A **green** approach

In an engaging conversation with *International Innovation*, **Professor Ali Elkamel** explains how his research is advancing sustainable development in the industrial world through the implementation of process systems engineering and mathematical optimisation techniques

Could you explain process systems engineering (PSE) in layman's terms?

PSE refers to the discovery, design, manufacturing and distribution of products under many conflicting goals. The use of PSE enables companies to operate inherently safe processes and reduce their production costs, subsequently improving quality, increasing efficiency, reducing pollution and bringing products to market more quickly. Traditionally, PSE has been concerned with the understanding and development of systematic procedures for the design and operation of chemical and biochemical process systems, ranging from microsystems to those on an industrial scale. Furthermore, the scope of PSE has recently broadened to incorporate systems at much larger scales, such as supply chains and the business enterprise, and at much smaller scales, such as molecular and atomic systems.

What is the core objective of your research on the environmental implications of PSE?

The long-term objective of my research is to build on the existing PSE toolset and integrate environmental impact assessment tools. Unlike the traditional approach that focuses on human-made systems and treats environmental requirements as constraints, we will focus on the interactions between PSE and the natural networks, with the aim of establishing harmonious social-economic-technological systems. This research is an emerging area of chemical engineering aimed at applying PSE tools to design, commercialise and use processes and products that are economic, and crucially, that have minimal environmental impact and risk to human health.

How important is collaboration in your research? With whom are you collaborating in order to ensure your objectives are reached?

Collaborations with other colleagues on topics of mutual interest bring together different areas of expertise and points of view – something that is very important in addressing research questions. These collaborations in turn contribute towards increased synergy and effectiveness in developing meaningful and impactful solutions to difficult yet significant challenges. This leads to higher quality manuscripts and publications, which serve to document and disseminate the obtained findings for the benefit of society at large. In addition to working directly with graduate students, postdoctoral researchers and undergraduate students, I have close partnerships with my departmental colleagues at the University of Waterloo, other institutions in Canada and around the world. In order to apply our research findings, we also collaborate with industrial partners in Canada and elsewhere.

As Professor of Chemical Engineering at the University of Waterloo, what teaching support do you offer to graduate and undergraduate students?

Teaching is an essential and honourable activity. Society entrusts to us the delicate job of educating future generations and we have a moral obligation to do the job well. I try to keep my students motivated by enlightening them as to why they should learn a particular topic and how they can apply what they have learned. I also explain how a given topic is related to the rest of the subject material or to the other courses they may be taking. I stress the fundamentals so that students can later learn on their own and try to use active learning techniques by engaging students in class discussions and encouraging them to constantly questions.

Recent advances in computer technology and electronic media have substantially impacted teaching techniques. A wide variety of powerful computational tools – including simulators, equation solvers and computer-assisted instructional programs – are now available and they permit engineers to routinely perform calculations that were once very difficult to execute. I always integrate the use of these tools into my courses, and believe that such integration fosters learning and enables the assignment of more realistic homework problems that mimic real-world situations and industrial applications.

Ultimately, how will your research contribute to improving existing methodologies in order to create and operate processes that have minimal environmental impacts?

Our long-term focus is just that, and to maximise economic benefits in order to advance sustainable development. Therefore, models and tools to improve the efficiency and sustainability of products and processes will be investigated. These methods will focus on the interactions between industrial and ecological systems, treating them as networks of interconnected flows.

Sustainable solutions

Researchers at the Department of Chemical Engineering at the **University of Waterloo** in Ontario, Canada, are investigating new and innovative ways of preventing pollution and reducing costs in the processing industry

MANY INDUSTRY SECTORS are facing unprecedented levels of market competition, with dwindling resources and exponential unit energy costs challenging their productivity and profits. This has been intensified by increasingly restrictive rules and regulations that aim to reduce pollution and implement more environmentally sustainable processes. Indeed, hazardous chemicals are often used in the processing industry, which can have detrimental effects on the environment. For instance, the emission of harmful gases presents real threats to the Earth and human health, leading to the greenhouse effect, ozone depletion and pollution. In view of this, there is an urgent need to help industries respond to these challenges and assist them in developing their competitiveness sustainably.

In response, researchers from the Department of Chemical Engineering at the University of Waterloo are focusing on process systems engineering, a field that incorporates the identification, creation, control and optimisation of a huge range of products. Their ultimate goal is to reduce the environmental impact of the processing industry through economical means: "We aim to develop systematic computer-aided methodologies that enable chemical engineers to identify creative strategies for the operation, design, integration and supply-chain management of chemical and biochemical processes in a sustainable and cost-effective way," elucidates Professor Ali Elkamel, a prominent researcher in the Department.

With a strong track record of research excellence – including an output of over 190 journal articles, 90

GREEN PROCESS ENGINEERING:
NINE PRINCIPLES

1. Use holistic methods to engineer processes and products, incorporating a range of tools that evaluate their environmental impact
2. Prioritise the conservation of natural ecosystems and the protection of human health and wellbeing
3. Take a life-cycle approach to all engineering activities and processes
4. Use safe, benign and environmentally friendly material and energy inputs and outputs
5. Ensure the depletion of natural resources is minimal
6. Implement strategies that prevent waste
7. Develop innovative engineering solutions that are simultaneously sensitive to local geography, cultures and needs
8. Generate cutting-edge engineering solutions that incorporate new, innovative technologies that prize sustainability
9. Involve local communities and stakeholders in the planning and development stages of new engineering solutions

conference proceedings, 250 conference papers and 30 book chapters – Elkamel is well-placed to lead research into the promotion of sustainable development via the application of systems engineering and mathematical optimisation techniques. At present, his activities largely fall into two categories: sustainable process modelling, scheduling and integration; and sustainable energy production systems.

SUSTAINABILITY AND INTEGRATION

To manage carbon and address other environmental issues, Elkamel and his colleagues have designed a range of mathematical programming models and solution strategies for the planning and scheduling of process operations. These models operate on the basis of evaluating and selecting available reduction strategies, while simultaneously attempting to reduce total investment and operating costs. To date, they have been applied to drying processes, methanol production, plastics extrusion, the power industry and cement industry, and perhaps most significantly, petroleum refineries and petrochemical processes: "In order to incorporate sustainability into our models, we created preliminary indices to assess the sustainability of a chemical process and integrated them into a planning model for the development of the petrochemical industry," Elkamel discloses.

As a crucial means of maximising the efficiency and sustainability of industrial processes, process integration is a key element of Elkamel's research. In this area, the long-term vision of the Waterloo researchers is to develop solutions that successfully meet growing energy demands, as well as facilitating the reduction, capture and sequestration of carbon dioxide. Based on the premise that no single technology will be able to respond to these significant energy challenges, Elkamel and his team are using a systems approach that captures data on a range of different technologies.

The models took different carbon dioxide strategies into consideration, as well as the use of fuel-balancing and fuel-switching techniques and the incorporation of alternative energy sources and advanced technologies. Excitingly, they were then applied in real-world scenarios such as in their Ontario Power Generation work, where the team successfully calculated the amount of plug-in hybrid vehicles in Ontario that could be recharged from the grid during off-peak hours without affecting the system's reliability.

RESEARCH IMPACTS

Elkamel and his collaborators have prepared models and solution algorithms that maximise the operation and design of complex systems: "We developed a novel methodology based on combining dimensional, inspectional and order-of-magnitude analysis in order to model complex processes," Elkamel explains. "This has proven very useful in optimising various processes whose models have been traditionally too large or with run times too long to allow for rigorous optimal solutions."

In addition, Elkamel's extensive research has led to a number of industry improvements. For instance, along with his students at Waterloo, he has developed innovative, cost-effective and region-wide carbon management strategies that have been key for effective carbon capture and storage, as well as for converting them into useful products.

Finally, Elkamel's research has also generated cutting-edge methods for pollution monitoring. Since pollution reduction depends on acquiring a comprehensive understanding of environmental violations, the team developed two complementary models for predicting the concentrations of pollutants due to process operations activities. Despite being based on limited information, these models gave reliable estimates of emissions rates. A new methodology for optimising air quality monitoring networks has also been designed.

OPTIMAL PRODUCT DESIGN

The researchers have developed systematic methodologies for many different applications. In partnership with Virox Technologies Inc., they designed a green disinfectant product. As a result, the collaborating company received the Design for the Environment Champion Status Award from the Safer Detergents Stewardship Initiative (SDSI).

They developed novel natural plant fibre plastic composite products in an attempt to use renewable resources in material production. The results have shown great promise for the automotive industry, and at present, they

PROCESS INTEGRATION

Elkamel and his team have proposed a number of solutions to energy-efficiency challenges, incorporating both process-level and enterprise-wide integrations. Examples include:

- A novel superstructure and global optimisation algorithm for designing an integrated water system that combines water-using and water-treating units
- An optimisation strategy for the simultaneous integration of refinery planning and hydrogen management
- The development of models of the various energy demands and greenhouse gas emissions of industries working in the Canadian oil sands

are seeking to integrate nanotechnology to enhance material properties. Two major applications they are working on include the development of graphene-based coatings for inhibiting the corrosion of metal surfaces and the development of nanofluids to improve the thermal properties and efficiency of heat transfer devices.

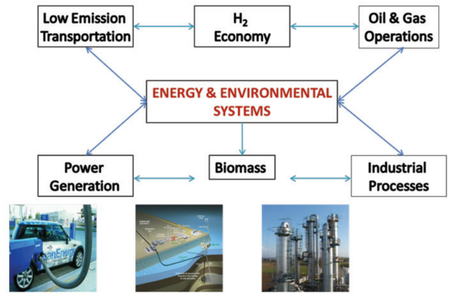
FORGING AHEAD

To date, the group has made significant progress in quantifying sustainability in the process industry and weaving innovative sustainability measures into their modelling attempts. They have come up with simple metrics that clearly determine the economic, environmental, safety and sustainability performances of potential production routes, including the conversion of waste into valuable inputs and the minimisation of material throughput. Additionally, they have pioneered a number of leading-edge product designs. For example, in the field of biotechnology they have generated a systematic approach that identifies the key amino acids in a specific medium, optimising their concentrations. This was achieved by integrating an alternative statistical design with distance-based multivariate analysis.

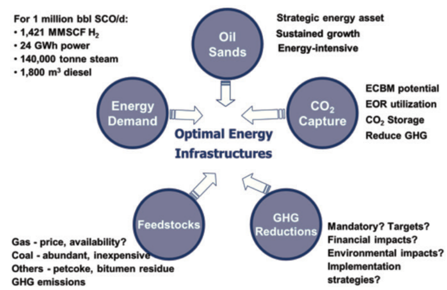
Elkamel and his colleagues are eager to continue designing models and solutions that address both environmental and cost-effectiveness issues in industrial processes. Moreover, they are aiming to concentrate on short-term pollution prevention strategies at an operational level. This makes sense economically because operational modifications to existing processes are generally less expensive: "To this end, we will look at reactive scheduling to absorb disturbances that violate environmental standards," Elkamel states. "We will also prepare scheduling models that avoid waste generation and minimise environmental impact – these models will also produce schedules with reduced equipment cleaning and maximum reuse of raw materials."

In terms of sustainable energy systems, Elkamel and his team are also planning to focus on various renewable energy sources – such as wind turbines and photovoltaic solar cells – that lower greenhouse emissions while meeting ever-increasing energy demands.

The innovation of their activities in this field lies in their multi-region and multi-technology decision-making framework, which takes a bottom-up approach to industrial activities and a broad-brush view of energy demands. Specific plans include assessing hydrogen production as an energy storage carrier and developing a multi-period modelling framework that takes into account predictable trends. Ultimately, the hope is that the researchers' holistic methods will lead to the development of sustainable, long-term planning solutions for designing integrated systems, equally accommodating both economic and environmental demands.



Integrated energy and environmental systems.



Comprehensive oil sands infrastructure.

DESIGN AND DEVELOPMENT

Elkamel and his colleagues are aiming to develop a robust set of tools that can be used to refine product and process design, along with advancing operational planning and scheduling. Efforts in this area include:

- Modifying processes in order to reduce waste and energy consumption, improve efficiency and draw on renewable resources
- Planning process operations with an emphasis on minimising pollution under adverse environmental conditions or under changing regulations
- Implementing computer-aided design of green product
- Designing robust sustainable energy and power production pathways
- Developing energy and material co-production systems

INTELLIGENCE

SUSTAINABLE PROCESS SYSTEMS ENGINEERING

OBJECTIVE

To create systematic computer-aided methodologies that allow chemical engineers to identify strategies for sustainable process systems engineering. These strategies involve the selection of system components, interconnections of units, operating conditions, infrastructure development decisions, or even interactions along supply chains or the ecosystem at large.

KEY COLLABORATORS/PARTNERS

P L Douglas; **M Fowler**; **E Croiset**; **L Simon**; **A Yu**; **H Budman**; **C M R Madhuranthakan**, University of Waterloo, Canada • **A Almansoori**; **K Wang**; **A Abdala**; **V Mittal**; **A Alshoaibi**, Petroleum Institute, Abu Dhabi • **S A Alsulaiman**, Sultan Qaboos University, Oman • **Z M Shareefdeen**, American University Sharjah

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CONTACT

Professor Ali Elkamel
Project Coordinator

University of Waterloo
Department of Chemical Engineering
200 University Avenue West
Waterloo
Ontario, N2L 3G1
Canada

T +1 519 888 4567 x 37157
E aelkamel@uwaterloo.ca

bit.ly/1stitF8

ALI ELKAMEL is Professor of Chemical Engineering at the University of Waterloo. He holds a BSc in Chemical Engineering, BSc in Mathematics from Colorado School of Mines, MS in Chemical Engineering from the University of Colorado-Boulder and PhD in Chemical Engineering from Purdue University – West Lafayette, Indiana. His specific research interests are in computer-aided modelling, optimisation and simulation with applications to energy production planning, sustainable operations and product design. He has supervised over 70 graduate students (of which 30 are PhDs) in these fields and his graduate students all obtain good jobs in the chemical process industry and in academia. He has been funded for numerous research projects from government and industry, and is also a co-author of four books; two recent books were published by Wiley and entitled *Planning of Refinery and Petrochemical Operations* and *Environmentally Conscious Fossil Energy Production*.

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