow Batteries for Energy Storage
Supervisor: Prof Nigel Brandon  
Start date: September 2017

Ruomu Tan
Kernel Based Nonlinear Condition Monitoring for Operation under Varying Production Regimes
Supervisor: Prof Nina Thornhill  
Start date: July 2018

Naveed Tariq
Model Based Analysis of Low Carbon Energy Pathways based on Natural Gas
Supervisors: Prof Nilay Shah and Prof Paul Fennell  
Start date: October 2012

Fabian Thiemann
Understanding Interfacial Properties of Water on Hexagonal Boron Nitride Using Machine Learning
Supervisor: Prof Erich Müller  
Start date: October 2018
Aikaterini Tsatse
Reactive Distillation: Modelling and mitigation strategies
Supervisors: Prof Eva Sørensen and Dr Matteo Salvalaglio
Start date: March 2017

Chinedu K. Unamba
Experimental Exploration of Low-Temperature Organic Rankine Cycle (ORC) Systems
Supervisor: Prof Christos Markides
Start date: March 2016

Ariel Uribe-Rodríguez
Large Scale Deterministic Mixed Integer Bilinear Global Optimization to Solve Petroleum Supply Chain Problems
Supervisors: Dr Benoît Chachuat and Dr Gonzalo Guillén-Gosálbez
Start date: October 2017

Yukun Wang
Two-phase Thermofluidic Engines for Low-Grade Heat Recovery: System Analysis and Supporting Algorithms
Supervisor: Dr Benoît Chachuat
Start date: October 2015

Oliver Watson
Solvent Design for Pharmaceutical Processes
Supervisors: Prof Claire Adjiman Prof George Jackson and Prof Amparo Galindo
Start date: September 2017

Patrick Wehner
A Systems Perspective for Addressing the Complexity of Localization in Emerging Markets
Supervisor: Prof Nilay Shah
Start date: September 2014

Johannes Wiebe
Computational Methods in Sustainable Process Systems Engineering
Supervisor: Dr Ruth Misener
Start date: September 2017

James Turner Wilson
Machine Learning and Computational Neuroscience
Supervisor: Prof Marc Deisenroth
Start date: September 2017

Stuart Fraser Wright
Liquid–Liquid Mixing in Horizontal Pipes by Transverse Jets
Supervisor: Prof Christos Markides
Start date: November 2014

Yuhua Xia
Energy, Environment, Modelling and Minerals
Supervisor: Prof Nigel Brandon
Start date: February 2015

Iván Ying Xuan
Electricity Demand-Side Response from Heavy Industrial Loads
Supervisor: Prof Nina Thornhill
Start date: October 2015

Sai Sharath Yadavalli
Computational Design of Poisoning-Resistant Catalysts for Methane-Steam Reforming
Supervisor: Dr Michail Stamatakis
Start date: October 2018

Marta Zagorowska
Condition-Based Control Systems Taking Account of Stress on Equipment
Supervisors: Prof Nina Thornhill and Dr Charlotte Skourup (ABB Norway)
Start date: September 2016

Sophia Zemenides
The Role of Metabolism and its Immune Effects in Acute Myeloid Leukaemia using a 3-Dimensional Culture System that Recapitulates the Bone Marrow
Supervisor: Prof Athanasios Mantalaris
Start date: June 2015

Yanlin Zha
Distributed Global Optimization Algorithms for Large-Scale Chemical Processes
Supervisor: Dr Benoît Chachuat
Start date: October 2018

Rui Zhang
Design of Nanostructured Catalysts for CO₂ Conversion to Methanol
Supervisors: Prof David Chadwick and Dr Benoît Chachuat
Start date: September 2017

Yizhuo Zhang
Crystal Structure Prediction for Organic Molecules in the Presence of Water
Supervisors: Prof Claire Adjiman and Prof Costas Pantelides
Start date: October 2018

Lingru (Lynn) Zheng
Understanding Fluid-Surface Interactions Using Molecular Dynamics Simulations
Supervisors: Prof Erich Müller, Prof Martin Trusler and Prof Fernando Bresme
Start date: October 2016

Kezheng Zhu
Combining Artificial Intelligence and Molecular Simulation to Develop Engineering Correlations for Fluid Properties
Supervisor: Prof Erich Müller
Start date: October 2018
PhD Graduates 2016-2017

Dr Alexandros Adam
System Modelling and Optimization Studies of Fuel Cell Based Micro-CHP for Residential Energy Demand Reduction
Supervisors: Prof Eric Fraga and Prof Dan Brett
Employer: Technical University of Athens

Dr Fo’lashade Akinmolayan
Mathematical Modelling of Clear Water Treatment Works
Supervisor: Prof Eva Sørensen
Employer: Queen Mary University

Dr Ali Salim Al-Qahtani
Technical, Economic and Environmental Impact of Future Fuel Formulations
Supervisor: Prof Nilay Shah
Employer: Research Engineer at Saudi Aramco

Dr Amos B. Aleji
Viscosity and Density of Crude Oils and their Mixtures with Injected CO$_2$
Supervisors: Prof Geoffrey Maitland and Prof Martin Trusler
Employer: Research Engineer

Dr Mark Colin Allenby
Development of a Bio-Inspired in Silico-in Vitro Platform: Towards Personalised Healthcare through Optimisation of a Bone Marrow Mimicry Bioreactor
Supervisors: Prof Athanasios Mantalaris and Dr Nicki Panoskaltsis
Employer: Postdoctoral Research Fellow in Advanced Manufacturing for Medicine, QUT

Dr Nihat Almuraikhi
Production of Red Blood Cells from Human iPS Cells in a Bioreactor
Supervisor: Prof Athanasios Mantalaris
Employer: Assistant Professor, The Medical School, King Saud University

Dr Diego Alonso-Martinez
A Computational Design Strategy for Discovering the Protein Targets of Histone Lysine Methyltransferases
Supervisor: Dr Peter DiMaggio
Employer: Research Associate in University of Groningen, Netherlands

Dr Daniel E. Aluma
Model-Based Optimisation of the Operation of Integrated Natural Gas Production, Processing and Supply Networks
Supervisors: Prof Nilay Shah and Prof Constantinos Pantelides
Employer: Shell

Dr Oluwamayowa Amusat
Design and Optimization of Hybrid Renewable Energy Systems for Off-Grid Continuous Operations
Supervisors: Prof Eric Fraga and Prof Paul Shearing
Employer: Postdoctoral Researcher at Berkeley University of California

Dr Benaiah Uchechukwu Anabaraonye
Experimental and Modelling Studies of Reservoir Minerals Dissolution Following Carbon Dioxide Injection
Supervisor: Prof Geoffrey Maitland
Employer: Research Associate at Imperial College London

Dr William Ashworth
Systems Biology of the Liver
Supervisors: Prof David Bogle and Dr Nathan Davies (UCL Division of Medicine)
Employer: Okinawa Institute of Technology Japan

Dr Vitali Avagyan
Essays on Risk and Profitability in the Future British Electricity Industry
Supervisors: Prof Berc Rustem, Dr Panos Parpas and Prof Richard Green
Employer: Research Associate in Electricity System Simulation and Optimisation at University of Edinburgh

Dr Styliani Avraamidou
Mixed-Integer Multi-level Optimization through Multi-Parametric Programming
Supervisors: Prof Athanasios Mantalaris, Prof Efstratios Pistikopoulos and Prof Nilay Shah
Employer: Research Associate at Texas A&M University

Dr Asif Bhatti
Synthesis and Design of Biological Systems under Uncertainty
Supervisor: Dr Vivek Dua
Employer: Self Employed

Dr Hao Bian
Formation, Phase Equilibrium and Gas Exchange of Methane Hydrates
Supervisor: Prof Geoffrey Maitland
Employer: Graduate Production Manager at Syngenta

Dr William Ashworth
In Vitro Erythropoiesis in a 3D Bone Marrow Biomimicry: Reproducing Physiologic Biochemical and Microenvironmental Factors Involved in Red Blood Cell Formation
Supervisors: Prof Athanasios Mantalaris and Dr Nicki Panoskaltsis
Employer: Puridify

Dr Sara Budinis
Control and Operation of Centrifugal Gas Compressors, with an Emphasis on CO$_2$ Compression
Supervisor: Prof Nina Thornhill
Employer: Energy Analyst at International Energy Agency

Dr Gizem Buldum
Investigation of Bacterial Cellulose Production in Genetically Modified Escherichia Coli
Supervisors: Prof Athanasios Mantalaris and Prof Alexander Bismarck
Employer: Assistant Professor at Marmara University

Dr Gonzalo Bustos-Turu
Integrated Modelling Framework for the Analysis of Demand Side Management Strategies in Urban Energy Systems
Supervisor: Prof Nilay Shah
Employer: Research Associate at Imperial College London

Dr Claudio Calabrese
Viscosity and Density of Reservoir Fluids under CO$_2$ Addition
Supervisors: Prof Geoffrey Maitland and Prof Martin Trusler
Employer: Technical Project Manager & Process Engineer at Procter & Gamble - Product Supply & Manufacturing
Dr Andres Calderon Vergara  
*Optimisation of Biomass-Based Supply Chains*  
Supervisor: Prof Lazaros Papageorgiou  
Employer: National Energy Technology Laboratory

Dr Vassilis M. Charitopoulos  
*Uncertainty-Aware Integration of Control with Process Operations and Multi-Parametric Programming under Global Uncertainty*  
Supervisors: Dr Vivek Dua and Prof Lazaros Papageorgiou  
Employer: Lecturer at UCL

Dr Florence Yu Tsing Chow  
*Interfacial Properties of Reservoir Fluids and Carbon Dioxide with Impurities*  
Supervisor: Prof Geoffrey Maitland  
Employer: Hong Kong Transportation Authority (Engineering)

Dr Edward James Close  
*The Derivation of Bioprocess Understanding from Mechanistic Models of Chromatography*  
Supervisors: Prof Eva Sørensen and Dr Dan Bracewell (UCL)  
Employer: Senior Consultant at Process Systems Enterprise (PSE)

Dr Ibrahim Daher  
*Salt Transport Experiments in Fractured Media*  
Supervisors: Dr John Crawshaw and Prof Geoffrey Maitland  
Employer: Qatar Petroleum

Dr Aikaterini Diamanti  
*On the Determination of the Reaction Rate Constant and Selectivity in Gas and Liquid-Phase Organic Reactions: Temperature and Solvent Effects*  
Supervisors: Prof Claire Adjiman and Prof Amparo Galindo  
Employer: Universidad de Guadalajara, Mexico

Dr Nikolaos Diangelakis  
*Model-Based Multi-Parametric Programming Strategies towards the Integration of Design, Control and Operational Optimization*  
Supervisors: Prof Efstratios Pistikopoulos and Prof Athanasios Mantalaris  
Employer: Research Associate at Texas A&M University

Dr Daniel Kunisch Eriksen  
*Molecular-Based Approaches to Modelling Carbonate-Reservoir Fluids: Electrolyte Phase Equilibria, and the Description of the Fluid–Fluid Interface*  
Supervisors: Prof Amparo Galindo and Prof George Jackson  
Employer: Researcher in Process Simulation at Shell

Dr Christina-Anna Gatsiou  
*Improving the Accuracy of Lattice Energy Calculations in Crystal Structure Prediction using Experimental Data*  
Supervisors: Prof Claire Adjiman and Prof Constantinos Pantelides  
Employer: Demokritos (Athens)/Scienomics

Dr Anastasia Georgiou  
*Generation of Mineralised Cellular Constructs Using Mouse Embryonic Stem Cells Encapsulated in Alginate Hydrogels and Cultured within a Custom-Made Rotating Wall Vessel Perfusion Bioreactor*  
Supervisor: Prof Athanasios Mantalaris  
Employer: Technological Park of Thessaloniki, Greece

Dr Cher Hui Goey  
*Cascading Effects in Bioprocessing: The impact of Cell Culture Environment on CHO Cell Behaviour and Host Cell Protein Species*  
Supervisor: Dr Cleo Kontoravdi  
Employer: Research Scientist at Autolus Ltd.

Dr Smitha Gopinath  
Supervisors: Prof George Jackson, Prof Amparo Galindo and Prof Claire Adjiman  
Employer: Researcher at Los Alamos National Lab

Dr Boram Gu  
*Modelling of RO Membrane Process Performance and Transport Phenomena for Performance Analysis and Optimisation*  
Supervisors: Prof Claire Adjiman and Prof Yun Xu  
Employer: Research Associate at Imperial College London

Dr Ching-Pang Ho  
*Optimization Algorithms for Multiscale Models*  
Supervisors: Dr Panos Parpas and Dr Wolfram Wiesemann  
Employer: Research Fellow at Imperial College Business School

Dr Rayane Hoballah  
*On the Solubility of Acid and Sour Gases in Water and Brines under Reservoir Conditions*  
Supervisors: Prof Martin Trusler and Prof Geoffrey Maitland  
Employer: Intern at Regina University

Dr Vahan Hovhannisyan  
*Multilevel Optimisation for Computer Vision*  
Supervisors: Dr Panos Parpas and Dr Stefanos Zafeiriou  
Employer: Machine Learning Engineer at nPlan

Dr Sei Howe  
*Upper and Lower Bounds for Singularly Perturbed Linear Quadratic Optimal Control Problems*  
Supervisors: Dr Panos Parpas and Prof Berc Rustem  
Employer: Associate at Morgan Stanley

Dr Panatpong Hutacharoen  
*Prediction of Partition Coefficients and Solubilities of Active Pharmaceutical Ingredients with the SAFT-y Mie Group- Contribution Approach*  
Supervisors: Prof Claire Adjiman, Prof Amparo Galindo and Prof George Jackson  
Employer: Medical Science Liaison at Janssen, Johnson & Johnson, Thailand

Dr Francisca Alejandra Jalil Vega  
*Development of a Systems Approach for Studying Decarbonisation Pathways of Heat Demand in the UK*  
Supervisor: Dr Adam Hawkes  
Employer: Research Associate at Imperial College London
Dr Suela Jonuzaj
Rational Mixture Design: Optimisation-Based Approaches
Supervisor: Prof Claire Adjiman
Employer: Research Associate at Imperial College London

Dr Nikolaos Kazazakis
Parallel Computing, Interval Derivative Methods, Heuristic Algorithms, and their Implementation in a Numerical Solver, for Deterministic Global Optimization
Supervisor: Prof Claire Adjiman
Employer: Chief Technology Officer at Octeract

Dr Gabriel Lau
Droplets: From Molecular Nanoclusters to the Atmospheric Aerosols
Supervisor: Prof George Jackson
Employer: Chief Executive Officer at Octeract

Dr Georgia Lazarou
Development of the SAFT-γ Mie Equation of State for Predicting the Thermodynamic Behaviour of Strong and Weak Electrolyte Solutions
Supervisors: Prof Amparo Galindo, Prof Georgia Jackson and Prof Claire Adjiman
Employer: Certara

Dr Kristian McAul
A Multiscale Modelling Framework for the Processes Involved in Consolidated Bioprocessing
Supervisors: Prof Nilay Shah, Dr Cleo Kontoravdi and Prof Yun Xu
Employer: CAPCO

Dr Nur Amirah Izzati Mohd Noor
Flexible Operation of Industrial Plants for Power Management and Demand-Side Response
Supervisor: Prof Nina Thornhill
Employer: Commerzbank Trading Technologies

Dr Eðvald Moller
Robust Optimisation and Modelling for Rotables in Supply Chains for Airline Technical Services: Opportunities for Improving Decision-Making
Supervisors: Prof Nilay Shah and Prof Lazaros Papageogiu
Employer: University of Iceland

Dr Ioana Nascu
Advanced Multiparametric Optimization and Control Studies for Anaesthesia
Supervisor: Prof Efstratios Pistikopoulos
Employer: Postdoctoral Research Associate at Texas A&M University and Eli Lilly and Company

Dr Dimitrios Nerantzis
Deterministic Global Optimisation and Location of Transition States
Supervisor: Prof Claire Adjiman
Employer: Research Associate, Department of Civil Engineering, Imperial College London

Dr Andreas Nikolau
Multi-Scale Modelling of Light-limited Growth in Microalgae Production Systems
Supervisor: Dr Benoît Chachuat
Employer: Research Associate at Evidera

Dr Richard Oberdieck
Theoretical and Algorithmic Advances in Multi-Parametric Optimization and Control
Supervisors: Prof Athanasios Mantalaris and Prof Efstratios Pistikopoulos
Employer: Numerical Specialist at Ørsted, Denmark

Dr Oyeniyi Alabi Oyewunmi
Supervisor: Prof Christos Markides
Employer: Research Associate at Imperial College London

Dr Anna Panteli
Biorenewable Value Chain Optimization with Multi-Layered Value Chains and Advanced Analytics
Supervisor: Prof Nilay Shah
Employer: Research Associate at Imperial College London

Dr Maria Papathanasiou
Towards Continuous Biomansufacturing a Computational Approach for the Intensification of Monoclonal Antibody Production
Supervisors: Prof Efstratios Pistikopoulos and Prof Athanasios Mantalaris
Employer: Lecturer at Imperial College London

Dr Nehal Patel
Development of Aqueous Two-Phase Separations by Combining High-Throughput Screening and Process Modelling
Supervisors: Prof Eva Sørensen and Prof Dan Bracewell (UCL, Biochemical Engineering)
Employer: GSK

Dr Carlos Perez-Galvan
Global Optimisation of Dynamic Process Systems
Supervisor: Prof David Bogle
Employer: Procter & Gamble, Newcastle

Dr Nikola Peric
Complete Search Methods and Tools for Robust Parameter Estimation
Supervisor: Dr Benoît Chachuat
Employer: Vice President at Goldman Sachs

Dr Stefan Pfenninger
Multi-Scale Energy Systems Modelling of the Renewable Energy Transition
Supervisors: Dr James Keirstead and Dr Jenny Nelson
Employer: Postdoctoral Researcher at ETH Zürich

Dr Channarong Puchongkawarin
Optimisation-Based Methodology for the Design and Operation of Sustainable Wastewater Treatment Facilities
Supervisors: Dr Benoît Chachuat and Prof David Stuckey
Employer: Lecturer at Ubon Ratchathani University, Thailand

Dr Ana Luz Quiroga Campano
Mathematical Modelling and Experimental Validation for Optimisation and Control of Mammalian Cell Culture Systems
Supervisor: Prof Athanasios Mantalaris
Employer: Postdoctoral Fellow, Department of Chemical Engineering, Imperial College London

Dr Sadia Rahman
Development of Coarse-Grained Models of Ionic and Non-Ionic Surfactants for the Molecular Simulation of Structural, Thermodynamic and Dynamical Properties
Supervisors: Prof Erich Müller, Prof Amparo Galindo and Prof George Jackson
Employer: Senior Scientist at Pfizer
Dr Jai Rajyaguru  
*Rigorous Numerical Analysis with Polynomial Models: Applications to Implicit and Differential-Algebraic Equations*  
Supervisor: Dr Benoît Chachuat  
Employer: Consultant at Capco

Dr Kristzian Ronaszegi  
*Water Splitting for Hydrogen Production for Use in Dwellings*  
Supervisor: Prof Eric Fraga  
Employer: Development Engineer and Software Developer at GreenLab Ltd

Dr Daniel Ross  
*Multi-Scale Simulation of the Transport of Hydrocarbons in Porous Engine Deposits*  
Supervisor: Prof Erich Müller  
Employer: Travelling

Dr Si Nga Sou  
*Understanding the Impact of Bioprocess Conditions on Monoclonal Antibody Glycosylation in Mammalian Cell Cultures through Experimental and Computational Analyses*  
Supervisors: Dr Cleo Kontoravdi and Dr Karen M Polizi  
Employer: Scientist at MEDIMMUNE U.K. LIMITED

Dr Flávio Strutzel  
*Economically Optimal Integrated Process and MPC Control Design*  
Supervisor: Prof David Bogle  
Employer: Process Control Engineer at Petrobras

Dr Muxin Sun  
*Design of Multi-Parametric NCO-Tracking Controllers for Linear Continuous-Time Systems*  
Supervisors: Prof Elstratios Pistikopoulos and Dr Benoit Chachuat  
Employer: Algorithm Engineer at Luckin Coffee

Dr Thapanwar Suwanmajo  
*Modelling and Systems Engineering Approaches for Elucidating Dynamics and Information Processing of Multi-Site Phosphorylation Systems*  
Supervisor: Dr Jawahar Krishnan  
Employer: Lecturer at Chiang Mai University

Dr Asma Abdulaziz Tahlawi  
*Materials Design and Modification for a Three Dimensional Hollow Fibres Bioreactor for the Production of Blood Cells*  
Supervisors: Prof Athanasios Mantalaris and Kang Li  
Employer: Saudi Aramco

Dr Quang Tran  
*Sampling Algorithms for Stochastic Programming Using Importance Sampling and Markov Chain Monte Carlo*  
Supervisors: Prof Berc Rustem and Dr Panos Parpas  
Employer: Associate at Goldman Sachs

Dr Cristian Triana  
*Towards Improved Ethanol Production from Lignocellulosic Biomass*  
Supervisors: Prof Eric Fraga and Prof Eva Serensen  
Employer: Process Systems Enterprise

Dr Argyro Tsipa  
*An Integrated Experimental/Modelling Approach Connecting Transcriptional Regulation and Microbial Growth Kinetics in Bacterial Cell Cultures*  
Supervisor: Prof Athanasios Mantalaris  
Employer: Postdoctoral Fellow, Innovation and Knowledge Centre for Synthetic Biology, Imperial College London

Dr Thapanet Usakanup  
*An Integrated Experimental and Modelling Approach for the Study of Apoptosis in GS-NS0 Cell Cultures*  
Supervisor: Prof Athanasios Mantalaris  
Employer: Lecturer, Department of Biotechnology, Silpakorn University

Dr Avinash Vijay  
*Techno-Economics of Optimised Residential Heating under Power Sector Decarbonisation*  
Supervisor: Dr Adam Hawkes  
Employer: University of Oxford

Dr Mario Villanueva  
*Set-Theoretic Methods for Analysis, Estimation and Control of Nonlinear Systems*  
Supervisor: Dr Benoit Chachuat  
Employer: Research Associate, School of Information Science and Technology, ShanghaiTech University

Dr Carmen Wouters  
*Optimal Design and Regulation of Residential Distributed Energy Systems*  
Supervisors: Prof Eric Fraga and Dr Ady James  
Employer: DNV GL Energy Advisory Benelux

Dr Dionysios Xenos  
*Optimal Operation of Industrial Compressor Stations in Systems with Large Energy Consumption*  
Supervisor: Prof Nina Thornhill  
Employer: Founder and Director of Flexciton

Dr Joseph Yao  
*Investigations of the Combination of Carbon Capture and Storage via the Calcium Looping Cycle with Biomass Combustion*  
Supervisors: Prof Paul Fennel and Prof Geoffrey Maitland  
Employer: Research Associate at Imperial College London

Dr Mauricio Zamorano  
*Human Dental Pulp Stem Cells: Characterisation and in Vitro 3D Bone Ontogeny*  
Supervisor: Prof Athanasios Mantalaris  
Employer: Assistant Professor, Department of Chemical Engineering, Universidad de La Frontera
Acknowledgement

Editors
- Claire Adjiman
- Benoît Chachuat
- Graham Elkes
- Andrew Haslam
- Paul Rutter
- Senait Selassie

Writers
- Andrea Bernardi
- Benoît Chachuat
- Vassilis M. Charitopoulos
- Miao Guo
- Suela Jonuzaj
- (Scott) Qingyuan Kong
- Kamal Kuriyan
- Silvia Di Lecce
- António Lima Grilo
- José Morais
- Gbemi Oluleye
- Di Zhang

Photographer
- Karl Attard – Karl Attard Photography

Designer
- Rory Morrison – Look Project Ltd