# cpse

**The Sargent Centre for Process Systems Engineering**

Report no. 1

Imperial College London | UCL



# Introduction

## 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

| Industrial Consortium Company Members | |
|---|---|
| **Company** | **Friend** |
| ABB Corporate Research | Professor Nina Thornhill |
| AkzoNobel | Professor George Jackson |
| BP | Professor Nilay Shah |
| ExxonMobil | Dr Ruth Misener |
| Petronas | Professor Amparo Galindo |
| PSE | Professor Costas Pantelides |
| Proctor and Gamble | Professor Erich Müller |
| Shell Research & Technology | Professor Geoffrey Maitland |
| Syngenta | Professor Claire Adjiman |

## Professor Claire S. Adjiman

**CPSE Director**

"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

L to R: Jonathan Seville (IChemE's President) and Roger Sargent

### Recognitions 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, utilization, conversion, or storage.

### 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.

**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.

President's Medal in Excellence in External Collaboration and Partnerships in 2018

## 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).

**Octeract**, a company co-founded by **Nikolaos Kazazakis** (supervisor Professor Claire Adjiman) and **Gabriel Lau** (supervisor Professor George Jackson) was launched in 2017. Octeract 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 Sørensen** 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).

Dr Ruth Misener

**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




Professor Nina Thornhill receiving the Nordic Process Control Award

team employed the SAFT coarse-grained force fields developed within the Molecular Systems Engineering group at CPSE.

**Dr Ven Chian Quek**, **Professor Nilay Shah** and **Dr Benoît Chachuat** were awarded the IChemE's **2018 Senior Moulton Medal**, which rewards the most meritorious, forward-looking paper in topic areas that will be important in the future.

## Selected Awards and Recognitions – CPSE Researchers

**Panatpong (Obb) Hutacharoen** (supervisors Professors Claire Adjiman, Amparo Galindo and George Jackson) was awarded the **2016 Anglo-Thai Education Award for Excellence in Engineering and Technology** by the Anglo-Thai Society. Founded in 2005, the Engineering and Technology category has been awarded to students from Imperial since 2010 and Panatpong is the third CPSE student in a row to receive the award.

**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 $CO_2$.

**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).

Professor Geoffrey C. Maitland

## 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: PROcess NeTwork 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.

2016 Annual Consortium Meeting

## 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 Benoît 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.


L to R: Professor Claire Adjiman, Professor Anton Kiss, Dr Benoît 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:

**2018 – Professor Babatunde A Ogunnaike**, University of Delaware.
*"Biological Control Systems: Systems Biology of Diseases and the Design of Effective Treatments"*

**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."*



Professor Sargent and his Academic Sons

## 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

**Professor Roger Guimerà**
Universitat Rovira i Virgili

**Professor Mark Huijbregts**
Radboud University Nijmegen

**Professor Stephanie Hellweg**
ETH Zurich

**Professor Fengqi You**
Cornell University

**Professor Uwe Sauer**, ETH Zurich

### 2017 Seminar Series

**Professor Ignacio E. Grossmann**, Carnegie Mellon University

**Dr Jie Li**, University of Manchester

**Dr Xiaoxia "Nina" Lin**
University of Michigan - Ann Arbor

**Professor Vassily Hatzimanikatis**
Ecole Polytechnique Fédérale de Lausanne

**Professor Stratos Pistikopoulos**
Texas A&M University

**Professor Costas D. Maranas**, Pennsylvania State of 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[1]. 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.[2] 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 (CAM$^{b}$D) 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 Adjiman[3] 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).

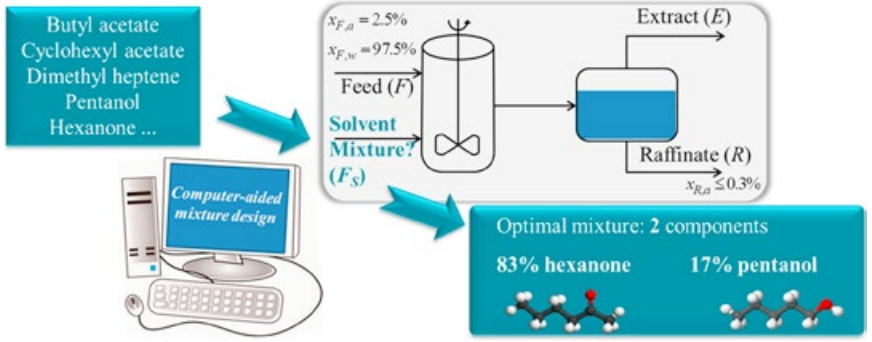


**Figure 1:** *Solvent mixture design for separating acetic acid from water via liquid-liquid extraction[3].*

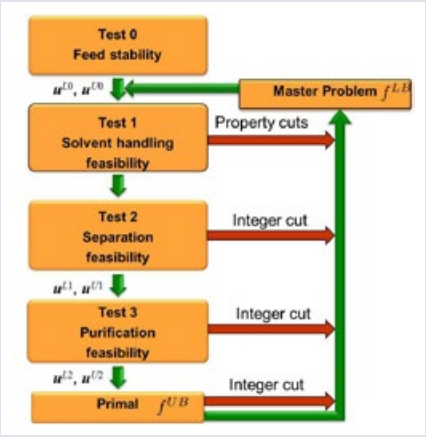


**Figure 2:** *Flowchart of the outer approximation CAPD algorithm.*

Integrated molecular and process design**:** The Molecular Systems Engineering group brings molecular-level decisions into process design through fundamental advances in optimisation methods, and follows this through to implementation and application. In particular, the work by Gopinath et al.[4] focuses on developing an integrated molecular and process synthesis methodology which involves the simultaneous solution of optimal molecular and process variables for a given system. They investigate the design of fluid–fluid separation systems at steady state, where the molecules (materials) to be designed are pure-component solvents that act as mass separating agents in the process. The integrated molecular and process design flowsheet results in a challenging mixed integer nonlinear programming (MINLP) problem. A deterministic outer-approximation algorithm is developed for the solution of the computer-aided molecular and process design (CAMPD) problem. Novel tests are embedded within the MINLP solution framework, 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 $CO_2$ from methane (Fig. 3) and of butanol from water[4,5].

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 flowsheets[6-8].

In addition, they employ multi-objective optimization techniques to formulate competing objectives, such as performance, economic and environmental metrics[9-10] (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-



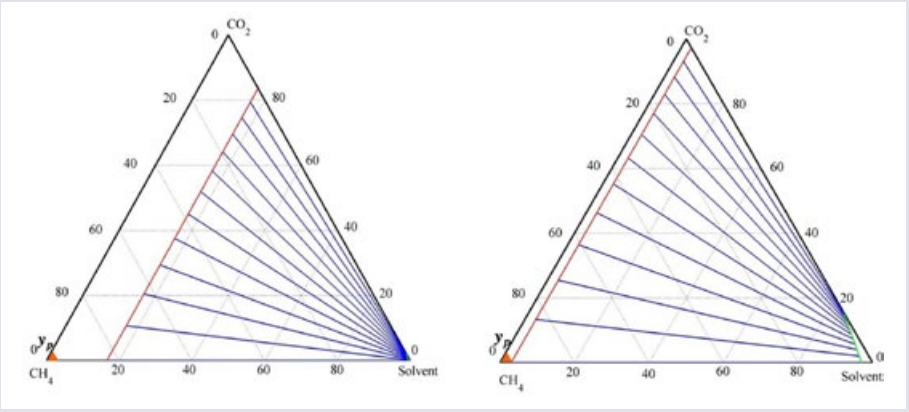


**Figure 3:** *Phase diagram for $CO_2$–methane–solvent (propyl-methyl ether) at $T_1$ = 270 K and pressure $P_1$. (a) $P_1$ = 0.10 MPa. (b) $P_1$ = 0.61 MPa. The shaded region represents* [4].

efficient molecules for $CO_2$ 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[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.[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[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.

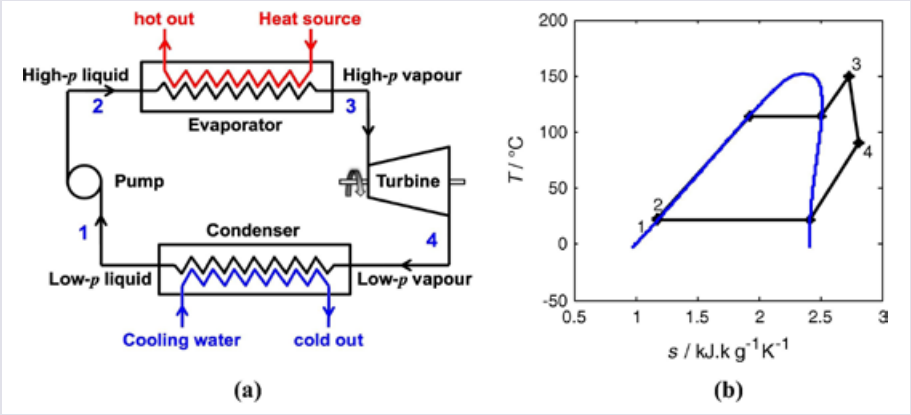


**Figure 4:** *(a) Schematic diagram of an ORC engine, and (b) a corresponding T–s diagram for the case of a pure (single-component) working fluid*[11].



White et al.[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-γ 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 assesment[14].

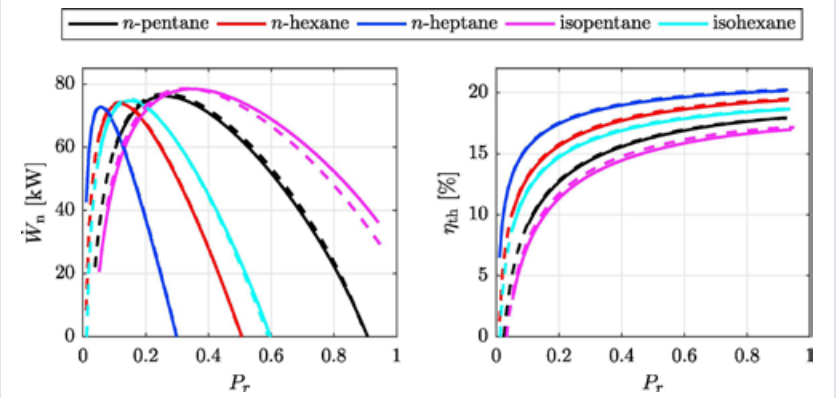


**Figure 5:** *Comparison between the net power and thermal efficiency* $\eta_{th}$, *as functions of reduced pressure, obtained from the ORC model when using SAFT-γ Mie (solid) and NIST REFPROP (dashed) for hydrocarbon working-fluids*[13].

## 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 $CO_2$ 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 $CO_2$ capture solvents that lead to improved process performance and lower cost.

The adoption of some well-established industrial technologies for $CO_2$ 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 $CO_2$ 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 $CO_2$ 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 $CO_2$ 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.



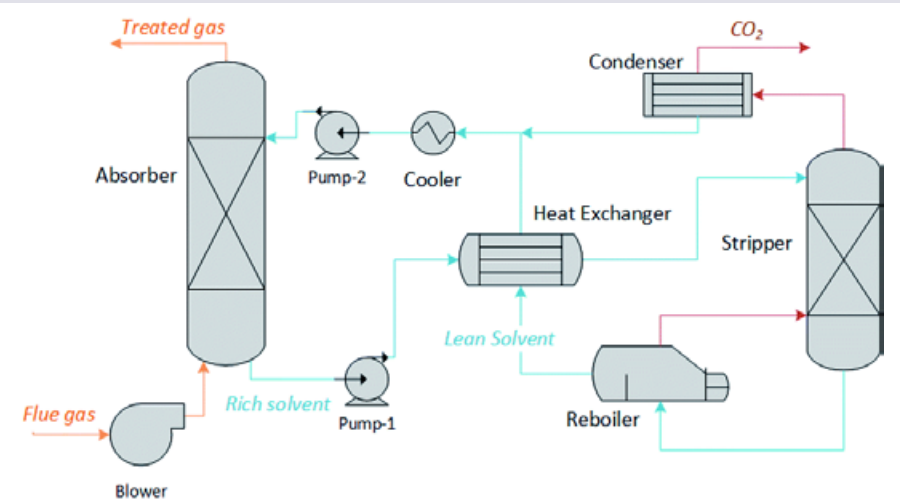


**Figure 6:** *Process flow diagram of the $CO_2$ absorption capture plant modelled in the work of Mota-Martinez et al.[17]*

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.[20] 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.

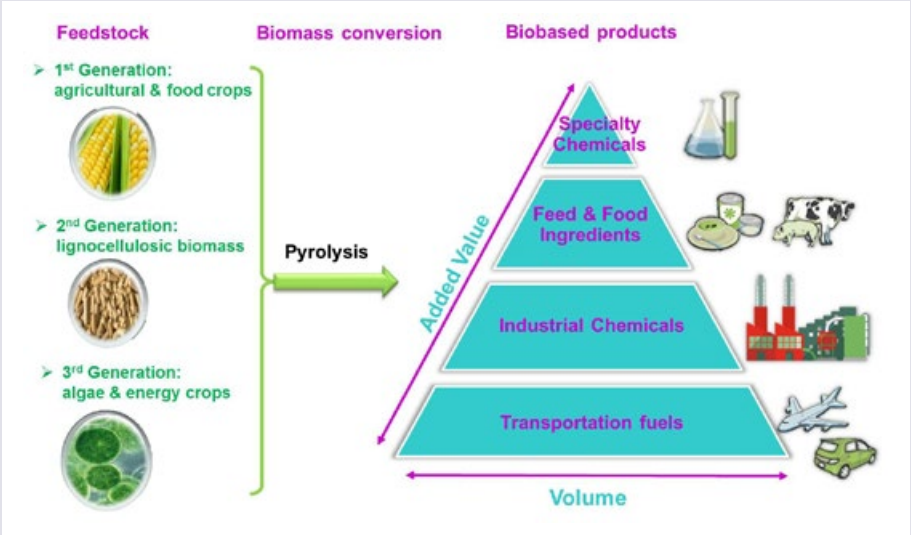


**Figure 7:** *Biobased products derived from different biomass feedstocks via pyrolysis.*

## References


1. Adjiman, C.S., Bardow, A. (2017) Editorial to iCAMD special issue. Chemical Engineering *Science* 159, 1–2.
2. Jonuzaj, S., Akula, P.T., Kleniati, P.M., Adjiman, C.S. (2016) The formulation of optimal mixtures with Generalized Disjunctive Programming: A solvent design case study. *AIChE Journal* 62, 1616–1633.
3. Jonuzaj, S., Adjiman, C.S. (2017) Designing optimal mixtures using Generalized Disjunctive Programming: Hull relaxations. *Chemical Engineering Science* 159, 106–130.
4. Gopinath, S., Jackson, G., Galindo, A., Adjiman, C.S. (2016) Outer approximation algorithm with physical domain reduction for computer-aided molecular and separation process design. *AIChE Journal* 62, 3484–3504.
5. Gopinath, S. (2017) Molecular design, process design and process synthesis of separation systems. PhD Thesis. Imperial College London.
6. Limleamthong, P., Gonzalez-Miquel, M., Papadokonstantakis, S., Papadopoulos, A.I., Seferlis, P., Guillén-Gosálbez, G. (2016) Multi-criteria screening of chemicals considering thermodynamic and life cycle assessment metrics via data envelopment analysis: application to $CO_2$ capture. *Green Chemistry* 18, 6468–6481.
7. Calvo-Serrano, R., Gonzalez-Miquel, M., Papadokonstantakis, S., Guillen-Gosalbez, G., 2018. Predicting the cradle-to-gate environmental impact of chemicals from molecular descriptors and thermodynamic properties via mixed-integer programming. *Computers & Chemical Engineering* 108, 179–193.
8. Ibrahim, D., Jobson, M., Guillen-Gosalbez, G. (2017) Optimization-Based Design of Crude Oil Distillation Units Using Rigorous Simulation Models. *Industrial & Engineering Chemistry Research* 56, 6728–6740.
9. Pascual-Gonzalez, J., Jimenez-Esteller, L., Guillen-Gosalbez, G., Siirola, J.J., Grossmann, I.E., 2016. Macro-economic multi-objective input–output model for minimizing $CO_2$ emissions: Application to the U.S. economy. *AIChE Journal* 62, 3639–3656.
10. Wheeler, J., Caballero, J.A., Ruiz-Femenia, R., Guillen-Gosalbez, G., Mele, F.D. (2017) MINLP-based analytic hierarchy process to simplify multi-objective problems: Application to the design of biofuels supply chains using on field surveys. *Computers and Chemical Engineering* 102, 64–80.
11. Oyewunmi, O.A., Taleb, A.I., Haslam, A.J., Markides, C.N. (2016) On the use of SAFT-VR Mie for assessing large-glide fluorocarbon working-fluid mixtures in organic rankine cycles. *Applied Energy* 163, 263–282.
12. Oyewunmi, O.A., Kirmse, C.J.W., Pantaleo, A.M., Markides, C.N. (2017) Performance of working-fluid mixtures in ORC-CHP systems for different heat-demand segments and heat-recovery temperature levels. *Energy Conversion and Management* 148, 1508–1524.
13. White, M.T., Oyewunmi, O.A., Haslam, A.J., Markides, C.N. (2017) Industrial waste-heat recovery through integrated computer-aided working-fluid and ORC system optimisation using SAFT-γ Mie. *Energy Conversion and Management* 150, 851–869.
14. White, M.T., Oyewunmi, O.A., Chatzopoulou, M.A., Pantaleo, A.M., Haslam, A.J., Markides C.N. (2017) Integrated computer-aided working-fluid design and thermoeconomic ORC system optimisation. *Energy Procedia* 129, 152–159.
15. Papadopoulos, A.I., Badr, S., Chremos, A., Forte, E., Zarogiannis, T., Seferlis, P., Papadokonstantakis, S., Galindo, A., Jackson, G., Adjiman, C.S. (2016) Computer-aided molecular design and selection of $CO_2$ capture solvents based on thermodynamics, reactivity and sustainability. *Molecular Systems Design & Engineering* 1, 313–334.
16. Mota-Martinez, M.T., Hallett, J.P., Mac Dowell, N. (2017) Screening solvents properties for $CO_2$ capture based on the process performance. *Energy Procedia* 114, 1551–1557.
17. Mota-Martinez, M.T., Hallett, J.P., Mac Dowell, N. (2017) Solvent selection and design for $CO_2$ capture – How we might have been missing the point. *Sustainable Energy Fuels* 1, 2078–2090.
18. Zhang, D., del Rio-Chanona, A.E., Shah, N. (2017) Screening synthesis pathways for biomass-derived sustainable polymer production. ACS Sustainable Chem. Eng. 5, 4388–4398.
19. del Rio-Chanona, A.E., Zhang, D., Shah, N. (2017) Sustainable Biopolymer Synthesis via Superstructure and Multiobjective Optimization. *AIChE Journal* 64, 91–103.
20. Jonuzaj, S., Shah, N., Adjiman, C.S. (2018) Computer-aided design of products derived from biomass pyrolysis. AIChE Annual Meeting, Pittsburgh, PA, US. Conference Proceedings.

## 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.

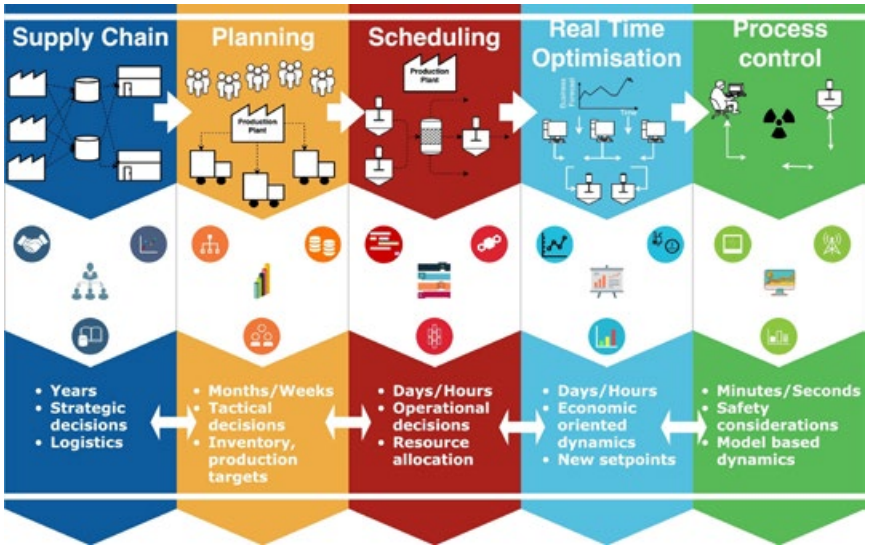


**Figure 1:** *Interdependence of the different level of decision making in the process industries.*

### 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.

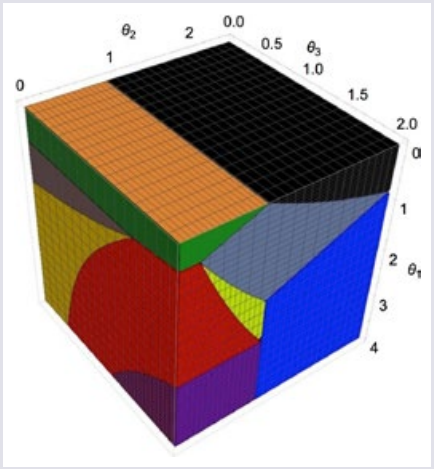


**Figure 2:** *Regions of optimality in the parametric space where different control laws are optimal. The parameters indicate the different states of the dynamic system at each sampling instance. For polynomial systems the regions may not be convex.*

Within the CPSE a number of researchers have presented new algorithms for the design of mp-MPC. Sun et al.[4] 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 backing-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 nature[5]. The computational efficiency and effectiveness of the proposed scheme was tested on a fluidized catalytic cracker case study. Charitopoulos and Dua[6] 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.[7] 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[8] 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.[9], 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[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. Papathanasiou et al.[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.[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.[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[14]. Alvarado et al.[15] presented a Technology Selection and Operation (TSO) model that enables a new approach for the optimal

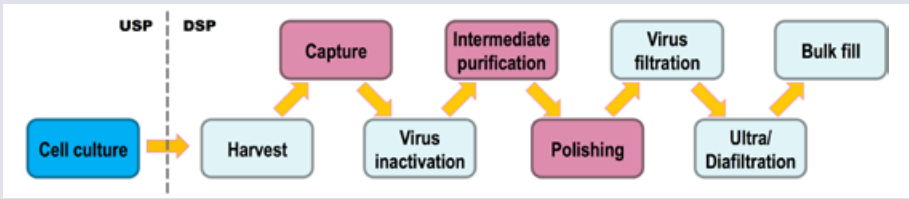


**Figure 3:** *Typical upstream (USP) and downstream (DSP) monoclonal antibody process.*

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.[16]

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.[17] 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.[18]. Real variability in electricity prices from spot and future markets was also considered. In Liu et al.[19], a mixed integer linear programming model for the optimal operation of a network of gas oil separation plants can be found.

## References


1. Charitopoulos V.M., Dua V., Papageorgiou L.G. (2017). Traveling Salesman Problem-Based Integration of Planning, Scheduling, and Optimal Control for Continuous Processes. *Ind. Eng. Chem. Res.* 56(39), 11186–11205.
2. Charitopoulos V.M., Dua V., Papageorgiou L.G. (2017). Closed loop integration of planning, scheduling and control via exact multi-parametric nonlinear programming. In *Comput. Aid. Chem. Eng.* 40, 1273–1278.
3. Strutzel F.A.M., Bogle I.D.L (2016). Assessing plant design with regard to MPC performance. *Comput. Chem. Eng.* 94, 180–211.
4. Sun M., Villanueva M.E., Pistikopoulos E.N., Chachuat, B. (2017). Robust Multi-Parametric Control of Continuous-Time Linear Dynamic Systems. *IFAC-PapersOnLine* 50(1), 4660–4665.
5. Sun M., Chachuat B., Pistikopoulos E.N. (2016). Design of multi-parametric NCO tracking controllers for linear dynamic systems. *Comput. Chem. Eng.* 92, 64–77.
6. Charitopoulos V.M., Dua V. (2016). Explicit model predictive control of hybrid systems and multiparametric mixed integer polynomial programming. *AIChE J.* 62(9), 3441–3460.
7. Oberdieck R., Diangelakis N.A., Pistikopoulos E.N. (2017). Explicit model predictive control: A connected-graph approach. *Automatica* 76, 103–112.
8. Che Mid E., Dua V. (2017). Model-Based Parameter Estimation for Fault Detection Using Multiparametric Programming. *Ind. Eng. Chem. Res.* 56.28, 8000–8015.
9. Villanueva M.E., Quirynen R., Diehl M. , Chachuat B., Houska B. (2017). Robust MPC via min– max differential inequalities, *Automatica* 77, 311–321.
10. Jamili E., Dua V. (2016). Modelling and Optimal Control of Non-Viral siRNA Delivery. *Comput. Aid. Chem. Eng.* 38, 673–678.
11. Papathanasiou M.M., Quiroga-Campano A.L., Steinebach F., Elviro M., Mantalaris A., Pistikopoulos E.N. (2017). Advanced model-based control strategies for the intensification of upstream and downstream processing in mAb production. *Biotechnol. Prog.* 33(4), 966–988.
12. Koleva M.N., Styan, C A., Papageorgiou, L. G. (2017). Optimisation approaches for the synthesis of water treatment plants. *Comput. Chem. Eng.* 106, 849–871.
13. Lira-Barragán L.F., Ponce-Ortega J.M., Guillén-Gosálbez G., El-Halwagi M.M. (2016). Optimal water management under uncertainty for shale gas production. *Ind. Eng. Chem. Res.* 55(5), 1322–1335.
14. Silvente J., Papageorgiou L.G. (2017). An MILP formulation for the optimal management of microgrids with task interruptions. *Appl. Energy* 206, 1131–1146.
15. Alvarado D.C., Acha S., Shah N., Markides C.N. (2016). A Technology Selection and Operation (TSO) optimisation model for distributed energy systems: Mathematical formulation and case study. *Appl. Energy* 180, 491–503.
16. Liu S., Farid S.S., Papageorgiou L.G. (2016). Integrated optimization of upstream and downstream processing in biopharmaceutical manufacturing under uncertainty: a chance constrained programming approach. *Ind. Eng. Chem. Res.* 55(16), 4599–4612.
17. Aguirre A.M., Liu S., Papageorgiou L.G. (2017). Mixed Integer Linear Programming Based Approaches for Medium-Term Planning and Scheduling in Multiproduct Multistage Continuous Plants. *Ind. Eng. Chem. Res*. 56(19), 5636–5651.
18. Fernández, D., Pozo, C., Folgado, R., Guillén-Gosálbez, G., & Jiménez, L. (2017). Multiperiod model for the optimal production planning in the industrial gases sector. *Appl. Energy* 206, 667–682.
19. Liu S., Alhasan I., Papageorgiou L.G. (2016). A mixed integer linear programming model for the optimal operation of a network of gas oil separation plants. *Chem. Eng. Res. Des.* 111, 147–160.

## 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[1]. The predictive capability of the software has been showcased in many relevant catalytic systems: catalytic reduction of CO, biomass conversion in biofuels, and methane-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[2]. 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.[3] 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.

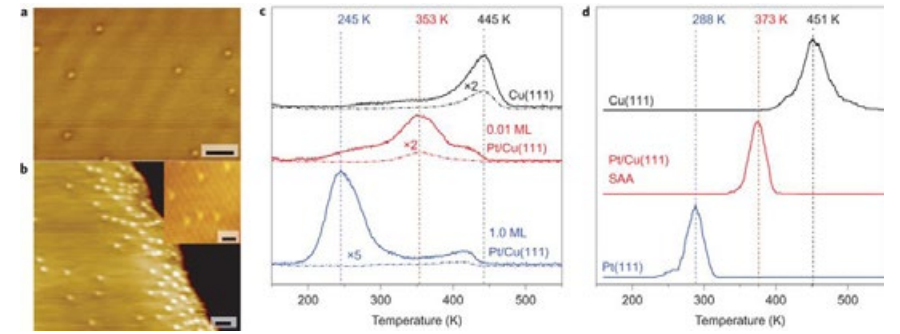


**Figure 1:** *(a) and (b) shows STM image of a 0.01 ML Pt/Cu(111) SAA surface. (c) Experimental TPR traces showing evolution of methane (solid lines) and ethene (dashed lines) from different catalysts surfaces following deposition of $CH_3I$. (d) Simulated TPR of methyl-covered Cu(111) (black), Pt/Cu(111) SAA (red) and Pt(111) (blue).*[4]

More recently, the activation of methane and its coupling towards higher hydrocarbons has been investigated[4]. 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[5] 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[6]. 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**)[7], 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.[8] 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

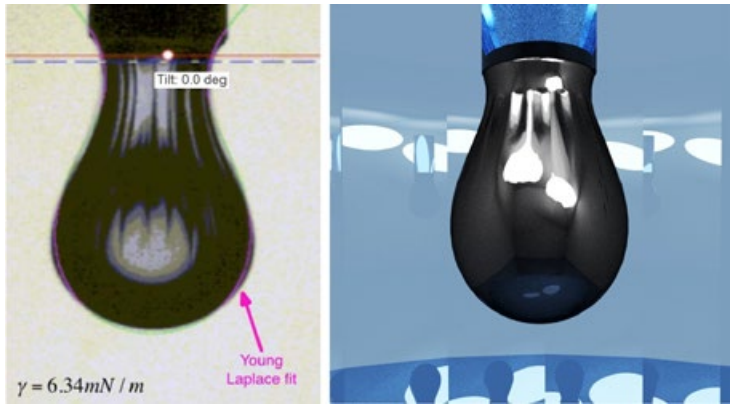


**Figure 2:** *Left:Image of a deflated asphaltene-stabilised water drop in oil from Pauchard et al. Langmuir 30 (2014) 12795–12803. Right:Raytrace of the drop profile from simulations, revolved around the symmetry axis and with crumples inserted into the region where* $T\phi = 0$.[9]

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[9]. 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 asphaltenes 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.[10] 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 $CO_2$ from concentrated sources, such as power plants, which are among the main contributors to the overall world's $CO_2$ 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 $CO_2$ 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 $H_2O$ and $CO_2$. In particular, alkyl-functional primary and secondary amines react (reversibly) with $CO_2$ to form carbamates. Chremos et al.[11] use the SAFT-γ SW group-contribution approach to provide a predictive thermodynamic description of solvents and their mixtures with $CO_2$, enabling the computer-aided design of optimal solvents and solvent blends to separate $CO_2$ 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 $CO_2$ 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.[12] 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 nano-meter length and pico-second time scales, neither of which are realistic for most

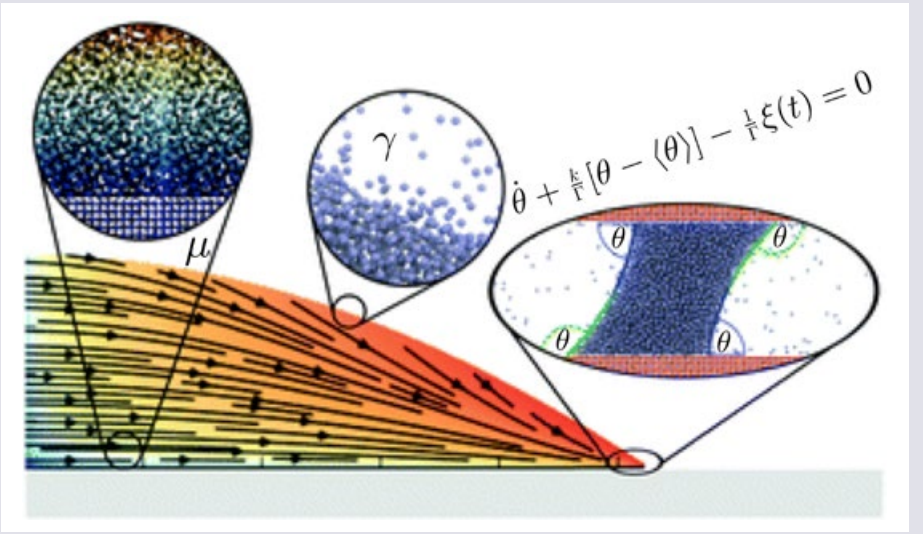


**Figure 3:** *Graphical representation of the parameterised Langevin model proposed by Smith et al.*[12]

simulations. To avoid these limitations the proposed method aims to extract generalised contact-line behaviour, which can then be incorporated in a continuous-scale model. The resulting modelling tool has a wide range of potential applications which will be explored as future work.

## 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[13] and the pricing of multi-asset options[14]. Recent developments in extending and enhancing GSA methods are discussed below.

Lambert et al.[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[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.

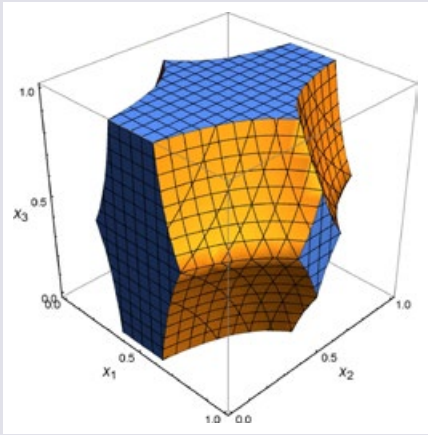


**Figure 4:** *Complex domains created by an output constraint, which cannot be evaluated independently from the model function itself.*[17]

Kucherenko et al.[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[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.[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. Joint experimental design methods have been proposed to overcome these limitations. Prior work in this area has relied on evaluating the dual objectives on a grid of experimental conditions without formally evaluating the trade-offs. The proposed joint MBDOE procedure uses multi-objective optimisation methods to analyse the trade-offs between information and discrimination metrics.

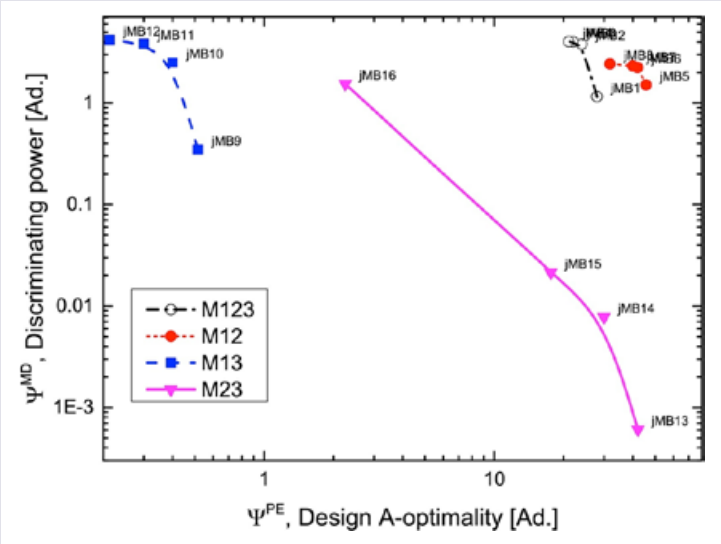


**Figure 5:** *Pareto solutions from joint MBDOE for model discrimination and parameter estimation.*[19]



The joint MBDOE method by Galvanin et al.[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.[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.[21]. The compounds in PO are classified in terms of hyrdoxy 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.[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


1. Pineda, M., Stamatakis, M. (2017) Beyond mean-field approximations for accurate and computationally efficient models of on-lattice chemical kinetics. *The Journal of Chemical Physics* 147 (2), 024105.
2. Stamatakis, M., Piccinin, S. (2016) Rationalizing the Relation between Adlayer Structure and Observed Kinetics in Catalysis. *ACS Catalysis* 6 (3), 2105–2111.
3. Liu, G., Robertson, A. W., Li, M. M.-J., Kuo, W. C. H., Darby, M. T., Muhieddine, M. H., Lin, Y.-C., Suenaga, K., Stamatakis, M., Warner, J. H., Tsang, S. C. E., MoS2 monolayer catalyst doped with isolated Co atoms for the hydrodeoxygenation reaction. *Nature Chemistry* **2017**, *9*, 810.
4. Marcinkowski, M. D., Darby, M. T., Liu, J., Wimble, J. M., Lucci, F. R., Lee, S., Michaelides, A., Flytzani-Stephanopoulos, M., Stamatakis, M., Sykes (2018) E. C. H., Pt/Cu single-atom alloys as coke-resistant catalysts for efficient C–H activation. *Nature Chemistry* 10, 325.
5. Müller, E. A., Mejía, A. (2017) Extension of the SAFT-VR Mie EoS To Model Homonuclear Rings and Its Parametrization Based on the Principle of Corresponding States. *Langmuir* 33 (42), 11518–11529.
6. Ervik, Å., Serratos, G. J., Müller, E. A. (2017) raaSAFT: A framework enabling coarse-grained molecular dynamics simulations based on the SAFT-γ Mie force field. *Computer Physics Communications* 212, 161–179.
7. Ervik, Å., Mejía, A., Müller, E. A. (2016) Bottled SAFT: A Web App Providing SAFT-γ Mie Force Field Parameters for Thousands of Molecular Fluids. *Journal of Chemical Information and Modeling* 56 (9), 1609–1614.
8. Jiménez-Serratos, G., Herdes, C., Haslam, A. J., Jackson, G., Müller, E. A. (2017) Group Contribution Coarse-Grained Molecular Simulations of Polystyrene Melts and Polystyrene Solutions in Alkanes Using the SAFT-γ Force Field. *Macromolecules* 50 (12), 4840–4853.
9. Ervik, Å., Lysgaard, M. O., Herdes, C., Jiménez-Serratos, G., Müller, E. A. (2016) Munkejord, S. T., Müller, B., A multiscale method for simulating fluid interfaces covered with large molecules such as asphaltenes. *Journal of Computational Physics* 327, 576–611.
10. Muscatello, J., Müller, E. A., Mostofi, A. A., Sutton, A. P. (2017) Multiscale molecular simulations of the formation and structure of polyamide membranes created by interfacial polymerization. *Journal of Membrane Science* 527, 180–190.
11. Chremos, A., Forte, E., Papaioannou, V., Galindo, A., Jackson, G., Adjiman, C. S. (2016) Modelling the phase and chemical equilibria of aqueous solutions of alkanolamines and carbon dioxide using the SAFT-γ SW group contribution approach. *Fluid Phase Equilibria* 407, 280–297.
12. Smith, E. R., Müller, E. A., Craster, R. V., Matar, O.K. (2016) A Langevin model for fluctuating contact angle behaviour parametrised using molecular dynamics, *Soft Matter* 12, 9604–9615.
13. Molkenthin, C., Scherbaum, F., Griewank, A., Leovey, H., Kucherenko, S., Cotton, F. (2017) Derivative-Based Global Sensitivity Analysis: Upper Bounding of Sensitivities in Seismic-Hazard Assessment Using Automatic Differentiation, *Bulletin of the Seismological Society of America* 107 (2), 984–1004.
14. Bianchetti, M., Kucherenko, S., Scoleri, S. (2016) Pricing and Hedging Multi-Asset Options with High-Dimensional Quasi Monte Carlo: FD vs AAD Greeks, *Argo*.
15. Lambert, R. S. C., Lemke, F., Kucherenko, S. S., Song, S., Shah, N.(2016) Global sensitivity analysis using sparse high dimensional model representations generated by the group method of data handling. *Mathematics and Computers in Simulation* 128, 42–54.
16. Kucherenko, S., Song, S. (2017) Different numerical estimators for main effect global sensitivity indices. *Reliability Engineering & System Safety* 165, 222–238.
17. Kucherenko, S., Klymenko, O. V., Shah, N. (2017) Sobol' indices for problems defined in non-rectangular domains. *Reliability Engineering & System Safety* 167, 218–231.
18. De-Luca, R., Galvanin, F., Bezzo, F. (2016) A methodology for direct exploitation of available information in the online model-based redesign of experiments. *Computers & Chemical Engineering* 91, 195–205.
19. Galvanin, F., Cao, E., Al-Rifai, N., Gavriilidis, A., Dua, V. (2016) A joint model-based experimental design approach for the identification of kinetic models in continuous flow laboratory reactors. *Computers & Chemical Engineering* 95, 202–215.
20. Galvanin, F., Marchesini, R., Barolo, M., Bezzo, F., Fidaleo, M. (2016) Optimal design of experiments for parameter identification in electrodialysis models. *Chemical Engineering Research and Design* 105, 107–119.
21. Sharifzadeh, M., Richard, C. J., Shah, N. (2017) Modelling the kinetics of pyrolysis oil hydrothermal upgrading based on the connectivity of oxygen atoms, quantified by 31P-NMR. *Biomass and Bioenergy* 98, 272–290.
22. Bernardi, A., Nikolaou, A., Meneghesso, A., Morosinotto, T., Chachuat, B., Bezzo, F. (2016) High-Fidelity Modelling Methodology of Light-Limited Photosynthetic Production in Microalgae. *PLOS ONE* 11 (4), e0152387.

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 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), stochastic and robust optimisation (Rustem, Wiesemann), 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, Parpas[3] 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 & Adjiman[5] 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.

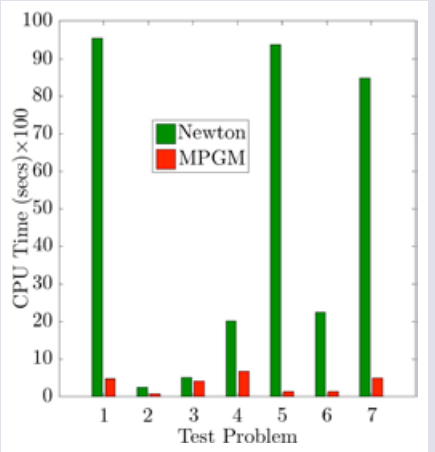


**Figure 1:** *Comparison of the multilevel proximal gradient method (MPGM) with the Newton algorithm for computational test problems in transition paths.*

## Nonconvex and mixed-integer nonlinear optimisation

The paper by Boukouvala et al.[6] reviews recent advances in global optimisation for both MINLP and constrained derivative-free optimisation (CDFO), 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 & Misener[7] presents an analysis of the piecewise parametric structure of such pooling problems and its links with computational tractability. Further, Ceccon et al.[8] 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

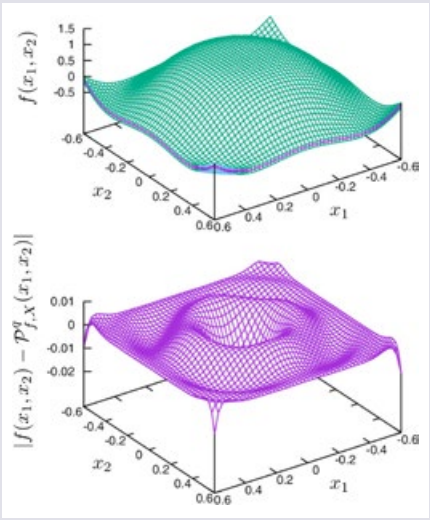

**Figure 2:** *Top plot – Chebyshev model enclosure (green) of a two-variate function (purple); Bottom plot – Corresponding approximation error.*

approximant (see Fig. 2), and they perform better than their Taylor model counterparts. Nerantzis & Adjiman[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, Nerantzis & Adjiman[11] develop exclusion tests for enclosing all the transition states of a function, namely index-1 saddle points, and embed these tests within a complete search algorithm. Such transition states play a crucial role, e.g., in determining the rates of chemical transformations.

## 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.[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.[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.[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.[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.[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[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).

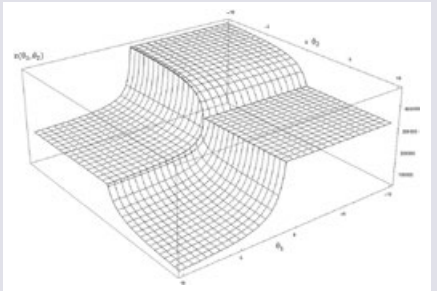

**Figure 3:** *Explicit mapping of optimal solution values in multi-parametric LP with left-hand side constraint uncertainty.*

## 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.[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[19] use such set-valued integration combined with interval

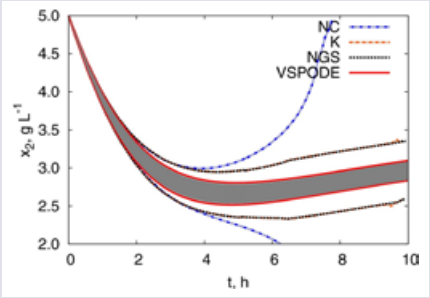


**Figure 4:** *State bounds computed with various set-valued integration techniques for a three-state bioreactor problem.*

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.[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[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[22] 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.[23] 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.[24] 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.[25].

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.[26] 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.[27] 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 Caladra et al.[28] 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.[29] 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).



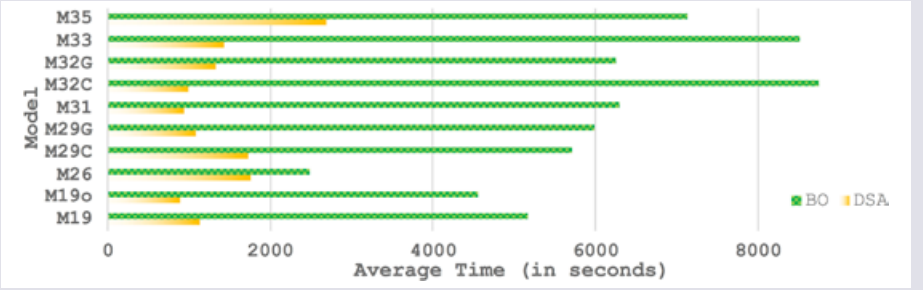


**Figure 5:** *Average computation time of DSA vs. BO in various parameter estimation problems.*

## References


1. Luong DVN, Parpas P, Rueckert D, Rustem B (2016) A weighted Mirror Descent algorithm for nonsmooth convex optimization problem, *Journal of Optimization Theory & Applications*, 170(3), 900-915.
2. Hovhannisyan V, Parpas P, Zafeiriou S (2016) MAGMA: Multi-level accelerated gradient mirror descent algorithm for large-scale convex composite minimization, *SIAM Journal on Imaging Sciences*, 9(4), 1829-1857.
3. Parpas P (2017) A Multilevel Proximal Gradient Algorithm for Large Scale Optimization, *SIAM Journal on Scientific Computing*, 39(5), S681-S701.
4. Gopinath S, Jackson G, Galindo A, Adjiman CS (2016) Outer Approximation Algorithm with Physical Domain Reduction for Computer-Aided Molecular and Separation Process Design, *AIChE Journal*, 62, 3484-3504.
5. Jonuzaj S, Adjiman CS (2017) Designing optimal mixtures using generalized disjunctive programming: Hull relaxations, *Chemical Engineering Science*, 159, 106-130.
6. Boukouvala F, Misener R, Floudas CA (2016) **Global Optimization Advances in Mixed-Integer Nonlinear Programming, MINLP, and Constrained Derivative-Free Optimization, CDFO**, *European Journal of Operational Research*, 252, 701-727.
7. Baltean-Lugojan R, Misener R (2018) **Piecewise parametric structure in the pooling problem: from sparse strongly-polynomial solutions to NP-hardness**, *Journal of Global Optimization*, 71, 655–690.
8. Ceccon F, Kouyialis G, Misener R (2016) **Using functional programming to recognize named structure in an optimization problem: Application to pooling**, *AIChE Journal*, 62, 3085-3095.
9. Rajyaguru J, Villanueva ME, Houska B, Chachuat B (2017) Chebyshev model arithmetic for factorable functions, *Journal of Global Optimization*, 68, 413-438.
10. Nerantzis D, Adjiman CS (2017) An interval-matrix branch-and-bound algorithm for bounding eigenvalues, Optimization Methods & Software, 32, 872-891.
11. Nerantzis D, Adjiman CS (2017) Enclosure of all index-1 saddle points of general nonlinear functions, *Journal of Global Optimization*, 67, 451-474.
12. Hanasusanto GA, Kuhn D, Wiesemann W (2016) A comment on “computational complexity of stochastic programming problems”, *Mathematical Programming*, 159 (1-2), 557-569.
13. Hanasusanto GA, Kuhn D, Wiesemann W (2016) K-adaptability in two-stage distributionally robust binary programming, *Operations Research Letters*, 44 (1), 6-11.

14. Subramanyam A, Gounaris CE, Wiesemann W (2017) K-Adaptability in Two-Stage Mixed-Integer Robust Optimization, *arXiv preprint* arXiv:1706.07097.
15. Hanasusanto GA, Roitch V, Kuhn D, Wiesemann W (2017) Ambiguous joint chance constraints under mean and dispersion information, *Operations Research*, 65 (3), 751-767.
16. Rujeerapaiboon N, Schindler K, Kuhn D, Wiesemann W (2017) Scenario reduction revisited: Fundamental limits and guarantees, *arXiv preprint* arXiv:1701.04072.
17. Charitopoulos VM, Papageorgiou LG, Dua V (2017). Multi-parametric linear programming under global uncertainty, *AIChE Journal*, 63(9), 3871-3895.
18. Peric ND, Villanueva ME, Chachuat B (2017) Sensitivity analysis of uncertain dynamic systems using set-valued integration, *SIAM Journal on Scientific Computing*, 39, A3014-A3039.
19. Bogle IDL, Perez-Galvan C (2017) Global Optimisation for Dynamic Systems using Interval Analysis, *Computers & Chemical Engineering*, 107, 343-356.
20. Paulen R, Villanueva ME, Chachuat B (2016) Guaranteed parameter estimation of non-linear dynamic systems using high-order bounding techniques with domain and CPU-time reduction strategies, *IMA Journal of Mathematical Control & Information*, 33, 563-587.
21. Houska B, Chachuat B (2017) Global optimization in Hilbert space, *Mathematical Programming*, in press (DOI: 10.1007/s10107-017-1215-7).
22. Baltean-Lugojan R, Parpas P (2016) Robust Numerical Calibration for Implied Volatility Expansion Models, *SIAM Journal on Financial Mathematics*, 7(1), 917-946.
23. Kapsos M, Christofides N, Rustem B (2018) Robust risk budgeting, *Annals of Operations Research*, 266, 199–221.
24. Rujeerapaiboon N, Kuhn D, Wiesemann W (2016) Robust growth-optimal portfolios, *Management Science*, 62 (7), 2090-2109.
25. Arulkumaran K, Deisenroth MP, Brundage M, Bharath AA (2017) Deep Reinforcement Learning: A Brief Survey, *IEEE Signal Processing Magazine*, 34(6), 26-38.
26. Calandra R, Peters J, Rasmussen CE, Deisenroth MP (2016) Manifold Gaussian processes for regression, *International Joint Conference on Neural Networks (IJCNN)*, pp. 3338-3345.
27. Eleftheriadis S, Nicholson TFW, Deisenroth MP, Hensman J (2017) Identification of Gaussian Process State Space Models, *arXiv preprint* arXiv:1705.10888.
28. Calandra R, Seyfarth A, Peters J, Deisenroth MP (2016) Bayesian optimization for learning gaits under uncertainty, *Annals of Mathematics & Artificial Intelligence*, 76 (1-2), 5-23.
29. Ulmasov D, Baroukh C, Chachuat B, Deisenroth MP, Misener R (2016) **Bayesian Optimisation with Dimension Scheduling Algorithm: Application to Biological Systems**, *Computer-Aided Chemical Engineering*, 38, 1051-1056.




## 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.

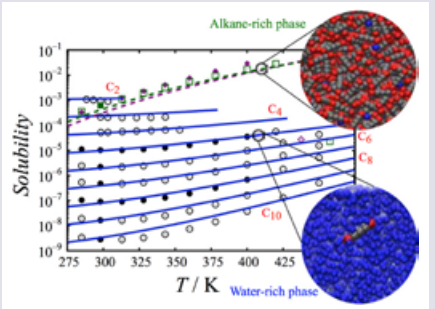


**Figure 1:** *Comparison between the model-predicted solubility (lines) and experimental data (circles). Reproduced from Reference 3.*

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

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).

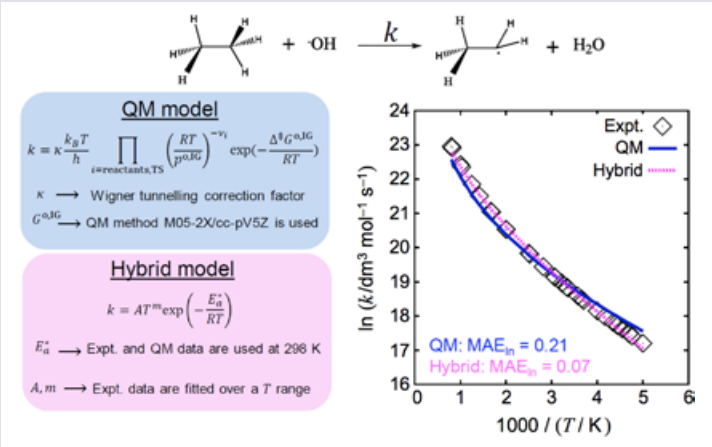


**Figure 2:** *Illustration of the hybrid model combining the QM calculation and the experimental data.*

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 ($H_2O$), 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.

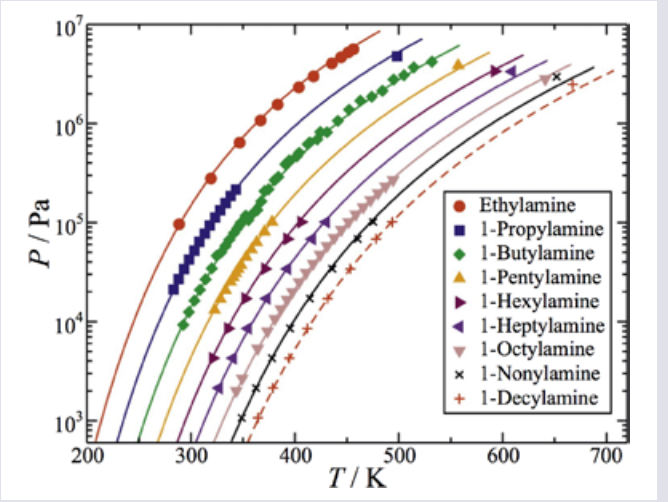


**Figure 3:** *Vapour pressure in a pressure–temperature PT representation. The symbols correspond to experimental data, and the curves represent the SAFT-γ SW calculations. Reproduced from Reference 5*

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.

## 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 processes. Gonzalez-Garay, et al.[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[9] investigate whether it is possible to inject $CO_2$ 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 $CO_2$ conversion. It is concluded from the assessment that that $CO_2$ 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 $CO_2$ conversion with the methanol/two-step DME systems. Giarola, et al.[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.[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[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.[13]

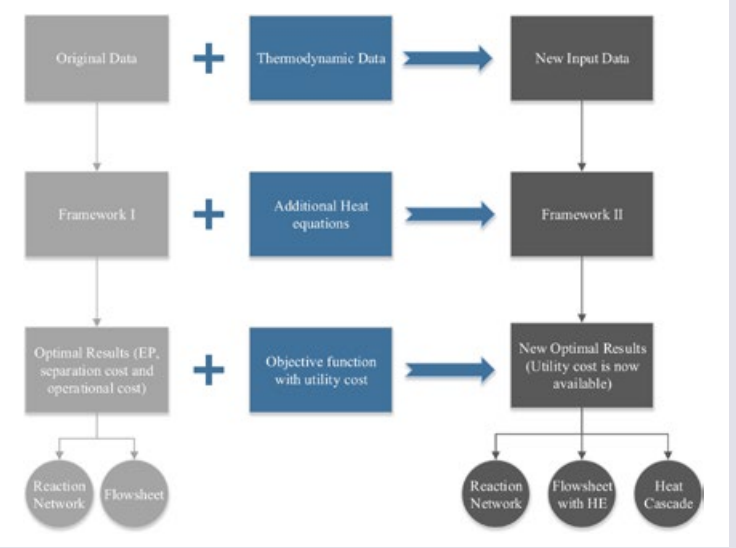


**Figure 5:** *Implementation of simultaneous heat integration with process synthesis*.

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.[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.[15] utilise the concept of superstructure optimisation and presents 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. [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).

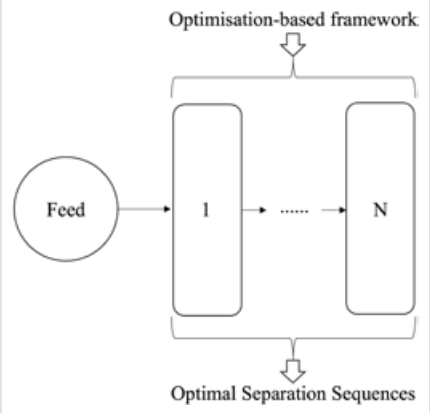


**Figure 6:** *Conceptual design of multicomponent distillation sequence.*

Ibrahim, et al.[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.[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.[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[20] and the treatment system for the flowback water from shale gas production[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.[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.[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.



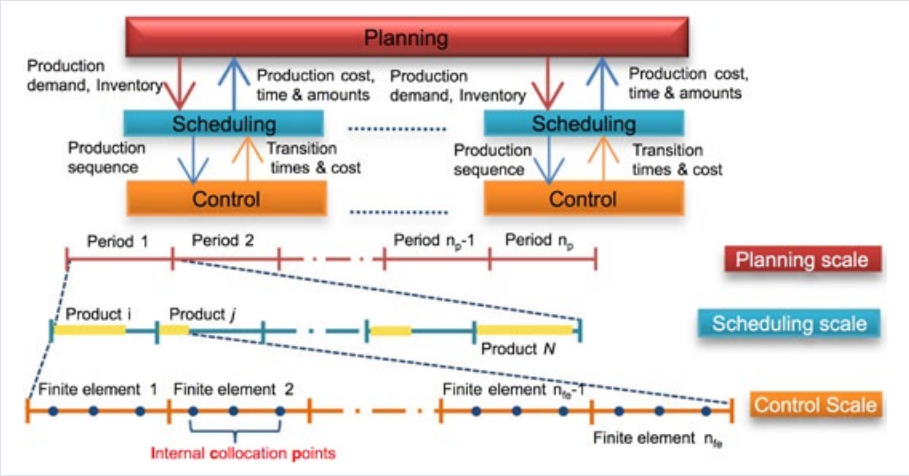


**Figure 7:** *Concept of the integrated planning, scheduling and optimal control problem.*

Vieira, et al.[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.[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.[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


1. Papaioannou, V.; Calado, F.; Lafitte, T.; Dufal, S.; Sadeqzadeh, M.; Jackson, G.; Adjiman, C. S.; Galindo, A., Application of the SAFT-γ Mie group contribution equation of state to fluids of relevance to the oil and gas industry. *Fluid Phase Equilibria* **2016**, *416*, 104119.
2. Hutacharoen, P.; Dufal, S.; Papaioannou, V.; Shanker, R. M.; Adjiman, C. S.; Jackson, G.; Galindo, A., Predicting the Solvation of Organic Compounds in Aqueous Environments: From Alkanes and Alcohols to Pharmaceuticals. *Ind Eng Chem Res* **2017**, *56* (38), 10856–10876.
3. Diamanti, A.; Adjiman, C. S.; Piccione, P. M.; Rea, A. M.; Galindo, A., Development of Predictive Models of the Kinetics of a Hydrogen Abstraction Reaction Combining Quantum-Mechanical Calculations and Experimental Data. *Ind Eng Chem Res* **2017**, *56* (4), 815–831.
4. Galvanin, F.; Psyrraki, C.; Morris, T.; Gavriilidis, A., Development of a kinetic model of ethylene methoxycarbonylation with homogeneous Pd catalyst using a capillary microreactor. *Chemical Engineering Journal* **2017**, *329*, 25–34.
5. Chremos, A.; Forte, E.; Papaioannou, V.; Galindo, A.; Jackson, G.; Adjiman, C. S., Modelling the phase and chemical equilibria of aqueous solutions of alkanolamines and carbon dioxide using the SAFT-γ SW group contribution approach. *Fluid Phase Equilibria* **2016**, *407*, 280–297.
6. Jonuzaj, S.; Akula, P. T.; Kleniati, P.-M.; Adjiman, C. S., The formulation of optimal mixtures with generalized disjunctive programming: A solvent design case study. *AIChE Journal* **2015**, *62* (5), 1616–1633.
7. Struebing, H.; Obermeier, S.; Siougkrou, E.; Adjiman, C. S.; Galindo, A., A QM-CAMD approach to solvent design for optimal reaction rates. *Chemical Engineering Science* **2017**, *159*, 69–83.
8. Gonzalez-Garay, A.; Gonzalez-Miquel, M.; Guillen-Gosalbez, G., High-Value Propylene Glycol from Low-Value Biodiesel Glycerol: A Techno-Economic and Environmental Assessment under Uncertainty. *ACS Sustainable Chemistry & Engineering* **2017**, *5* (7), 5723–5732.
9. Hankin, A.; Shah, N., Process exploration and assessment for the production of methanol and dimethyl ether from carbon dioxide and water. *Sustainable Energy & Fuels* **2017**, *1* (7), 1541–1556.
10. Giarola, S.; Romain, C.; Williams, C. K.; Hallett, J. P.; Shah, N., Techno-economic assessment of the production of phthalic anhydride from corn stover. *Chemical Engineering Research and Design* **2016**, *107*, 181–194.
11. Lin, Y.; Guo, M.; Shah, N.; Stuckey, D. C., Economic and environmental evaluation of nitrogen removal and recovery methods from wastewater. *Bioresource technology* **2016**, *215*, 227–238.
12. Kong, Q.; Shah, N., An optimisation-based framework for the conceptual design of reaction-separation processes. *Chemical Engineering Research and Design* **2016**, *113*, 206–222.
13. Kong, Q.; Shah, N., Development of an Optimization-Based Framework for Simultaneous Process Synthesis and Heat Integration. *Ind Eng Chem Res* **2017**, *56* (17), 5000–5013.
14. Zhang, D.; del Rio-Chanona, E. A.; Shah, N., Screening Synthesis Pathways for Biomass-Derived Sustainable Polymer Production. *ACS Sustainable Chemistry & Engineering* **2017**, *5* (5), 4388–4398.
15. Koleva, M. N.; Styan, C. A.; Papageorgiou, L. G., Optimisation approaches for the synthesis of water treatment plants. *Computers & Chemical Engineering* **2017**, *106*, 849–871.
16. Leeson, D.; Fennell, P.; Mac Dowell, N.; Shah, N., Simultaneous design of separation sequences and whole process energy integration. *Chemical Engineering Research and Design* **2017**, *125*, 166–180.
17. Ibrahim, D.; Jobson, M.; Guillén-Gosálbez, G., Optimization-Based Design of Crude Oil Distillation Units Using Rigorous Simulation Models. *Ind Eng Chem Res* **2017**, *56* (23), 6728-6740.





18. Gopinath, S.; Jackson, G.; Galindo, A.; Adjiman, C. S., Outer approximation algorithm with physical domain reduction for computer-aided molecular and separation process design. *AIChE Journal* **2016**, *62* (9), 3484–3504.
19. Liu, S.; Gerontas, S.; Gruber, D.; Turner, R.; Titchener-Hooker, N. J.; Papageorgiou, L. G., Optimization-based framework for resin selection strategies in biopharmaceutical purification process development. *Biotechnology progress* **2017**, *33* (4), 1116–1126.
20. Onishi, V. C.; Carrero-Parreño, A.; Reyes-Labarta, J. A.; Fraga, E. S.; Caballero, J. A., Desalination of shale gas produced water: A rigorous design approach for zero-liquid discharge evaporation systems. *Journal of Cleaner Production* **2017**, *140*, 1399–1414.
21. Carrero-Parreño, A.; Onishi, V. C.; Salcedo-Díaz, R.; Ruiz-Femenia, R.; Fraga, E. S.; Caballero, J. A.; Reyes-Labarta, J. A., Optimal Pretreatment System of Flowback Water from Shale Gas Production. *Ind Eng Chem Res* **2017**, *56* (15), 4386–4398.
22. Charitopoulos, V. M.; Dua, V.; Papageorgiou, L. G., Traveling Salesman Problem-Based Integration of Planning, Scheduling, and Optimal Control for Continuous Processes. *Ind Eng Chem Res* **2017**, *56* (39), 11186–11205.
23. Aguirre, A. M.; Liu, S.; Papageorgiou, L. G., Mixed Integer Linear Programming Based Approaches for Medium-Term Planning and Scheduling in Multiproduct Multistage Continuous Plants. *Ind Eng Chem Res* **2017**, *56* (19), 5636–5651.
24. Vieira, M.; Pinto-Varela, T.; Moniz, S.; Barbosa-Póvoa, A. P.; Papageorgiou, L. G., Optimal planning and campaign scheduling of biopharmaceutical processes using a continuous-time formulation. *Computers & Chemical Engineering* **2016**, *91*, 422–444.
25. Fernández, D.; Pozo, C.; Folgado, R.; Guillén-Gosálbez, G.; Jiménez, L., Multiperiod model for the optimal production planning in the industrial gases sector. *Applied Energy* **2017**, *206*, 667–682.
26. Liu, S.; Alhasan, I.; Papageorgiou, L. G., A mixed integer linear programming model for the optimal operation of a network of gas oil separation plants. *Chemical Engineering Research and Design* **2016**, *111*, 147–160.

## 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.

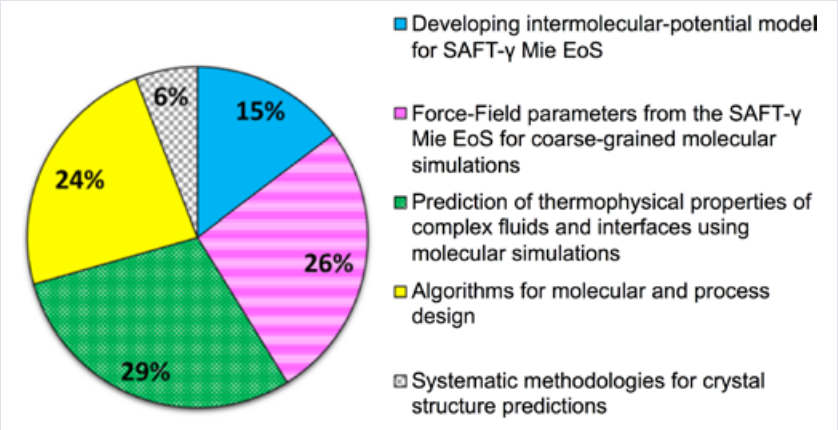


**Figure 1:** *Percentages of recent research works published in the application areas indicated in the legend.*



### 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.

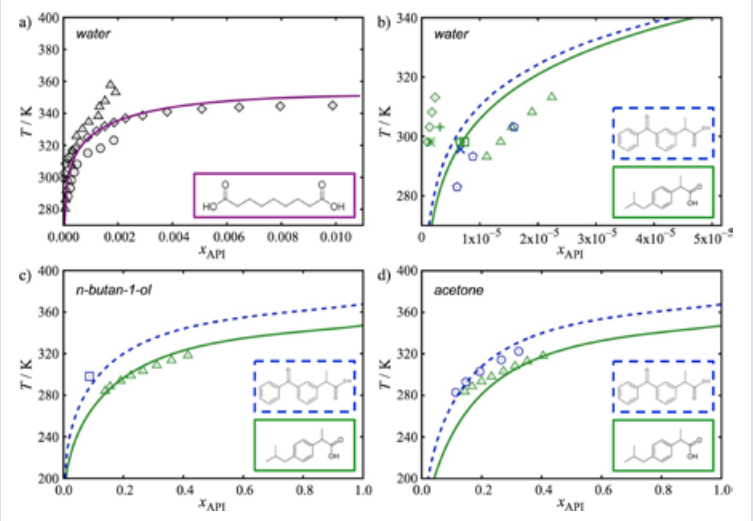


**Figure 2:** *Prediction of solid-liquid equilibria of active pharmaceutical ingredients (APIs) in different solvents as a function of temperature at ambient pressure (p = 0.101MPa). The symbols represents the experimental data and the continuous and dashed curves the description with the SAFT-γ-Mie approach:(a) azelaic acid in water; (b) ibuprofen and ketoprofen in water; (c) ibuprofen in n-butan-1-ol; and (d) ibuprofen and ketoprofen in acetone[1].*

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 prospective. 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.[2] 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.[3]considers mixtures of *n*-alkanes (methane and alkanes) and carbon dioxide ($CO_2$). 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, caloric 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.[4] 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 $CO_2$ emissions. Many works have focused on $CO_2$ absorption using amines, especially monoethanolamine (MEA), in order to minimize the energy consumption of the process and the $CO_2$ 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 $CO_2$. Furthermore, they can identify new solvents or highlight the best operating conditions and mixtures that lead to optimal performance without exhaustive reliance on experimental data. In this context, Brand et al.[5] adopt a physical approach to model the chemical equilibria inherent to the reactive capture of $CO_2$ 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.

Lobavanova et al.[6] 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 anomalous miscibility of $CO_2$ 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[7] 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.[8] 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.[9,10] 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. The missing parameter in the equation (the influence parameter) is calculated through molecular simulations. The large database of pseudo-data produced allowed the development of a predictive correlation with an accuracy that surpasses most (if not all) available correlations.

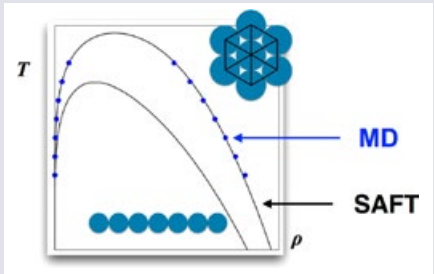


**Figure 3:** *Phase equilibrium (ϱ–T projection) of linear and ring molecules described using molecular-dynamics simulations and the SAFT-VR Mie EoS approach.*[13]

The classical theoretical SAFT approach restricts the model to chains of segments connected in a linear fashion. The recent paper by Müller et al.[13] extends the SAFT approach to consider ring molecules. The agreement of the theory and the simulations allows the EoS to be used to back-trace parameters for the coarse-graining models. It is interesting to note that the thermophysical behaviour of ring molecules is significantly different from that of linear chains (see Figure 3).

Parameters for SAFT force field can also be derived from Bottled SAFT[14], 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.[15].

## 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 desalinization of water, the flow of gases and crude oils through reservoirs and the efficient separation of gases[16-20]. 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, a continuous distribution of cluster sizes was observed with average aggregation number ranging between 3.6 and 5.6, monomers and dimers being the predominant species. As expected for mixtures in heptane, the asphaltene molecules tend to aggregate to form a segregated phase.

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.[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.[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.[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.



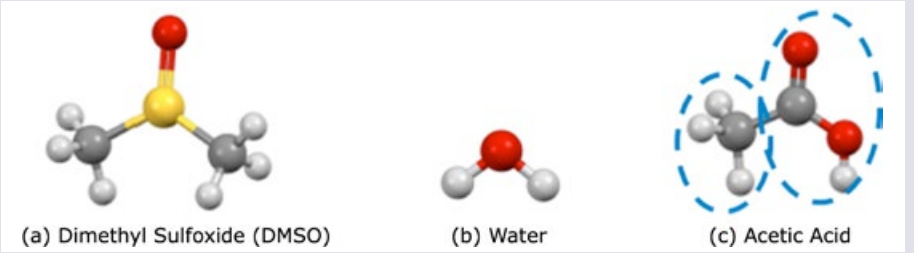


**Figure 4:** *Solvent (a) and antisolvent (b, c) molecular structures for drowning out crystallization. The solvent and antisolvent compounds are built from UNIFAC groups*[28].

## 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.[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.[30] 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).

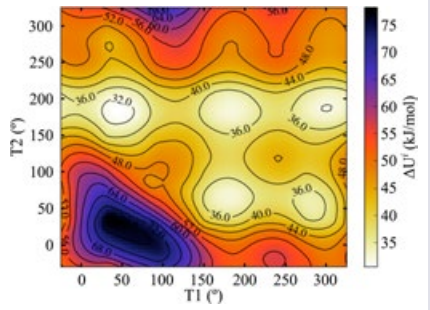


**Figure 5:** *Intramolecular energy variation in β-D-Glucose, as a function of two of the flexible torsions.*

## References


1. Panatpong Hutacharoen, Simon Dufal, Vasileios Papaioannou, Ravi M Shanker, Claire S Adjiman, George Jackson, and Amparo Galindo. Predicting the solvation of organic compounds in aqueous environments: from alkanes and alcohols to pharmaceuticals. *Industrial & Engineering Chemistry Research*, 56(38):10856–10876, 2017.
2. Majid Sadeqzadeh, Vasileios Papaioannou, Simon Dufal, Claire S. Adjiman, George Jackson, and Amparo Galindo. The development of unlike induced association-site models to study the phase behaviour of aqueous mixtures comprising acetone, alkanes and alkyl carboxylic acids with the SAFT-γ Mie group contribution methodology. *Fluid Phase Equilibria*, 407:39 – 57, 2016.
3. Vasileios Papaioannou, Filipe Calado, Thomas Lafitte, Simon Dufal, Majid Sadeqzadeh, George Jackson, Claire S Adjiman, and Amparo Galindo. Application of the SAFT-γ mie group contribution equation of state to fluids of relevance to the oil and gas industry. *Fluid Phase Equilibria*, 416:104–119, 2016.
4. Daniel K Eriksen, Georgia Lazarou, Amparo Galindo, George Jackson, Claire S Adjiman, and Andrew J Haslam. Development of intermolecular potential models for electrolyte solutions using an electrolyte SAFT-VR Mie equation of state. *Molecular Physics*, 114(18):2724–2749, 2016.
5. Charles V Brand, Edward Graham, Javier Rodríguez, Amparo Galindo, George Jackson, and Claire S Adjiman. On the use of molecular-based thermodynamic models to assess the performance of solvents for $CO_2$ capture processes: monoethanolamine solutions. *Faraday discussions*, 192:337–390, 2016.X
6. Olga Lobanova, Andrés Mejía, George Jackson, and Erich A Müller. SAFT-γ force field for the simulation of molecular fluids 6: Binary and ternary mixtures comprising water, carbon dioxide, and n-alkanes. *The Journal of Chemical Thermodynamics*, 93:320–336, 2016.
7. Guadalupe Jiménez-Serratos, Carmelo Herdes, Andrew J Haslam, George Jackson, and Erich A Müller. Group contribution coarse-grained molecular simulations of polystyrene melts and polystyrene solutions in alkanes using the SAFT-γ force field. *Macromolecules*, 50(12):4840–4853, 2017.
8. Binwu Zhao, Tom Lindeboom, Steven Benner, George Jackson, Amparo Galindo, and Carol K Hall. Predicting the fluid-phase behavior of aqueous solutions of ELP (VPGVG) sequences using SAFT-VR. *Langmuir*, 33(42):11733–11745, 2017.
9. Carmelo Herdes, Esther Forte, George Jackson, and Erich A Müller. Predicting the adsorption of n-perfluorohexane in bam-p109 standard activated carbon by molecular simulation using saft-γ mie coarse-grained force fields. *Adsorption Science & Technology*, 34(1):64–78, 2016.
10. Carmelo Herdes, Åsmund Ervik, Andrés Mejía, and Erich A Müller. Prediction of the water/oil interfacial tension from molecular simulations using the coarse-grained SAFT-γ Mie force field. *Fluid Phase Equilibria*, 2017.
11. Pedro Morgado, Olga Lobanova, Erich A Müller, George Jackson, Miguel Almeida, and Eduardo JM Filipe. SAFT-γ force field for the simulation of molecular fluids: 8. Hetero-segmented coarse-grained models of perfluoroalkylalkanes assessed with new vapour–liquid interfacial tension data. *Molecular Physics*, 114(18):2597–2614, 2016.
12. José Matías Garrido, Andrés Mejía, Manuel M Piñeiro, Felipe J Blas, and Erich A Müller. Interfacial tensions of industrial fluids from a molecular-based square gradient theory. *AIChE Journal*, 62(5):1781–1794, 2016.
13. Erich A Müller and Andrés Mejía. Extension of the SAFT-VR Mie EoS to model homonuclear rings and its parametrization based on the principle of corresponding states. *Langmuir*, 33(42):11518–11529, 2017.
14. Åsmund Ervik, Andrés Mejía, and Erich A Müller. Bottled SAFT: a web app providing saft-γ mie force field parameters for thousands of molecular fluids. *Journal of chemical information and modeling*, 56(9):1609–1614, 2016.
15. Åsmund Ervik, Guadalupe Jiménez Serratos, and Erich A Müller. raasaft: A framework enabling coarse-grained molecular dynamics simulations based on the saft-γ mie force field. *Computer Physics Communications*, 212:161–179, 2017.
16. Åsmund Ervik, Morten Olsen Lysgaard, Carmelo Herdes, Guadalupe Jiménez-Serratos, Erich A Müller, Svend Tollak Munkejord, and Bernhard Müller. A multiscale method for simulating fluid interfaces covered with large molecules such as asphaltenes. *Journal of Computational Physics*, 327:576–611, 2016.
17. Daniel Barreda, Ana Matilde Pérez-Mas, Ana Silvestre-Albero, Mirian Elizabeth Casco, Svemir Rudić, Carmelo Herdes, Erich A Müller, Clara Blanco, Ricardo Santamaria, Joaquín Silvestre-Albero, et al. Unusual flexibility of mesophase pitch-derived carbon materials: An approach to the synthesis of graphene. *Carbon*, 115:539–545, 2017.
18. E R Smith, E A Müller, RV Craster, and O K Matar. A langevin model for fluctuating contact angle behaviour parametrised using molecular dynamics. *Soft matter*, 12(48):9604–9615, 2016.
19. Jordan Muscatello, Erich A Müller, Arash A Mostofi, and Adrian P Sutton. Multiscale molecular simulations of the formation and structure of polyamide membranes created by interfacial polymerization. *Journal of Membrane Science*, 527:180–190, 2017.
20. Jordan Muscatello, Frederike Jaeger, Omar K Matar, and Erich A Müller. Optimizing water transport through graphene-based membranes: insights from nonequilibrium molecular dynamics. *ACS applied materials & interfaces*, 8(19):12330–12336, 2016.
21. Paul E Brumby, Henricus H Wensink, Andrew J Haslam, and George Jackson. Structure and interfacial tension of a hard-rod fluid in planar confinement. *Langmuir*, 33(42):11754–11770, 2017.
22. Carlos Braga, Jordan Muscatello, Gabriel Lau, Erich A Müller, and George Jackson. Nonequilibrium study of the intrinsic free-energy profile across a liquid-vapour interface. *The Journal of chemical physics*, 144(4):044703, 2016.
23. TF Headen, ES Boek, George Jackson, TS Totton, and Erich A Müller. Simulation of asphaltene aggregation through molecular dynamics: Insights and limitations. *Energy & Fuels*, 31(2):1108–1125, 2017.
24. Carlos Avendaño, George Jackson, Erich A Müller, and Fernando A Escobedo. Assembly of porous smectic structures

formed from interlocking high-symmetry planar nanorings. *Proceedings of the National Academy of Sciences*, 113(35):9699–9703, 2016.

25. Heiko Struebing, Stephan Obermeier, Eirini Siougkrou, Claire S Adjiman, and Amparo Galindo. A QM-CAMD approach to solvent design for optimal reaction rates. *Chemical Engineering Science*, 159:69–83, 2017.
26. Aikaterini Diamanti, Claire S Adjiman, Patrick M Piccione, Anita M Rea, and Amparo Galindo. Development of predictive models of the kinetics of a hydrogen abstraction reaction combining quantum-mechanical calculations and experimental data. *Industrial & Engineering Chemistry Research*, 56:815–831, 2017.
27. Smitha Gopinath, George Jackson, Amparo Galindo, and Claire S Adjiman. Outer approximation algorithm with physical domain reduction for computer-aided molecular and separation process design. *AIChE Journal*, 62(9):3484–3504, 2016.
28. Suela Jonuzaj, Aparana Gupta, and Claire S Adjiman. The design of optimal mixtures from atom groups using generalized disjunctive programming. *Computers & Chemical Engineering*, 2018.
29. Matthew Habgood, Isaac J Sugden, Andrei V Kazantsev, Claire S Adjiman, and Constantinos C Pantelides. Efficient handling of molecular flexibility in Ab initio generation of crystal structures. *Journal of chemical theory and computation*, 11(4):1957–1969, 2015.
30. Isaac Sugden, Claire S Adjiman, and Constantinos C Pantelides. Accurate and efficient representation of intramolecular energy in ab initio generation of crystal structures.I. Adaptive local approximate models. *Acta Crystallographica Section B: Structural Science, Crystal Engineering and Materials*, 72(6):864–874, 2016.



## 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 Panoskaltsis 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; Dos Santos et al., 2017; Velliou et al., 2017b; 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

reducing time-to-market. CPSE researchers are collaborating with Bayer and the University of Aachen (Germany).

Bioprocess optimization studies are being conducted by Dr Ruth Misener whose group is developing algorithms for bioprocess optimization under uncertainty. Robust optimisation 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, $pCO_2$, 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.



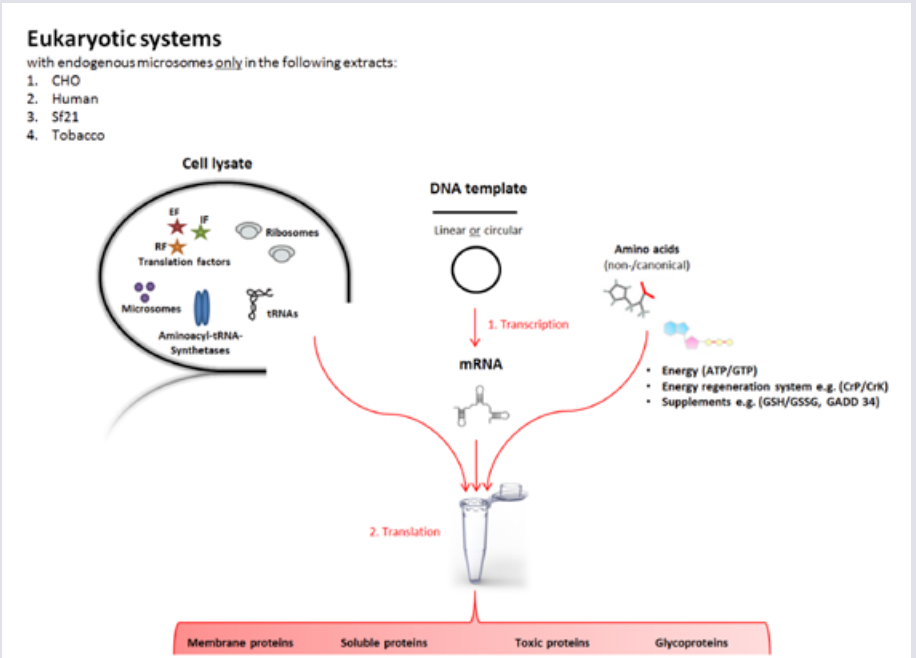


**Figure 1:** *Illustration of a cell-free protein synthesis system in linked mode (IF = Initiation factors, EF = Elongation factors, RF = Release factor). Proteins can be expressed from linear or circular plasmids, as well as PCR products. Based on the organism from which the cell extract is prepared, different target proteins can be expressed. Some extract contain translocationally active microsomal vesicles for post-translational modifications.*

## 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).

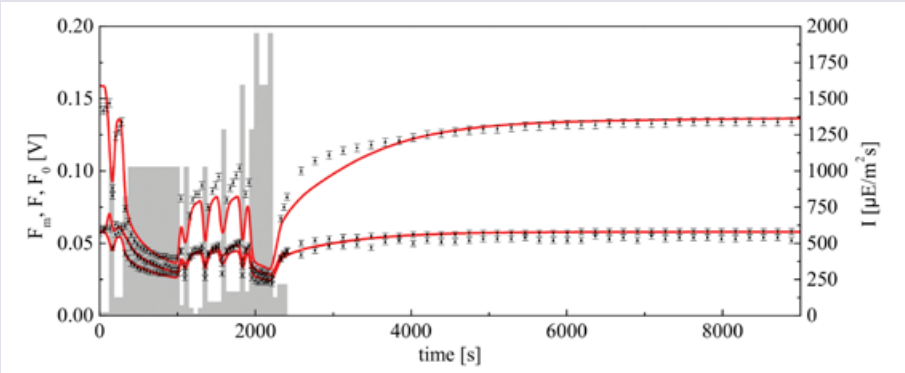


**Figure 2:** *PAM fluorescence profiles (points with error bars) compared with florescence flux predictions (red line) for an experiment with fast and slow changing light irradiance levels (gray-shaded area).*

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.

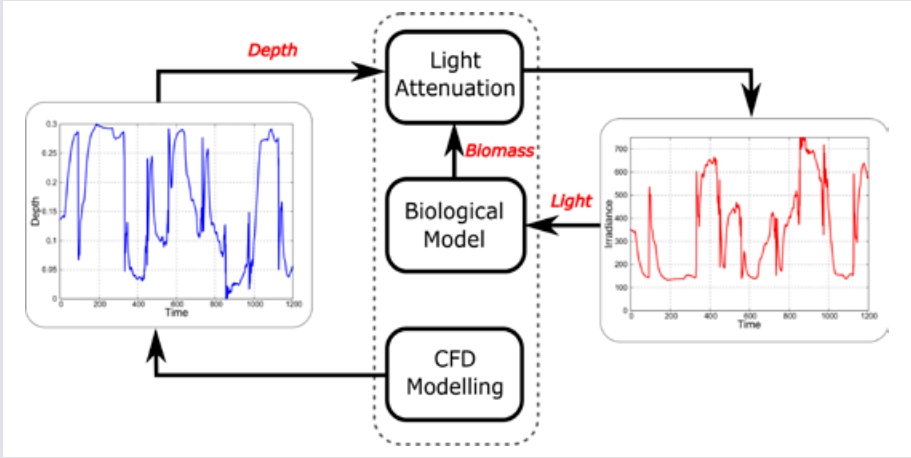


**Figure 3:** *Coupling methodology of photosynthesis kinetics, hydrodynamics and light attenuation in a multiphysics simulator of microaglae culture in raceway ponds.*

## 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.

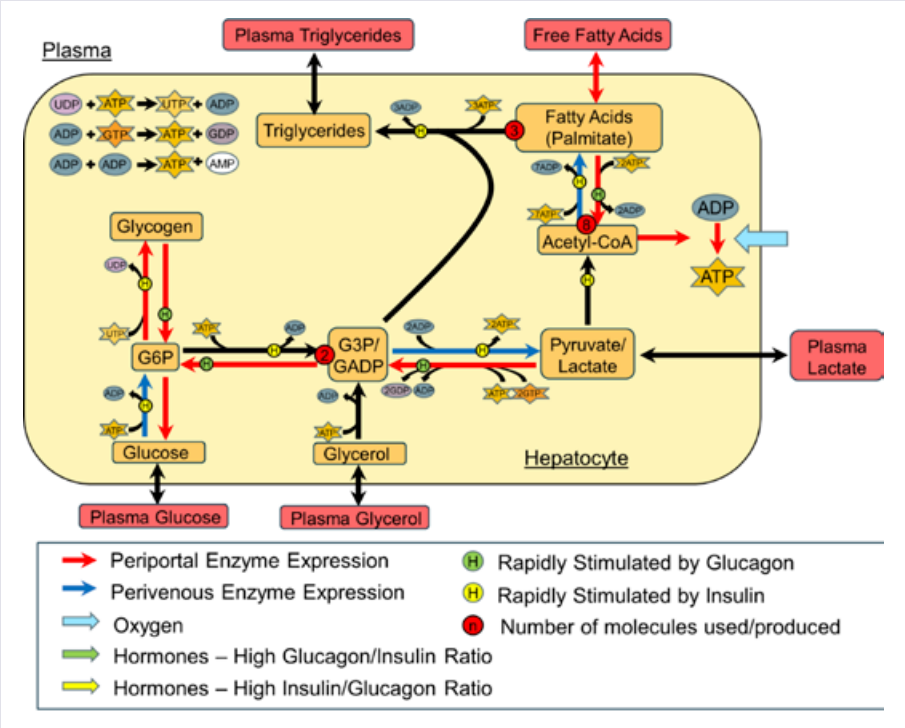


**Figure 4:** *Metabolic processes in Hepatocytes (liver cells).*

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.



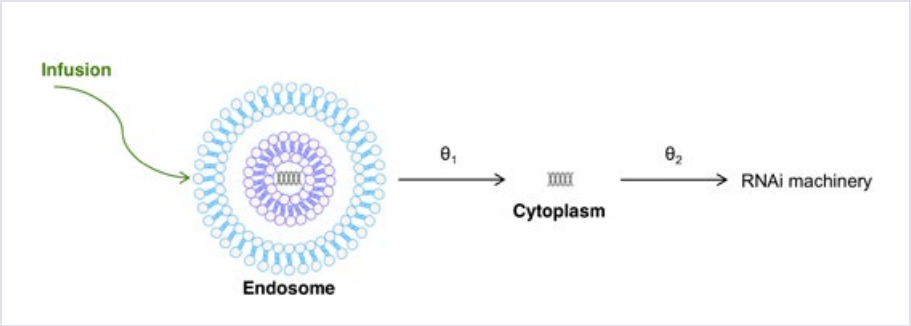


**Figure 5:** *Two-compartment model with infusion. A representation of the compartmentalization where θ» represents the rate constants:θ# controls movement out of the endosome and θ$ controls movement from the cytoplasm to the RNAi machinery.*

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.

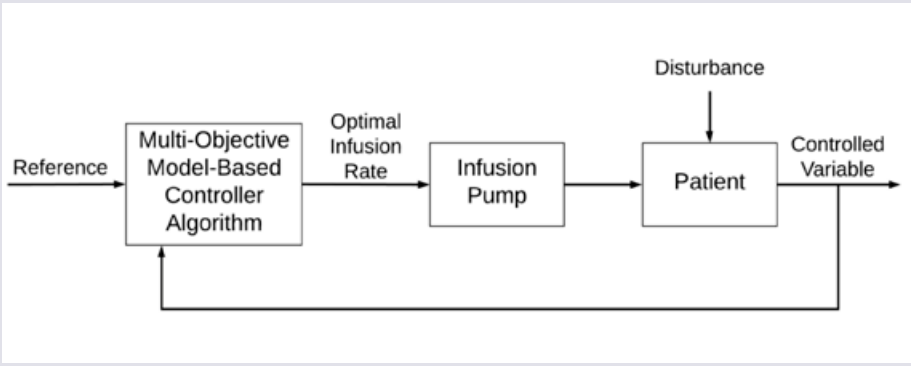


**Figure 6:** *Block diagram for a model-based optimal control of gene delivery. Depending on the disease type, the patient output variable of interest could be measured and supplied to a control algorithm.*

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 (intrinsic 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, PfSET7, 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 PfSET7 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 PfSET7, provide important therapeutic opportunities for targeting malaria.

Systems biology is also being studied as a means to improve bioprocess development. Dr. Kiparissides and co-workers 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


**31.** Allenby MC, Misener R, Panoskaltsis N, Mantalaris A. 2017. A Quantitative Three-Dimensional Image Analysis Tool for Maximal Acquisition of Spatial Heterogeneity Data. *Tissue Eng. Part C Methods* **23**:108–117. https://www.liebertpub.com/doi/10.1089/ten.tec.2016.0413.

**32.** Bernard O, Mairet F, Chachuat B. 2015. Modelling of Microalgae Culture Systems with Applications to Control and Optimization. In: Posten C., FCS, editor. *Microalgae Biotechnol. Adv. Biochem. Eng.* Spinger, pp. 59–87. http://link.springer.com/10.1007/10_2014_287.

**33.** Bernardi A, Nikolaou A, Meneghesso A, Chachuat B, Morosinotto T, Bezzo F. 2017. Semi-empirical modeling of microalgae photosynthesis in different acclimation states – Application to N. gaditana. *J. Biotechnol.* **259**:63–72. https://linkinghub.elsevier.com/retrieve/pii/S0168165617315882.

**34.** Bernardi A, Nikolaou A, Meneghesso A, Morosinotto T, Chachuat B, Bezzo F. 2016. High-Fidelity Modelling Methodology of Light-Limited Photosynthetic Production in Microalgae. Ed. Ive De Smet. *PLoS One* **11**:e0152387. http://dx.plos.org/10.1371/journal.pone.0152387.

**35.** Brito dos Santos S, Allenby MC, Mantalaris A, Panoskaltsis N. 2016. Early Erythroid Development Is Enhanced with Hypoxia and Terminal Maturation with Normoxia in a 3D Ex Vivo Physiologic Eythropoiesis Model. *Blood* **128**:2453 LP-2453. http://www.bloodjournal.org/content/128/22/2453.abstract.

**36.** Chen PB, Ding S, Zanghì G, Soulard V, DiMaggio PA, Fuchter MJ, Mecheri S, Mazier D, Scherf A, Malmquist NA. 2016. Plasmodium falciparum PfSET7: enzymatic characterization and cellular localization of a novel protein methyltransferase in

sporozoite, liver and erythrocytic stage parasites. *Sci. Rep.* **6**:21802. http://www.nature.com/articles/srep21802.

**37.** E. Klontzas M, I. Kenanidis E, J. MacFarlane R, Michail T, E. Potoupnis M, Heliotis M, Mantalaris A, Tsiridis E. 2016. Investigational drugs for fracture healing: preclinical & clinical data. *Expert Opin. Investig. Drugs* **25**:585–596. http://www.tandfonline.com/doi/full/10.1517/13543784.2016.1161757.

**38.** Goers L, Ainsworth C, Goey CH, Kontoravdi C, Freemont PS, Polizzi KM. 2017. Whole-cell Escherichia coli lactate biosensor for monitoring mammalian cell cultures during biopharmaceutical production. *Biotechnol. Bioeng.* **114**:1290–1300. http://doi.wiley.com/10.1002/bit.26254.

**39.** Goey CH, Tsang JMH, Bell D, Kontoravdi C. 2017. Cascading effect in bioprocessing-The impact of mild hypothermia on CHO cell behavior and host cell protein composition. *Biotechnol. Bioeng.* **114**:2771–2781. http://doi.wiley.com/10.1002/bit.26437.

**40.** Győrgy R, Klontzas ME, Kostoglou M, Panoskaltsis N, Georgiadis MC, Mantalaris A. 2017a. An Integrated Experimental-Modelling Approach of Mesenchymal Stem Cell Bioprocess towards Osteogenic Differentiation. *IFAC-PapersOnLine* **50**:9877–9882. https://linkinghub.elsevier.com/retrieve/pii/S2405896317322012.

**41.** Győrgy R, Klontzas ME, Kostoglou M, Panoskaltsis N, Mantalaris A, Georgiadis MC. 2017b. A Population Balance Model for Stem Cell Differentiation Bioprocesses. *Comput. Aided Chem. Eng.* **39**:2761–2766. https://linkinghub.elsevier.com/retrieve/pii/B9780444639653504621.

**42.** Klontzas ME, Vernardis SI, Heliotis M, Tsiridis E, Mantalaris A. 2017. Metabolomics Analysis of the Osteogenic Differentiation of Umbilical Cord Blood Mesenchymal Stem Cells Reveals Differential Sensitivity to Osteogenic Agents. *Stem Cells Dev.* **26**:723–733. https://www.liebertpub.com/doi/10.1089/scd.2016.0315.

**43.** Klymenko O V., Shah N, Kontoravdi C, Royle KE, Polizzi KM. 2016. Designing an Artificial Golgi reactor to achieve targeted glycosylation of monoclonal antibodies. *AIChE J.* **62**:2959–2973. http://doi.wiley.com/10.1002/aic.15388.

**44.** Menon G, Okeke C, Krishnan J. 2017. Modelling compartmentalization towards elucidation and engineering of spatial organization in biochemical pathways. *Sci. Rep.* **7**. http://dx.doi.org/10.1038/s41598-017-11081-8.

**45.** Menon G, Krishnan J. 2016. Bridging the gap between modules in isolation and as part of networks: A systems framework for elucidating interaction and regulation of signalling modules. *J. Chem. Phys.* **145**:035103. http://aip.scitation.org/doi/10.1063/1.4953914.

**46.** Nikolaou A, Booth P, Gordon F, Yang J, Matar O, Chachuat B. 2016a. Multi-Physics Modeling of Light-Limited Microalgae Growth in Raceway Ponds. *IFAC-PapersOnLine* **49**:324–329. https://linkinghub.elsevier.com/retrieve/pii/S2405896316328105.

**47.** Nikolaou A, Hartmann P, Sciandra A, Chachuat B, Bernard O. 2016b. Dynamic coupling of photoacclimation and photoinhibition in a model of microalgae growth. *J. Theor. Biol.* **390**:61–72. https://linkinghub.elsevier.com/retrieve/pii/S0022519315005408.

**48.** Pefani E, Velliou EG, Panoskaltsis N, Mantalaris A, Georgiadis MC, Pistikopoulos EN. 2017. In silico Acute Myeloid Leukaemia. In: . *Model. Optim. Control Biomed. Syst.* Chichester, UK: John Wiley & Sons, Ltd, pp. 265–300. http://doi.wiley.com/10.1002/9781118965580.ch8.

**49.** Quiroga-Campano AL, Mantalaris A, Kostoglou M, Georgiadis M, Panoskaltsis N. 2017. Precision Chemotherapy for Patients with Acute Myeloid Leukemia Using the πiChemo Prediction and Optimization Tool. *Blood* **130**:2074 LP-2074. http://www.bloodjournal.org/content/130/Suppl_1/2074.abstract.

**50.** Dos Santos J, Enfield L, Dos Santos SB, Allenby MC, Zemenides S, Mantalaris A, Panoskaltsis N. 2017. Primary Chronic Lymphocytic Leukemia Cells Can be Maintained Long-Term in Serum-Free, Cytokine-Free 3D Culture. *Blood* **130**:2989 LP-2989. http://www.bloodjournal.org/content/130/Suppl_1/2989.abstract.

**51.** Savvopoulos S, Misener R, Panoskaltsis N, Pistikopoulos EN, Mantalaris A. 2016. A Personalized Framework for Dynamic Modeling of Disease Trajectories in Chronic Lymphocytic Leukemia. *IEEE Trans. Biomed. Eng.* **63**:2396–2404. http://ieeexplore.ieee.org/document/7416207/.

**52.** Sou SN, Jedrzejewski PM, Lee K, Sellick C, Polizzi KM, Kontoravdi C. 2017. Model-based investigation of intracellular processes determining antibody Fc-glycosylation under mild hypothermia. *Biotechnol. Bioeng.* **114**:1570– 1582. http://doi.wiley.com/10.1002/bit.26225.

**53.** del Val IJ, Polizzi KM, Kontoravdi C. 2016. A theoretical estimate for nucleotide sugar demand towards Chinese Hamster Ovary cellular glycosylation. *Sci. Rep.* **6**:28547. http://www.nature.com/articles/srep28547.

**54.** Velliou EG, Fuentes-Gari M, Misener R, Pefani E, Panoskaltsis N, Mantalaris A, Georgiadis MC, Pistikopoulos EN. 2017a. An Integrated Platform for the Study of Leukaemia. In: . *Model. Optim. Control Biomed. Syst.* Chichester, UK: John Wiley & Sons, Ltd, pp. 225–232. http://doi.wiley.com/10.1002/9781118965580.ch6.

**55.** Velliou EG, Pefani E, dos Santos SB, Fuentes-Gari M, Misener R, Panoskaltsis N, Mantalaris A, Georgiadis MC, Pistikopoulos EN. 2017b. In vitro Studies of Acute Myeloid Leukaemia. In: . *Model. Optim. Control Biomed. Syst.* Chichester, UK: John Wiley & Sons, Ltd, pp. 233–264. http://doi.wiley.com/10.1002/9781118965580.ch7.

**56.** Vernardis SI, Terzoudis K, Panoskaltsis N, Mantalaris A. 2017. Human embryonic and induced pluripotent stem cells maintain phenotype but alter their metabolism after exposure to ROCK inhibitor. *Sci. Rep.* **7**:42138. http://www.nature.com/articles/srep42138.

## 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.[1] Their proposed energy system for this single-user is shown in Fig. 1. Soltani et al.[2] evaluated the performance of post-combustion $CO_2$ 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.[3] 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.[4] 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.[5] 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.[6] proposes an MILP framework which integrates optimal operation and maintenance applied to a network of compressors of large compressors of chemical plants.



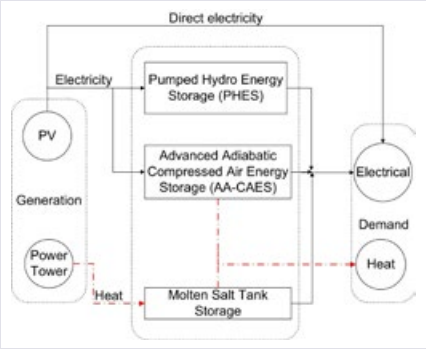


**Figure 1:** *Proposed integrated energy system for mining operation. The solid black lines show the possible electricity network while the broken red lines represent heat.*

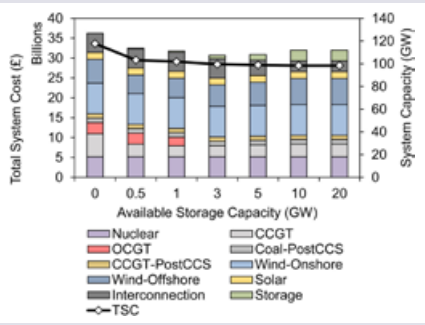


**Figure 2:** *Effect of MEA concentration in lean solvent on the reboiler energy efficiency (90% $CO_2$ capture, rich loading:0.5, 0.20 lean loading).*

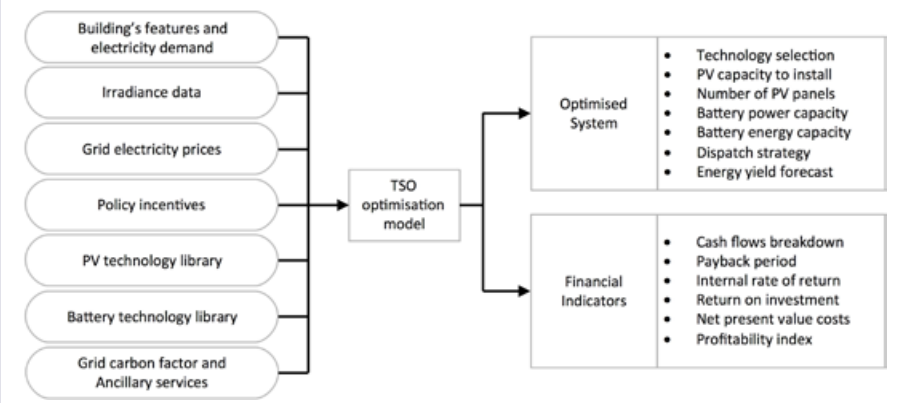


**Figure 3:** *Schematic diagram of SOFC-CCHP and conventional system.*

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.[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.[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.[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.[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.[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.

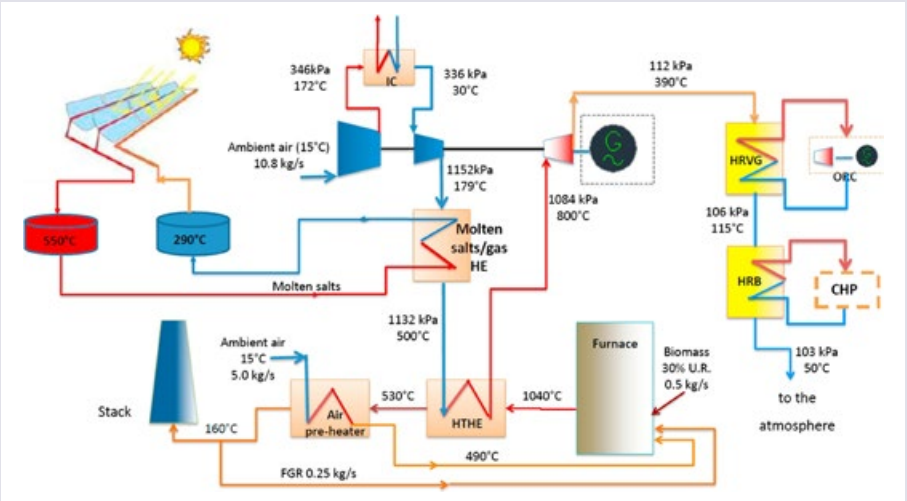


**Figure 4:** *Schematic representation of the Micro-grid.*

Micro-grids are decentralised networks that integrate electricity and heat generation systems close to the consumption points. Silvente and Papageorgiou[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.[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 ε-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.[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.

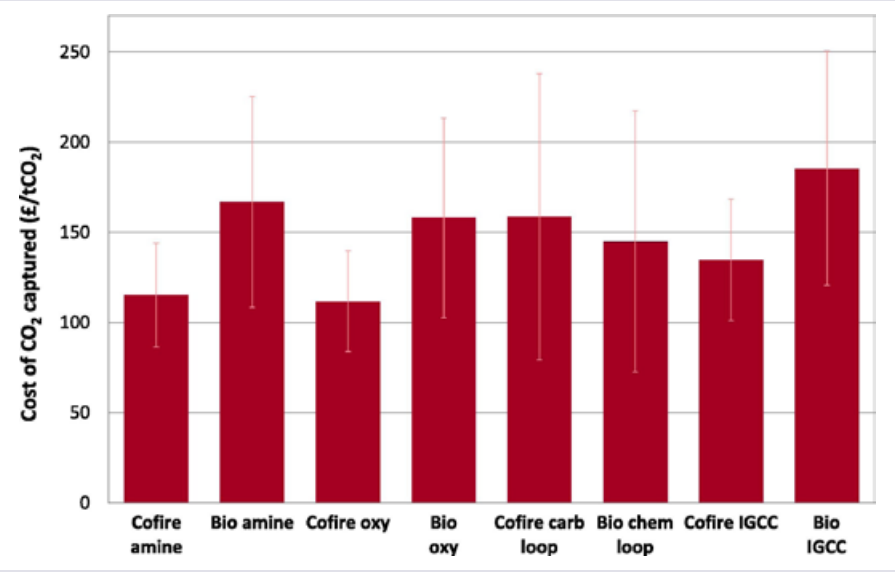


**Figure 5:** *Flow diagram of the Urban Energy System for the test case.*

## National Energy Systems

Decarbonising electricity systems on a national scale is essential to mitigating climate change. Vijay et al.[15] 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.[16] 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.[17] 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.

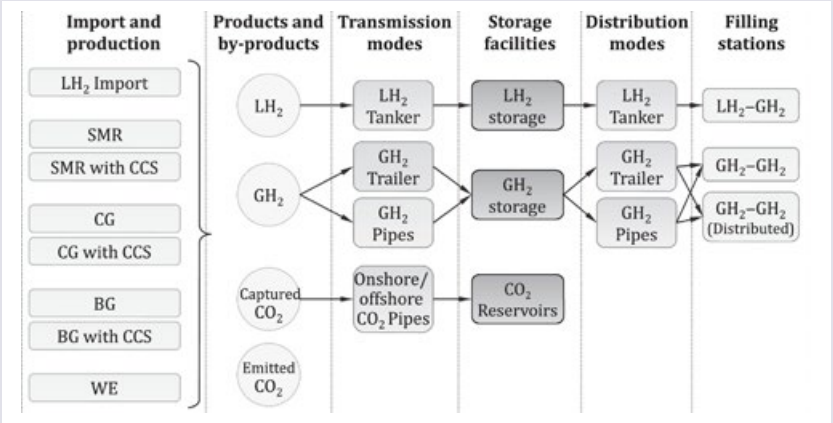


**Figure 6:** *Optimal capacity mix (right y-axis), and total system cost (left y-axis) under 2035 conditions depending on the level of CCGT post-combustion CCS capacity availability.*

## 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.[18] 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.



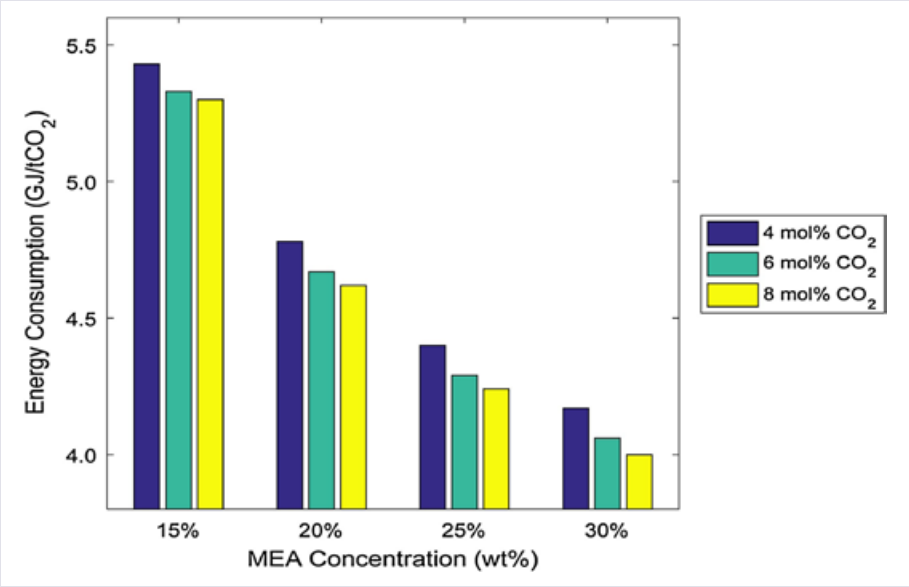


**Figure 7:** *Technical annual electricity generation potential (PWh yr–1) for onshore wind technologies for a range of annual average capacity factors. All countries included in the study (140) with annual average CFs above 15% are included, either on their own or aggregated into the associated region definition.*

Chavez-Rodriguez et al.[19] 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.[20] combine an integrated assessment model (TIAM-Grantham) representing $CO_2$ emissions (and their mitigation) from the fossil-fuel combustion and industrial sectors, coupled with a model covering non-$CO_2$ emissions (GAINS) to analyse the emissions and cost impacts of mitigation of non-$CO_2$ greenhouse gases at a global level, in scenarios aimed at meeting a range of long-term temperature goals.

Few et al.[21] 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.[22], using a model inter-comparison of three integrated assessment models (TIAM-Grantham, MESSAGE-GLOBIOM and WITCH) harmonized for

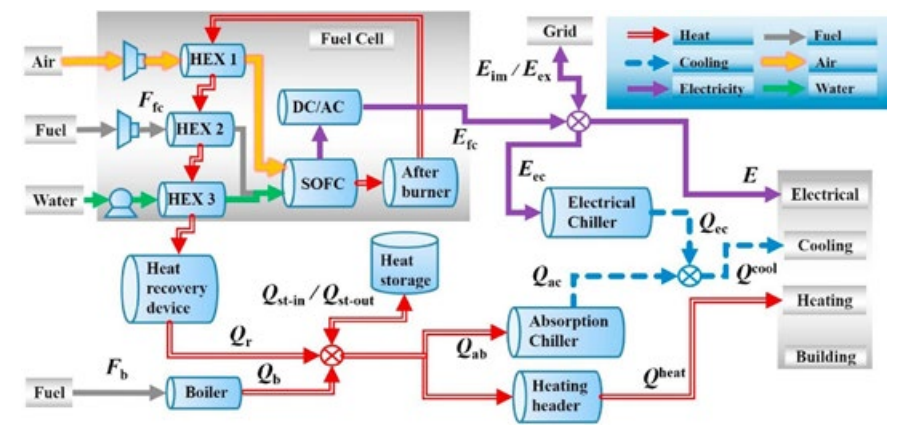


**Figure 8:** *Share of global primary energy supplied by (solid lines) all natural gas, and (dashed lines) shale gas in 2 °C consistent energy systems in a range of cost scenarios for conventional and shale gas. High-cost conventional, low-cost shale (HC_LS); medium-cost conventional, medium-cost shale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

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.[23] 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.

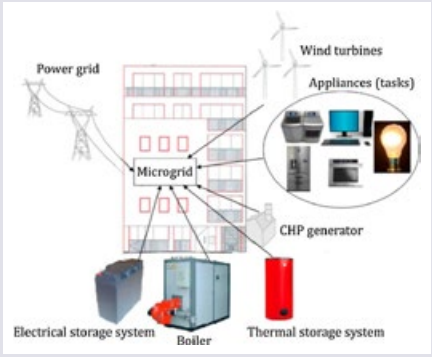


**Figure 9:** *Schematic illustrating the process used to derive emissions scenarios from $CO_2$ budgets and iterate for target temperature levels where appropriate. RCP:Representative Concentration Pathway; GHG:greenhouse gas; FFI:fossil fuels and industry; MAC:marginal abatement cost; MOHC:Met Office 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.[17] 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).

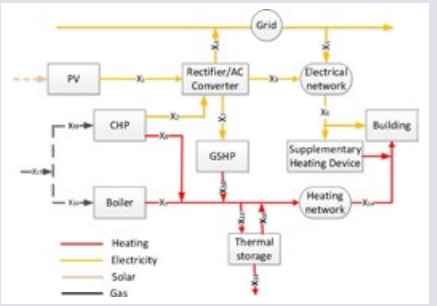


**Figure 10:** *Optimal capacity mix (right y-axis), and total system cost (left y-axis) under 2035 conditions depending on the level of grid-level energy-storage capacity availability.*

Mariaud et al.[24] 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.[25] 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].

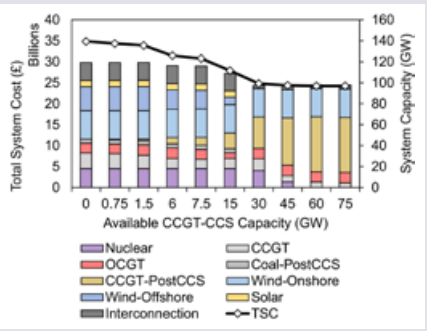


**Figure 11:** *Schematic description of the data inputs and output components of the TSO model.*

## 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.[1] 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.[18] characterise the technical and economic potential of global onshore wind energy based on a temporally-explicit Geospatial Information System (GIS). Pantaleo et al.[26] perform a techno-economic assessment of a hybrid solar-biomass combined heat and power

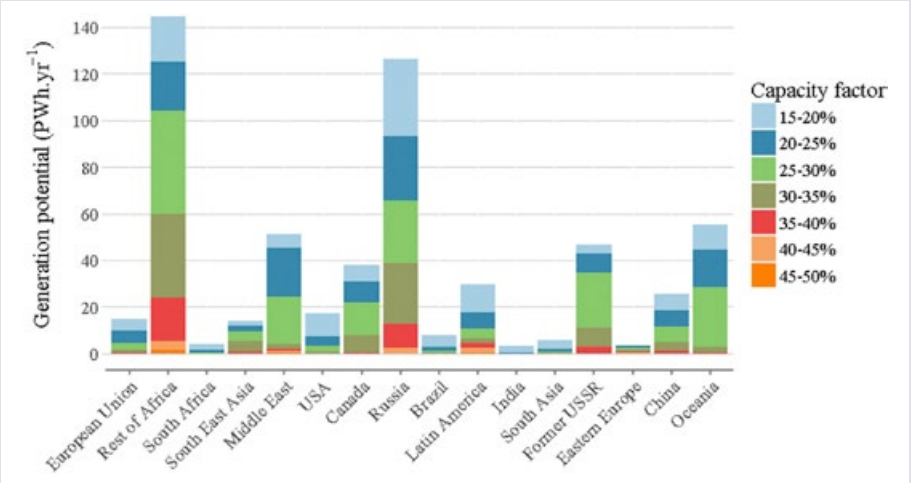


**Figure 12:** *Layout of the hybrid solar-biomass EFGT-ORC combined cycle power plant. Flow rate, temperature and pressure are referred to rated operating conditions.*

systems composed of a gas turbine, and bottoming Organic Rankine cycle as shown in Fig. 12.

Mariaud et al.[24] present a TSO model to optimise photovoltaic (PV) and battery systems. Herrando and Markides[27] 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.[28] 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[29]. Soltani et al.[2] simulate an MEA-based post-combustion $CO_2$ 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 $CO_2$ 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.[30] 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 $CO_2$ concentration. Bui et al.[31] 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 $CO_2$ 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.[32]. 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.

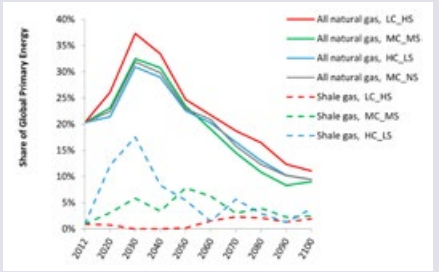


**Figure 13:** *Cost of $CO_2$ captured for the eight Biopower CCS technology options at 50 MWe.*

Alhajaj et al.[33] developed a detailed optimisation-orientated model of MEA-based $CO_2$ capture plant and compression train to simultaneously optimise the cost optimal control and design variables including feed fraction ratio at different degrees of capture. An optimisation methodology (based on MINLP) is presented to "right-size" $CO_2$ transport infrastructure in Mechleri et al.[34], explicitly accounting for the transient flow of $CO_2$ arising from the co-deploymentof intermittent renewable-energy generation. The impact of policy on CCS in power plant is studied in Zhang et al.[4] where an MILP model is developed for CCS infrastructure design under carbon trading, using two fairness scenarios.

## 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 $CO_2$ balance when carefully deployed. Bui et al.[35] address gap in efficiency improvement in biomass-fired plants via waste-heat recovery from the boiler system. Pantaleo et al.[26] 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[36]. Moreno-Benito,[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.

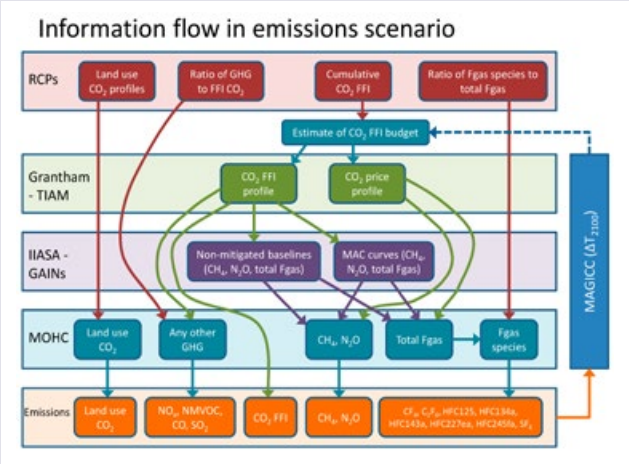


**Figure 14:** *Hydrogen and $CO_2$ pathways included in the optimisation framework. LH2 is liquid hydrogen, GH2 is gas hydrogen, SMR is steam methane reforming, BG is biomass gasification, WE is water electrolysis.*



## References


1. Amusat, O., Shearing, P. and **Fraga**, **E**. (2017). On the design of complex energy systems: Accounting for renewables variability in systems sizing. Computers & Chemical Engineering, 103, pp.103–115.
2. Soltani, S., Fennell, P. and **Mac Dowell**, **N**. (2017). A parametric study of CO 2 capture from gas- fired power plants using monoethanolamine (MEA). International Journal of Greenhouse Gas Control, 63, pp.321–328.
3. Xenos, D., Mohd Noor, I., Matloubi, M., Cicciotti, M., Haugen, T. and **Thornhill**, **N. F.** (2016). Demand-side management and optimal operation of industrial electricity consumers: An example of an energy-intensive chemical plant. Applied Energy, 182, pp.418–433.
4. Zhang, D., Alhorr, Y., Elsarrag, E., Marafia, A., Lettieri, P. and **Papageorgiou**, **L**. (2017). Fair design of CCS infrastructure for power plants in Qatar under carbon trading scheme. International Journal of Greenhouse Gas Control, 56, pp.43–54.
5. **Sharifzadeh**, **M**., Meghdari, M. and Rashtchian, D. (2017). Multi-objective design and operation of Solid Oxide Fuel Cell (SOFC) Triple Combined-cycle Power Generation systems: Integrating energy efficiency and operational safety. Applied Energy, 185, pp.345–361.
6. Xenos, P.D., Kopanos, G.M., Cicciotti, M., and **Thornhill**, **N.F.**, **2016**, Operational optimization of networks of compressors considering condition-based maintenance, Computers & Chemical Engineering, 84, 117–131.
7. Jing, R., Wang, M., **Brandon**, **N**. and Zhao, Y. (2017). Multi-criteria evaluation of solid oxide fuel cell based combined cooling heating and power (SOFC-CCHP) applications for public buildings in China. Energy, 141, pp.273–289.
8. Jing, R., Wang, M., Wang, W., **Brandon**, **N**., Li, N., Chen, J. and Zhao, Y. (2017). Economic and environmental multi-optimal design and dispatch of solid oxide fuel cell based CCHP system. Energy Conversion and Management, 154, pp.365–379.
9. Wouters, C., **Fraga**, **E**. and James, A. (2017). A multi-objective framework for cost-unavailability optimisation of residential distributed energy system design. Sustainable Energy, Grids and Networks, 9, pp.104–117.
10. Alvarado, C., D., Acha, S., **Shah**, **N**. and **Markides**, **C**. (2016). A Technology Selection and Operation (TSO) optimisation model for distributed energy systems: Mathematical formulation and case study. Applied Energy, 180, pp.491–503.
11. Delangle, A., Lambert, R., **Shah**, **N**., Acha, S. and **Markides**, **C**. (2017). Modelling and optimising the marginal expansion of an existing district heating network. Energy, 140, pp.209–223.
12. Silvente, J. and **Papageorgiou**, **L**. (2017). An MILP formulation for the optimal management of microgrids with task interruptions. Applied Energy, 206, pp.1131–1146.
13. Zhang, D., Evangelisti, S., Lettieri, P. and **Papageorgiou**, **L**. (2016). Economic and environmental scheduling of smart homes with microgrid: DER operation and electrical tasks. Energy Conversion and Management, 110, pp.113–124.
14. Zheng, X., Qiu, Y., Zhan, X., Zhu, X., Keirstead, J., **Shah**, **N**. and Zhao, Y. (2017). Optimization based planning of urban energy systems: Retrofitting a Chinese industrial park as a case-study. Energy, 139, pp.31–41.
15. Vijay, A., Fouquet, N., Staffell, I. and **Hawkes**, **A**. (2017). The value of electricity and reserve services in low carbon electricity systems. Applied Energy, 201, pp.111–123.
16. Limleamthong, P. and **Guillén-Gosálbez**, **G**. (2017). Rigorous analysis of Pareto fronts in sustainability studies based on bilevel optimization: Application to the redesign of the UK electricity mix. Journal of Cleaner Production, 164, pp.1602–1613.
17. Heuberger, C., Staffell, I., **Shah**, **N**. and **Mac Dowell**, **N**. (2017). A systems approach to quantifying the value of power generation and energy storage

technologies in future electricity networks. Computers & Chemical Engineering, 107, pp.247–256.

**18.** Bosch, J., Staffell, I. and **Hawkes**, **A**. (2017). Temporally-explicit and spatially-resolved global onshore wind energy potentials. Energy, 131, pp.207–217.

**19.** Chávez-Rodríguez M.F., Dias L., Simoes S., Seixas J., **Hawkes A.D.**, Szklo A., Lucena A.F.P. (2017) Modelling the role of natural gas in the Southern Cone of Latin America. Applied Energy 201, pp. 219–239.

**20.** Gambhir A., Napp T., **Hawkes A.D**., Hoglund-Isaksson L., Winiwarter W., Purohit P., Wagner F., Bernie D., Lowe J. (2017) The contribution of non-CO2 greenhouse gas mitigation to achieving long- term temperature goals. Energies 10(5) 602.

**21.** Few S., Gambhir A., Napp T., **Hawkes A.D**., Mangeon S., Bernie D., Lowe J. (2017) The impact of shale gas on the cost and feasibility of meeting climate targets – a global energy system model analysis and an exploration of uncertainties. Energies 10(2) 158.

**22.** Gambhir A., Drouet L., McCollum D., Napp T., Bernie D., **Hawkes A.D**., Fricko O., Havlik P., Riahi K., Bosetti V., Lowe J. (2017) Assessing the feasibility of global long-term mitigation scenarios. Energies 10(1) 89.

**23.** Napp T., Bernie D., Thomas R., Lowe J., **Hawkes A.D**., Gambhir A. (2017) Exploring the feasibility of low-carbon scenarios using historical energy transitions analysis. Energies 10(1) 116.

**24.** Mariaud, A., Acha, S., Ekins-Daukes, N., **Shah**, **N**. and **Markides**, **C**. (2017). Integrated optimisation of photovoltaic and battery storage systems for UK commercial buildings. Applied Energy, 199, pp.466–478.

**25.** Patsios, C., Wu, B., Chatzinikolaou, E., Rogers, D., Wade, N., **Brandon**, **N**. and Taylor, P. (2016). An integrated approach for the analysis and control of grid connected energy storage systems. Journal of Energy Storage, 5, pp.48–61.

**26.** Pantaleo, A., Camporeale, S., Miliozzi, A., Russo, V., **Shah**, **N**. and **Markides**, **C**. (2017). Novel hybrid CSP-biomass CHP for flexible generation: Thermo-economic analysis and profitability assessment. Applied Energy, 204, pp.994–1006.

**27.** Herrando, M. and **Markides**, **C**. (2016). Hybrid PV and solar-thermal systems for domestic heat and power provision in the UK: Techno-economic considerations. Applied Energy, 161, pp.512– 532.

**28.** **Sharifzadeh**, **M**., Lubiano-Walochik, H. and **Shah**, **N**. (2017). Integrated renewable electricity generation considering uncertainties: The UK roadmap to 50% power generation from wind and solar energies. Renewable and Sustainable Energy Reviews, 72, pp.385–398.

**29.** Budinis, S., **Mac Dowell**, N., Krevor, S., Dixon, T., Kemper, J. and **Hawkes**, **A.** (2017). Can Carbon Capture and Storage Unlock 'Unburnable Carbon'?. Energy Procedia, 114, pp.7504–7515.

**30.** Cabral, R. and **Mac Dowell**, **N**. (2017). A novel methodological approach for achieving £/MWh cost reduction of $CO_2$ capture and storage (CCS) processes. Applied Energy, 205, pp.529–539.

**31.** Bui, M., Fajardy, M. and **Mac Dowell**, **N**. (2017). Thermodynamic Evaluation of Carbon Negative Power Generation: Bio-energy CCS (BECCS). Energy Procedia, 114, pp.6010–6020.

**32.** Bhave, A., Taylor, R., Fennell, P., Livingston, W., **Shah**, **N**., **Mac Dowell**, **N**., Dennis, J., Kraft, M., Pourkashanian, M., Insa, M., Jones, J., Burdett, N., Bauen, A., Beal, C., Smallbone, A. and Akroyd, J. (2017). Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO2 targets. Applied Energy, 190, pp.481–489.

**33.** Alhajaj, A., **Mac Dowell**, **N**. and **Shah**, **N**. (2016). A techno-economic analysis of post-combustion $CO_2$ capture and compression applied to a combined cycle gas turbine: Part II. Identifying the cost-optimal control and design variables. International Journal of Greenhouse Gas Control, 52, pp.331–343.



**34.** Mechleri, E., Brown, S., Fennell, P. and **Mac Dowell**, **N**. (2017). $CO_2$ capture and storage (CCS) cost reduction via infrastructure right-sizing. Chemical Engineering Research and Design, 119, pp.130–139.

**35.** Bui, M., Fajardy, M. and **Mac Dowell**, **N**. (2017). Bio-Energy with CCS (BECCS) performance evaluation: Efficiency enhancement and emissions reduction. Applied Energy, 195, pp.289–302.

**36.** Moreno-Benito, M., Agnolucci, P. and **Papageorgiou**, **L**. (2017). Towards a sustainable hydrogen economy: Optimisation-based framework for hydrogen infrastructure development. Computers & Chemical Engineering, 102, pp.110–127.

## 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 $CO_2$ 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[1] (Fig 1). 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[1] was further improved by introducing photoacclimation process rules[2,3], 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 photo-production dynamic process[4]. The experimental verification demonstrated the predictive power of this ANN model, which could facilitate future investigation of lutein bioproduction process control and optimization.

In addition to the above modelling advances, CPSE researchers also explored the multi-scale modelling of algae. Nikolaou et al.[5] coupled an algae growth kinetic model with CFD models of imperfect mixing based on Lagrangian particle-tracking and heterogeneous light distribution. This study presents an approach to enable a realistic extrapolation of lab-scale measurements based on fluorometry and respirometry to large-scale algae cultivation in raceway ponds, which could be applied in the strain screening for improved productivity.

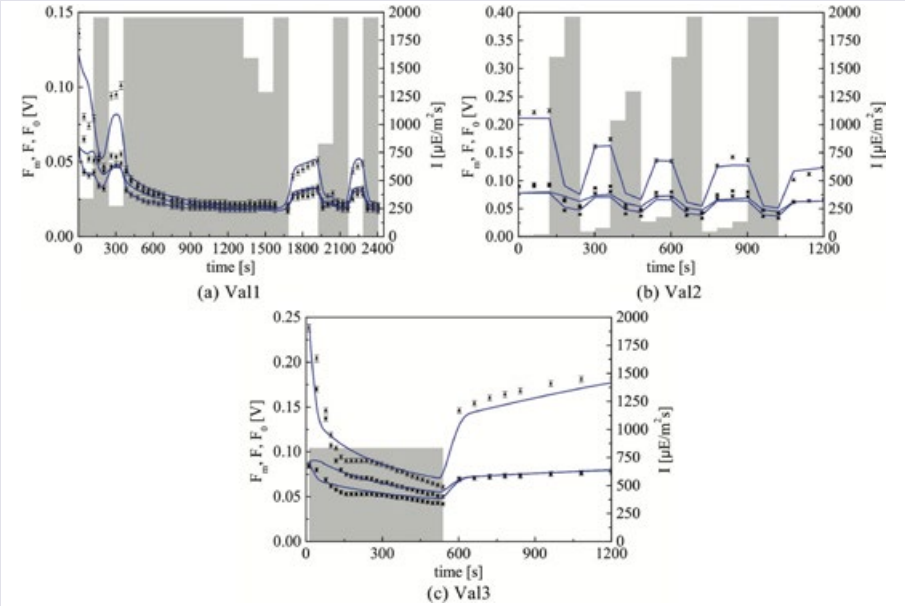


**Figure 1:** *Validation of the state model describing photoproduction and photoregulation and photoinhibition against experimental fluorescence fluxes* [1].

### 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 ϵ-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[14] to biochemical routes[11]. 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.[11] 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.[18] applied a reaction network flux balance method to screen over 100 synthesis pathways to identify the most promising low-carbon biopolymers. Limleamthong et al.[19] 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[13] 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[20]. 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[21]. A whole-systems model (shown in Fig 2) was developed[22] 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 [23].

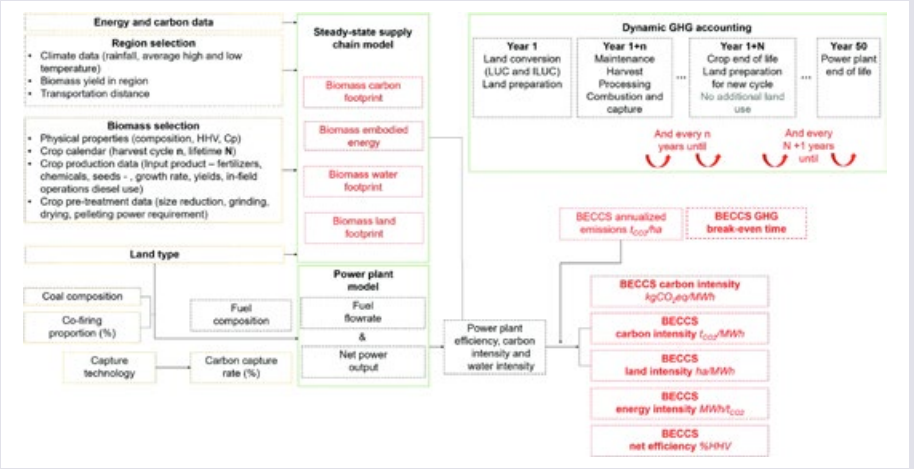


**Figure 2:** *Sub-model overview[22]. Biomass water, carbon, energy and land footprints were calculated using region specific data. The power plant modelled by IECM BECCS hydro, energy and carbon efficiencies were derived from supply chain and power plant models. The time-dependent carbon efficiency of BECCS was derived from GHG balance over a 50-year time horizon.*

## 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[24]. 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)[25]. This research confirmed the signification potential 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% $CO_2$ 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 technologies[26].

## Water treatment

The world water baseline scenario for year 2050 estimates that 5500 $km^3$ 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[27], 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.[27] presented a superstructure optimisation model to synthesize water-treatment technologies. The methodology was demonstrated in seawater desalination and surface-water-treatment optimisation problems[28].

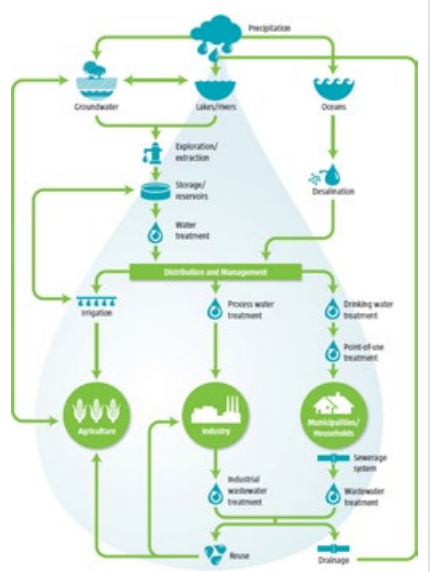


**Figure 3:** *Water path from precipitation to usage*[27].

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[29]. 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[30]. However, uncertainties in well data (e.g. flow rates, salinities) can hamper the process design tasks. Onishi et al.[31] 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.[32], 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[33].

## 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[16] and demand sides[34,35], addressing sustainability design under long-term strategic planning and mid/short-term operational decisions[36]. Another research challenge is dealing with uncertainty in the energy system. Recent progress in these areas is exemplified below.

Amusat et al.[37] 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[38] proposed a multi-parametric programming framework to solve multi-objective optimisation under uncertainty. They derived optimal solutions for electrical power systems that address the cost and environmental objectives simultaneously. Galán-Martín et al.[39] proposed a decision-making 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[40] to combine bi-level programming and multi-objective optimisation to identify the preferable pareto frontier solution, with applications to the UK electricity grid design.

The emerging role of fuel cells and hydrogen in energy decarbonisation has been highlighted[41,42]. 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[41] analysed the role of fuel cells in three hydrogen-production pathways namely power-to-gas, power-to-power and gas-to-gas (Fig 4).

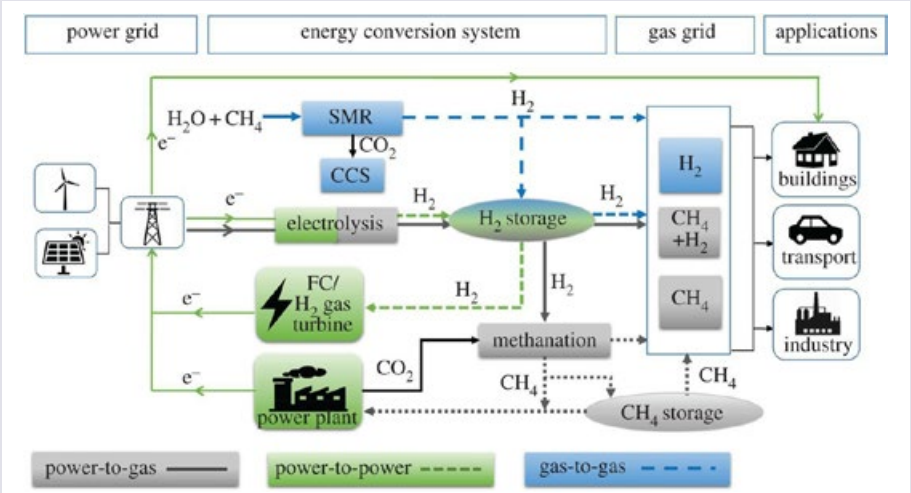


**Figure 4:** *Schematic diagram of main energy conversion pathways (power-to-gas, power-to-power and gas-to-gas) in a renewable energy integrated energy system. FC=fuel cell* [41].

Jing et al.[43] 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.[44] 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[43].

## 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[45] to building clusters e.g. industrial park[46]. Carreras et al.[47] 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[48].

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[46]. A mathematical modelling framework was also proposed to evaluate and optimise the life-cycle environmental impacts of mega-event project[49]. 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.[49] 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 re-development 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[50]. 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[51] (see Fig 5).

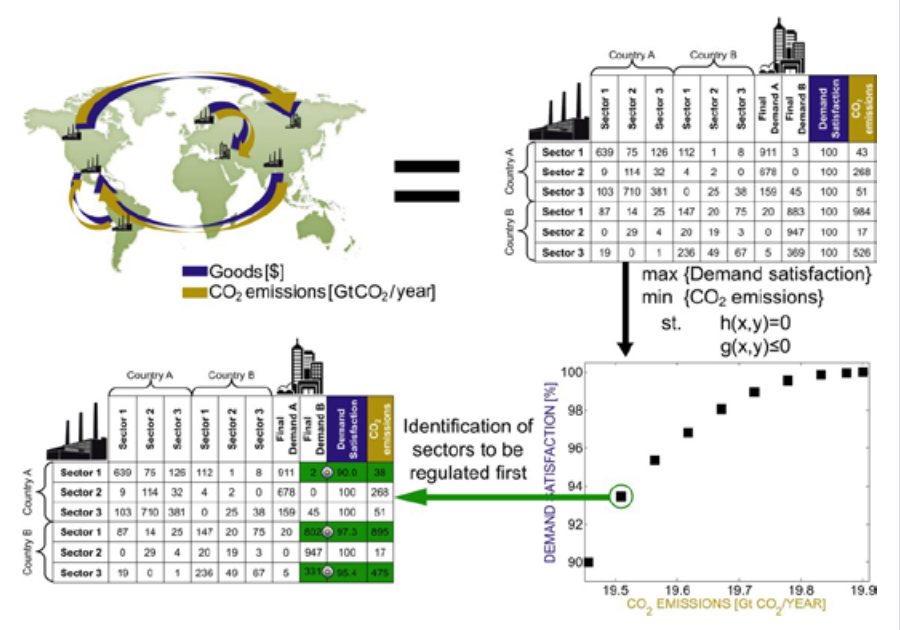


**Figure 5:** *Approach outline*[51]**.** *Environmental impacts are embodied in the flows of goods and services. Input–output tables describe the economic transactions taking place between sectors of an economy. The solution of a multi-objective model based on input–output tables identifies the sectors that need to be regulated first so as to attain significant improvements in environmental performance with little impact on the economy.*

## References


1. Bernardi, A., A. Nikolaou, A. Meneghesso, T. Morosinotto, B. Chachuat, and F. Bezzo, *High-Fidelity Modelling Methodology of Light-Limited Photosynthetic Production in Microalgae.* PLOS ONE, 2016. **11**(4): p. e0152387.
2. Bernardi, A., A. Nikolaou, A. Meneghesso, B. Chachuat, T. Morosinotto, and F. Bezzo, *Semi-empirical modeling of microalgae photosynthesis in different acclimation states – Application to N. gaditana.* Journal of Biotechnology, 2017. **259**: p. 63–72.
3. Nikolaou, A., P. Hartmann, A. Sciandra, B. Chachuat, and O. Bernard, *Dynamic coupling of photoacclimation and photoinhibition in a model of microalgae growth.* Journal of Theoretical Biology, 2016. **390**: p. 61–72.
4. del Rio-Chanona, E.A., F. Fiorelli, D. Zhang, N.R. Ahmed, K. Jing, and N. Shah, *An efficient model construction strategy to simulate microalgal lutein photo-production dynamic process.* Biotechnology and Bioengineering, 2017. **114**(11): p. 2518–2527.
5. Nikolaou, A., P. Booth, F. Gordon, J. Yang, O. Matar, and B. Chachuat, *Multi-Physics Modeling of Light-Limited Microalgae Growth in Raceway Ponds.* IFAC-PapersOnLine, 2016. **49**(26): p. 324–329.
6. Galán-Martín, Á., P. Vaskan, A. Antón, L.J. Esteller, and G. Guillén-Gosálbez, *Multi-objective optimization of rainfed and irrigated agricultural areas considering production and environmental criteria: a case study of wheat production in Spain.* Journal of Cleaner Production, 2017. **140**: p. 816–830.





7. Guo, M., G.M. Richter, R.A. Holland, F. Eigenbrod, G. Taylor, and N. Shah, *Implementing land-use and ecosystem service effects into an integrated bioenergy value chain optimisation framework.* Computers & Chemical Engineering, 2016. **91**: p. 392–406.
8. Copado-Méndez, P.J., C. Pozo, G. Guillén-Gosálbez, and L. Jiménez, *Enhancing the ϵ-constraint method through the use of objective reduction and random sequences: Application to environmental problems.* Computers & Chemical Engineering, 2016. **87**: p. 36–48.
9. Pascual-González, J., G. Guillén-Gosálbez, J.M. Mateo-Sanz, and L. Jiménez-Esteller, *Statistical analysis of the ecoinvent database to uncover relationships between life cycle impact assessment metrics.* Journal of Cleaner Production, 2016. **112**: p. 359–368.
10. Cárdenas-Fernández, M., M. Bawn, C. Hamley-Bennett, P.K.V. Bharat, F. Subrizi, N. Suhaili, D.P. Ward, S. Bourdin, P.A. Dalby, H.C. Hailes, P. Hewitson, S. Ignatova, C. Kontoravdi, D.J. Leak, N. Shah, T.D. Sheppard, J.M. Ward, and G.J. Lye, *An integrated biorefinery concept for conversion of sugar beet pulp into value-added chemicals and pharmaceutical intermediates.* Faraday Discussions, 2017. **202**(0): p. 415–431.
11. Niu, H., N. Shah, and C. Kontoravdi, *Modelling of amorphous cellulose depolymerisation by cellulases, parametric studies and optimisation.* Biochemical Engineering Journal, 2016. **105**: p. 455–472.
12. Gonzalez-Garay, A., M. Gonzalez-Miquel, and G. Guillen-Gosalbez, *High-Value Propylene Glycol from Low-Value Biodiesel Glycerol: A Techno-Economic and Environmental Assessment under Uncertainty.* ACS Sustainable Chemistry & Engineering, 2017. **5**(7): p. 5723–-5732.
13. Medina-González, S., M. Graells, G. Guillén-Gosálbez, A. Espuña, and L. Puigjaner, *Systematic approach for the design of sustainable supply chains under quality uncertainty.* Energy Conversion and Management, 2017. **149**: p. 722–737.
14. Calderón, A.J., P. Agnolucci, and L.G. Papageorgiou, *An optimisation framework for the strategic design of synthetic natural gas (BioSNG) supply chains.* Applied Energy, 2017. **187**: p. 929–955.
15. Giarola, S., C. Romain, C.K. Williams, J.P. Hallett, and N. Shah, *Techno-economic assessment of the production of phthalic anhydride from corn stover.* Chemical Engineering Research and Design, 2016. **107**: p. 181–194.
16. Farzad, S., M.A. Mandegari, M. Guo, K.F. Haigh, N. Shah, and J.F. Görgens, *Multi-product biorefineries from lignocelluloses: a pathway to revitalisation of the sugar industry?* Biotechnology for Biofuels, 2017. **10**(1): p. 87.
17. Patel, B., M. Guo, N. Shah, and K. Hellgardt, *Environmental profile of algal Hydrothermal Liquefaction — A country specific case study.* Algal Research, 2016. **16**: p. 127–140.
18. Zhang, D., E.A. del Rio-Chanona, and N. Shah, *Screening Synthesis Pathways for Biomass-Derived Sustainable Polymer Production.* ACS Sustainable Chemistry & Engineering, 2017. **5**(5): p. 4388–4398.
19. Limleamthong, P., M. Gonzalez-Miquel, S. Papadokonstantakis, A.I. Papadopoulos, P. Seferlis, and G. Guillén-Gosálbez, *Multi-criteria screening of chemicals considering thermodynamic and life cycle assessment metrics via data envelopment analysis: application to CO2 capture.* Green Chemistry, 2016. **18**(24): p. 6468–6481.
20. Mac Dowell, N., P.S. Fennell, N. Shah, and G.C. Maitland, *The role of CO2 capture and utilization in mitigating climate change.* Nature Climate Change, 2017. **7**: p. 243–249.

**21.** Bhave, A., R.H.S. Taylor, P. Fennell, W.R. Livingston, N. Shah, N.M. Dowell, J. Dennis, M. Kraft, M. Pourkashanian, M. Insa, J. Jones, N. Burdett, A. Bauen, C. Beal, A. Smallbone, and J. Akroyd, *Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO2 targets.* Applied Energy, 2017. **190**: p. 481–489.

**22.** Fajardy, M. and N. Mac Dowell, *Can BECCS deliver sustainable and resource efficient negative emissions?* Energy & Environmental Science, 2017. **10**(6): p. 1389–1426.

**23.** Al-Ansari, T., A. Korre, Z. Nie, and N. Shah, *Integration of greenhouse gas control technologies within the energy, water and food nexus to enhance the environmental performance of food production systems.* Journal of Cleaner Production, 2017. **162**: p. 1592–1606.

**24.** Lin, Y., M. Guo, N. Shah, and D.C. Stuckey, *Economic and environmental evaluation of nitrogen removal and recovery methods from wastewater.* Bioresource Technology, 2016. **215**: p. 227–238.

**25.** Torija, S., A. Castillo-Castillo, and N.P. Brandon, *The Prospects for Biogas Integration with Fuel Cells in the United Kingdom.* Fuel Cells, 2016. **16**(1): p. 55–79.

**26.** Cristóbal, J., P. Limleamthong, S. Manfredi, and G. Guillén-Gosálbez, *Methodology for combined use of data envelopment analysis and life cycle assessment applied to food waste management.* Journal of Cleaner Production, 2016. **135**: p. 158–168.

**27.** Koleva, M.N., C.A. Styan, and L.G. Papageorgiou, *Optimisation approaches for the synthesis of water treatment plants.* Computers & Chemical Engineering, 2017. **106**: p. 849–871.

**28.** Koleva, M., E. Polykarpou, S. Liu, C. Styan, and L. G. Papageorgiou, *Optimal design of water treatment processes*. Vol. 57. 2016. 1–22.

**29.** Carrero-Parreño, A., V.C. Onishi, R. Salcedo-Díaz, R. Ruiz-Femenia, E.S. Fraga, J.A. Caballero, and J.A. Reyes-Labarta, *Optimal Pretreatment System of Flowback Water from Shale Gas Production.* Industrial & Engineering Chemistry Research, 2017. **56**(15): p. 4386–4398.

**30.** Onishi, V.C., A. Carrero-Parreño, J.A. Reyes-Labarta, E.S. Fraga, and J.A. Caballero, *Desalination of shale gas produced water: A rigorous design approach for zero-liquid discharge evaporation systems.* Journal of Cleaner Production, 2017. **140**: p. 1399–1414.

**31.** Onishi, V.C., R. Ruiz-Femenia, R. Salcedo-Díaz, A. Carrero-Parreño, J.A. Reyes-Labarta, E.S. Fraga, and J.A. Caballero, *Process optimization for zero-liquid discharge desalination of shale gas flowback water under uncertainty.* Journal of Cleaner Production, 2017. **164**: p. 1219–1238.

**32.** Lira-Barragán, L.F., J.M. Ponce-Ortega, G. Guillén-Gosálbez, and M.M. El-Halwagi, *Optimal Water Management under Uncertainty for Shale Gas Production.* Industrial & Engineering Chemistry Research, 2016. **55**(5): p. 1322–1335.

**33.** Guerra, O.J., A.J. Calderón, L.G. Papageorgiou, J.J. Siirola, and G.V. Reklaitis, *An optimization framework for the integration of water management and shale gas supply chain design.* Computers & Chemical Engineering, 2016. **92**: p. 230–255.

**34.** Crémel, S., M. Guo, G. Bustos-Turu, K.H. van Dam, and N. Shah, *Optimal design of urban energy systems with demand side management and distributed generation*, in *Computer Aided Chemical Engineering*, A. Espuña, M. Graells, and L. Puigjaner, Editors. 2017, Elsevier. p. 2371–2376.

**35.** Oyewunmi, O.A., C.J.W. Kirmse, A.M. Pantaleo, and C.N. Markides, *Performance of working-fluid mixtures in ORC-CHP systems for different heat-demand segments and heat-recovery temperature levels.* Energy Conversion and Management, 2017. **148**: p. 1508–1524.

**36.** Mahdi, S., X. Wang, and N. Shah, *Interactions between the Design and Operation of Shale Gas Networks*, *Including CO2 Sequestration.* Engineering, 2017. **3**(2): p. 244–256.





**37.** Amusat, O.O., P.R. Shearing, and E.S. Fraga, *Optimal integrated energy systems design incorporating variable renewable energy sources.* Computers & Chemical Engineering, 2016. **95**: p. 21–37.

**38.** Charitopoulos, V.M. and V. Dua, *A unified framework for model-based multi-objective linear process and energy optimisation under uncertainty.* Applied Energy, 2017. **186**: p. 539–548.

**39.** Galán-Martín, Á., G. Guillén-Gosálbez, L. Stamford, and A. Azapagic, *Enhanced data envelopment analysis for sustainability assessment: A novel methodology and application to electricity technologies.* Computers & Chemical Engineering, 2016. **90**: p. 188–200.

**40.** Limleamthong, P. and G. Guillén-Gosálbez, *Rigorous analysis of Pareto fronts in sustainability studies based on bilevel optimization: Application to the redesign of the UK electricity mix.* Journal of Cleaner Production, 2017. **164**: p. 1602–1613.

**41.** Brandon, N.P. and Z. Kurban, *Clean energy and the hydrogen economy.* Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2017. **375**(2098): p. 20160400.

**42.** Samsatli, S., I. Staffell, and N.J. Samsatli, *Optimal design and operation of integrated wind-hydrogen-electricity networks for decarbonising the domestic transport sector in Great Britain.* International Journal of Hydrogen Energy, 2016. **41**(1): p. 447–475.

**43.** Jing, R., M. Wang, N. Brandon, and Y. Zhao, *Multi-criteria evaluation of solid oxide fuel cell based combined cooling heating and power (SOFC-CCHP) applications for public buildings in China.* Energy, 2017. **141**: p. 273–289.

**44.** Jing, R., M. Wang, W. Wang, N. Brandon, N. Li, J. Chen, and Y. Zhao, *Economic and environmental multi-optimal design and dispatch of solid oxide fuel cell based CCHP system.* Energy Conversion and Management, 2017. **154**: p. 365–-379.

**45.** Carreras, J., D. Boer, L.F. Cabeza, L. Jiménez, and G. Guillén-Gosálbez, *Eco-costs evaluation for the optimal design of buildings with lower environmental impact.* Energy and Buildings, 2016. **119**: p. 189–199.

**46.** Zheng, X., Y. Qiu, X. Zhan, X. Zhu, J. Keirstead, N. Shah, and Y. Zhao, *Optimization based planning of urban energy systems: Retrofitting a Chinese industrial park as a case-study.* Energy, 2017. **139**: p. 31–41.

**47.** Carreras, J., C. Pozo, D. Boer, G. Guillén-Gosálbez, J.A. Caballero, R. Ruiz-Femenia, and L. Jiménez, *Systematic approach for the life cycle multi-objective optimization of buildings combining objective reduction and surrogate modeling.* Energy and Buildings, 2016. **130**: p. 506–518.

**48.** Mariaud, A., S. Acha, N. Ekins-Daukes, N. Shah, and C.N. Markides, *Integrated optimisation of photovoltaic and battery storage systems for UK commercial buildings.* Applied Energy, 2017. **199**: p. 466–478.

**49.** Parkes, O., P. Lettieri, and I.D.L. Bogle, *Defining a quantitative framework for evaluation and optimisation of the environmental impacts of mega-event projects.* Journal of Environmental Management, 2016. **167**: p. 236–245.

**50.** Napp, T., D. Bernie, R. Thomas, J. Lowe, A. Hawkes, and A. Gambhir, *Exploring the Feasibility of Low-Carbon Scenarios Using Historical Energy Transitions Analysis.* Energies, 2017. **10**(1): p. 116.

**51.** Pascual-González, J., L. Jiménez-Esteller, G. Guillén-Gosálbez, J.J. Siirola, and I.E. Grossmann, *Macro-economic multi-objective input–output model for minimizing $CO_2$ emissions: Application to the U.S. economy.* AIChE Journal, 2016. **62**(10): p. 3639–3656.

## 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.[1] 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.[2] 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 programing (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.



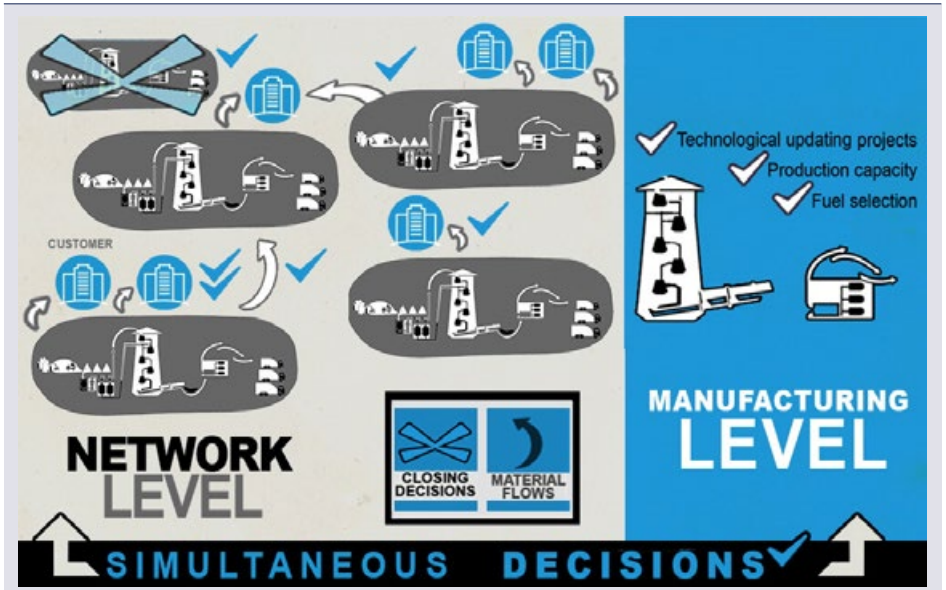


**Figure 1:** *Structure of the cement supply-chain problem.*

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.[3] 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.[4] 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.[5], 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, $CO_2$ 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.[6] 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.[7] 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).

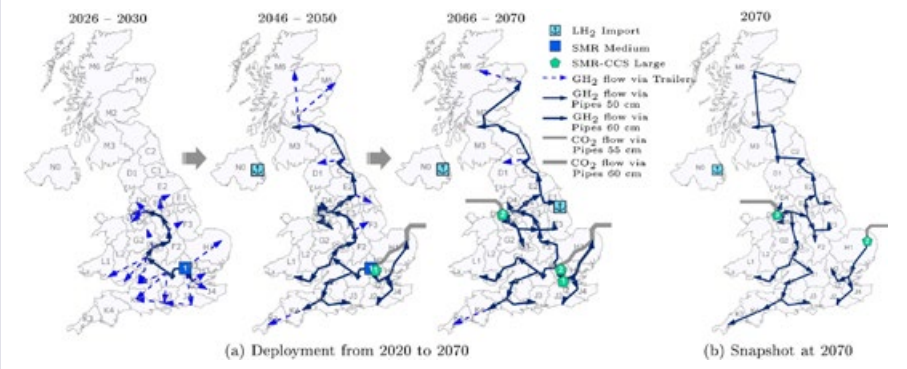


**Figure 2:** *Evolution of the hydrogen supply chain infrastructure over time.*

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.[8] 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-biobased products supply chain. Biomass yield uncertainty is considered in a follow-up work[9]. Delval et al.[10] present a bioenergy system modelling toolkit, soft-linking an agent-based model with an optimisation model to support the value chain design in a multi-level, multi-objective and multi-stakeholder context. The developed decision-making tool is demonstrated on a South African sugarcane biorefineries case study. Nguyen et al.[11] present a multi-objective optimization modelling framework configured to account for the economic and environmental impacts of a supply chain based on a mangrove-type feedstock, the Nipa palm. An MILP model is developed from scratch using the AIMMS platform in order to achieve optimal design of the biofuel supply chain at the cultivation, infrastructure, operation and transportation stages. This gives valuable insights on the implementation of the supply chain of a new alternative crop, which is required



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.[12], 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.[13] 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.[14] 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.

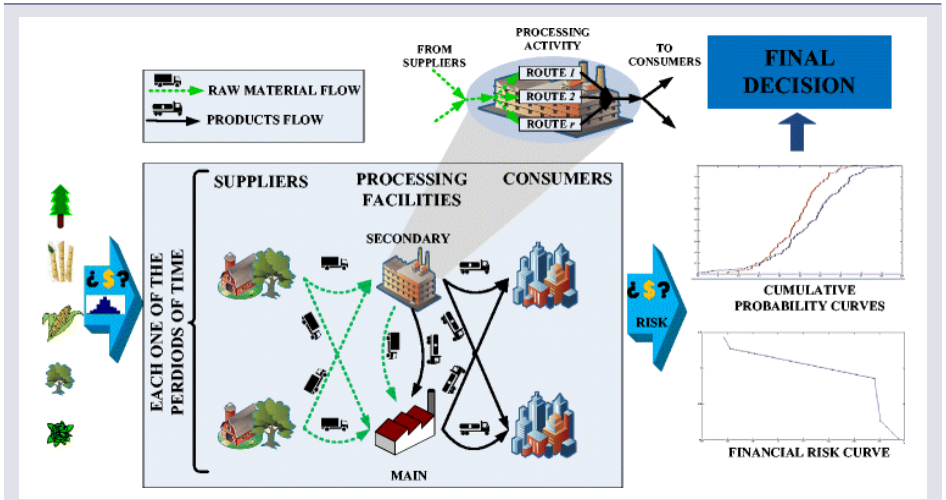


**Figure 3:** *Super structure of the proposed methodology.*

Food. For food supply chains, Georgiou et al.[15] 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.

## References


1. Medina-Gonzalez S, Pozo C, Corsano G, Guillen-Gosalbez G, Espuna A (2017) Using Pareto filters to support risk management in optimization under uncertainty: Application to the strategic planning of chemical supply chains, *Computers & Chemical Engineering*, 98, 236–255.
2. Cadavid-Giraldo N, Velez-Gallego MC, Guillen-Gosalbez G (2016) Technology updating decisions for improving the environmental performance of an operating supply chain: a multiobjective optimisation model for the cement industry, *Industrial & Engineering Chemistry Research* 55, 12287–12300.
3. Calderon AJ, Agnolucci P, Papageorgiou LG (2017) An optimisation framework for the strategic design of synthetic natural gas (BioSNG) supply chains, *Applied Energy* 187, 929–955.
4. Gueera OJ, Calderon AJ, Papageorgiou LG, Siirola JJ, Reklaitis GV (2016) An optimisation framework for the integration of water management and shale gas supply chain design, *Computers & Chemical Engineering* 92, 230–255.
5. Mahdi S, Wang X, Shah N (2017) Interaction between the design and operation of shale gas networks, including $CO_2$ sequestration, *Engineering* 3, 244–256.
6. Balcombe P, Anderson K, Speirs J, Brandon N, Hawkes A (2017) The natural gas supply chain: the importance of methane and carbon dioxide emissions, *ACS Sustainable Chemistry & Engineering*, 5, 3–20.
7. Moreno-Benito M, Agnolucci P, Papageorgiou LG (2017) Towards a sustainable hydrogen economy: optimisation-based framework for hydrogen infrastructure development, *Computers & Chemical Engineering* 102, 110–127.
8. Panteli A, Giarola S, Shah N (2016) Lignocellulosic supply chain MILP model: a Hungarian case study, Editors: Kravanja, Bogataj, Publisher: Elsevier Science BV, 253-258.
9. Panteli A, Giarola S, Shah N (2017) Biobased supply chain optimisation model under uncertainties, 27th European Symposium on Computer-Aided Process Engineering (ESCAPE), Publisher: Elsevier Science BV, 961–966.
10. Delval F, Guo M, van Dam KH, Stray J, Haigh K, Gorgens J, Shah N (2016) Integrated multi-level bioenergy supply chain modelling applied to sugarcane biorefineries in South Africa, 26th European Symposium on Computer-Aided Process Engineering (ESCAPE), Publisher: Elsevier Science BV, 2037–2042.
11. Nguyen R, Guo M, Musikavong C, Bamroongrugsa N, Shah N (2016) Supply chain optimisation of Nipa-based bioethanol industry in Thailand, 26th European Symposium on Computer-Aided Process Engineering (ESCAPE), Publisher: Elsevier Science BV, 913–918.
12. Wheeler J, Caballero JA, Ruiz-Femenia R, Guillen-Gosalbez G, Mele FD (2017) MINLP-based analytic hierarchy process to simplify multi-objective problems: application to the design of biofuels supply chains using on field surveys, *Computers & Chemical Engineering* 102, 64–80.
13. Medina-Gonzalez S, Graells M, Guillen-Gosalbez G, Espuna A, Puigianer L (2017) Systematic approach for the design of sustainable supply chains under quality uncertainty, *Energy Conversion and Management* 149, 722–737.
14. Ezequiel Santibanez-Aguilar J, Guillen-Gosalbez G, Morales-Rodriguez R, Jimenez-Esteller L, Jaime Gastro-Montoya A, Maria Ponce-Ortega J (2016) Financial risk assessment and optimal planning of biofuels supply chains under certainty, *BioEnergy Research* 9, 1053-1069.
15. Georgiou S, Markides CN, Shah N (2016) Decarbonisation of food supply chains from an energetic perspective through optimisation and technological modelling: A holistic approach, Perspective on environmental Change DTP Conference.

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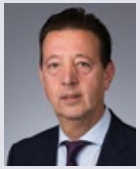

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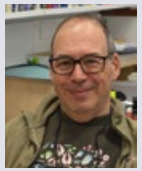

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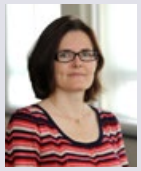

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Start date: November 2016

**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 $CO_2$ 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 Gosálbez
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 Cumicheo 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 Gosálbez
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

**Shubhechyya 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

**Pooya Hoseinpoori**
***Decarbonisation of Heat in the UK***
Supervisor: Dr Niall Mac Dowell
Start date: August 2017

**Chunbing Huang**
***Stochastic Collisional Exchange Processes: Theoretical Investigation and Numerical Platform Development***
Supervisor: Dr Federico Galvanin
Start date: September 2017

**Khairul Amilin Ibrahim**
***Fuel Cells***
Supervisor: Prof Nigel Brandon
Start date: January 2015

**Frederike Jaeger**
***Flow of Fluids through Porous Media with Application to Membranes: from the Molecular to the Continuum Scale***
Supervisors: Prof Erich Müller and Prof Omar Matar
Start date: October 2014

**Elnaz Jamili**
***Model-Based Optimal Control of Non-Viral Gene Delivery***
Supervisors: Dr Vivek Dua and Dr Michail Stamatakis
Start date: November 2012

**Erin Johnson**
***UK Green Gas: Exploring Bio-Methane Potential as a Relevant Low Carbon Energy Stream***
Supervisor: Prof Nilay Shah
Start date: October 2015

**Caroline Jones**
***Quantification and Monitoring of Fluid Phase Behaviour and Trapping in Geological Carbon Sequestration Sites***
Supervisor: Prof Geoffrey Maitland
Start date: October 2016

**Sanket Sayaji Kamthe**
***Reinforcement Learning for Robotics and Control***
Supervisor: Prof Marc Deisenroth
Start date: October 2016

**Ashkan Kavei**
***Fuel Cells***
Supervisor: Prof Nigel Brandon
Start date: September 2015

**Siti Khalit**
***Thermodynamic Modelling of Acid Gas Absorption***
Supervisors: Prof Claire Adjiman, Prof George Jackson and Prof Amparo Galindo
Start date: May 2015

**Christoph Kirmse**
***Waste-Heat Recovery and Power Generation with Reciprocating Motion***
Supervisor: Prof Christos Markides
Start date: December 2014

**Michail Klontzas**
***Bone Tissue Engineering***
Supervisor: Prof Athanasios Mantalaris
Start date: October 2014

**Esma Koca**
***Global Launch Decisions and Product Rollover Strategies for SMEs Introducing New Products***
Supervisor: Prof Wolfram Wiesemann
Start date: September 2013

**Mariya Koleva**
***Optimisation of Wastewater Systems***
Supervisor: Prof Lazaros Papageorgiou
Start date: March 2013



**Lukmaan Ebrahim Kolia**
***Development of a Kinetic Model for Green Microalgae Using Genetic Programming and Optimisation Techniques***
Supervisors: Dr Alexandros Kiparissides and Dr Frank Baganz
Start date: September 2016

**Loukas Kollias**
***Molecular Modelling of the Templated Growth of Hierarchical Materials***
Supervisor: Dr Matteo Salvalaglio
Start date: September 2016

**Clea Kolster**
***Evaluation of dynamic $CO_2$ injection in the North Sea***
Supervisor: Dr Niall Mac Dowell
Start date: October 2014

**Scott Qingyuan Kong**
***Optimisation-Based Process Synthesis of Emerging Reaction Pathways for Bio-Based Polymers and Monomers: An effective Mixed Integer Linear Programming Approach***
Supervisor: Prof Nilay Shah
Start date: October 2014

**Stefanos Konstantinopoulos**
***Free Energy Calculations for Crystal Structure Prediction***
Supervisor: Prof Constantinos Pantelides
Start date: December 2017

**Pavlos Kotidis**
***Model-Driven Optimization of Bioprocess Design***
Supervisor: Dr Cleo Kontoravdi
Start Date: October 2017

**Spyridon Kournopoulos**
***State-of-the-Art Thermodynamic Models for Mixtures Containing Water, Carbon Dioxide, Salts and Hydrocarbons in Bulk and in Confinement***
Supervisor: Prof George Jackson and Prof Amparo Galindo
Start date: September 2016

**Georgia Kouyialis**
***Symmetry and Degeneracy in Nonconvex Optimisation Problems: Application to Heat Recovery Networks***
Supervisor: Dr Ruth Misener
Start date: October 2014

**Kennedy Kusumo**
***Model-Based Experiment Design***
Supervisor: Prof Nilay Shah and Dr Benoît Chachuat
Start date: January 2018

**Georgia Kouyialis**
***Exploiting Symmetry in Mixed Integer Non-Linear Optimisation***
Supervisor: Dr Ruth Misener
Start date: October 2014

**Ye Seol (Lauren) Lee**
***Integrated Computer-Aided Molecular and Process Design: Optimal Solvent Design for $CO_2$ Chemical Absorption Process***
Supervisors: Prof Claire Adjiman, Prof George Jackson and Prof Amparo Galindo
Start date: October 2017

**Duncan Leeson**
***Development of a Modelling Framework for Energy-Efficient Oil Refining***
Supervisors: Prof Nilay Shah and Dr Niall Mac Dowell
Start date: October 2014

**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

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

**Matthieu Lucke**
***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 Gavriilidis
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 Combing 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-γ 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 Raffaello Salimbeni**
***Multi-Task Reinforcement Learning***
Supervisor: Prof Marc Deisenroth
Start date: October 2015

**Manfredi Giovanni San Martino D'Aglie Di San Germano**
***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 Savvopoulos**
***Mathematical Modelling of Chronic Lymphocytic Leukaemia***
Supervisors: Prof Athanasios Mantalaris and Dr Nicki Panoskaltsis
Start date: March 2014

**Oliver Schmidt**
***Innovation Potential of Energy Storage Technologies and the Value of Storage in Low-Carbon Energy Systems***
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 $CO_2$ Storage and Enhanced Oil Recovery in the North Sea. Rock Heterogeneity and Flow in Geologic Systems with Low Flow Potential – Applications to Subsurface $CO_2$ 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 $CO_2$ Conversion to Methanol***
Supervisors: Prof David Chadwick and Dr Benoît Chachuat
Start date: September 2017

**Yizu 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 Folashade 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 Yasmeen Aldawsari**
***Systems Analysis of Transport Decarbonisation Options***
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 Nihal 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 Aaron Borg**
***Expanding the Mass Spectrometry Toolkit for Interrogating Chromatin Proteomics***
Supervisor: Dr Peter DiMaggio
Employer: Senior Laboratory Research Scientist at the Francis Crick Institute

**Dr Susana Isabel Brito dos Santos**
***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

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***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)

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***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***
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**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
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***Cascading Effects in Bioprocessing: The impact of Cell Culture Environment on CHO Cell Behaviour and Host Cell Protein Species***
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***Molecular Design, Process Design and Process Synthesis of Separation Systems***
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***Modelling of RO Membrane Process Performance and Transport Phenomena for Performance Analysis and Optimisation***
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***Optimization Algorithms for Multiscale Models***
Supervisors: Dr Panos Parpas and Dr Wolfram Wiesemann
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***On the Solubility of Acid and Sour Gases in Water and Brines under Reservoir Conditions***
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***Multilevel Optimisation for Computer Vision***
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***Upper and Lower Bounds for Singularly Perturbed Linear Quadratic Optimal Control Problems***
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***Prediction of Partition Coefficients and Solubilities of Active Pharmaceutical Ingredients with the SAFT-γ Mie Group-Contribution Approach***
Supervisors: Prof Claire Adjiman, Prof Amparo Galindo and Prof George Jackson
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***Development of a Systems Approach for Studying Decarbonisation Pathways of Heat Demand in the UK***
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***Rational Mixture Design: Optimisation-Based Approaches***
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***Parallel Computing, Interval Derivative Methods, Heuristic Algorithms, and their Implementation in a Numerical Solver, for Deterministic Global Optimization***
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***Droplets: From Molecular Nanoclusters to the Atmospheric Aerosols***
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***Development of the SAFT-γ Mie Equation of State for Predicting the Thermodynamic Behaviour of Strong and Weak Electrolyte Solutions***
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***A Multiscale Modelling Framework for the Processes Involved in Consolidated Bioprocessing***
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***Flexible Operation of Industrial Plants for Power Management and Demand-Side Response***
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***Robust Optimisation and Modelling for Rotables in Supply Chains for Airline Technical Services: Opportunities for Improving Decision-Making***
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***Advanced Multiparametric Optimization and Control Studies for Anaesthesia***
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***Deterministic Global Optimisation and Location of Transition States***
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***Multi-Scale Modelling of Light-limited Growth in Microalgae Production Systems***
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***Theoretical and Algorithmic Advances in Multi-Parametric Optimization and Control***
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***Heat Recovery and Conversion Technologies with Organic Fluid Cycles: Optimal Working Fluid and System Design***
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***Biorenewable Value Chain Optimization with Multi-Layered Value Chains and Advanced Analytics***
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***Towards Continuous Biomanufacturing a Computational Approach for the Intensification of Monoclonal Antibody Production***
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***Development of Aqueous Two-Phase Separations by Combining High-Throughput Screening and Process Modelling***
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***Global Optimisation of Dynamic Process Systems***
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***Complete Search Methods and Tools for Robust Parameter Estimation***
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***Multi-Scale Energy Systems Modelling of the Renewable Energy Transition***
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***Optimisation-Based Methodology for the Design and Operation of Sustainable Wastewater Treatment Facilities***
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***Mathematical Modelling and Experimental Validation for Optimisation and Control of Mammalian Cell Culture Systems***
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***Development of Coarse-Grained Models of Ionic and Non-Ionic Surfactants for the Molecular Simulation of Structural, Thermodynamic and Dynamical Properties***
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***Rigorous Numerical Analysis with Polynomial Models: Applications to Implicit and Differential-Algebraic Equations***
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***Water Splitting for Hydrogen Production for Use in Dwellings***
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***Understanding the Impact of Bioprocess Conditions on Monoclonal Antibody Glycosylation in Mammalian Cell Cultures through Experimental and Computational Analyses***
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***Economically Optimal Integrated Process and MPC Control Design***
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***Design of Multi-Parametric NCO-Tracking Controllers for Linear Continuous-Time Systems***
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***Modelling and Systems Engineering Approaches for Elucidating Dynamics and Information Processing of Multi-Site Phosphorylation Systems***
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***Materials Design and Modification for a Three Dimensional Hollow Fibres Bioreactor for the Production of Blood Cells***
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***Sampling Algorithms for Stochastic Programming Using Importance Sampling and Markov Chain Monte Carlo***
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***Towards Improved Ethanol Production from Lignocellulosic Biomass***
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***An Intergrated Experimental/Modelling Approach Connecting Transcriptional Regulation and Microbial Growth Kinetics in Bacterial Cell Cultures***
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***An integrated Experimental and Modelling Approach for the Study of Apoptosis in GS-NS0 Cell Cultures***
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***Techno-Economics of Optimised Residential Heating under Power Sector Decarbonisation***
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***Set-Theoretic Methods for Analysis, Estimation and Control of Nonlinear Systems***
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***Optimal Design and Regulation of Residential Distributed Energy Systems***
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***Optimal Operation of Industrial Compressor Stations in Systems with Large Energy Consumption***
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***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
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***Human Dental Pulp Stem Cells: Characterisation and in Vitro 3D Bone Ontogeny***
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