https://doi.org/10.1038/s44286-024-00034-4

Drawing the line for process design

Check for updates

Systems-level thinking is an important practice, but accounting for system boundary expansion is a complex and timely challenge.

CREDIT: TAMBAKO THE JAGUAR / GETTY IMAGES

Systems-level thinking provides an integrated approach to developing, intensifying and optimizing coupled chemical processes. This holistic mindset has become increasingly important in recent years due to the growing collective effort to make deliberate design and operational choices that benefit our society. At the same time, the application of systems-level thinking to process design is becoming more complex, partly due to the challenge of drawing a clear system boundary. In the field today, these boundaries are expanding, and it is becoming important to consider them very early in the design process to expedite scientific progress and deploy practical solutions[1].

The expansion of system boundaries is being driven by both the inherent multiscale nature of chemical process design and the interconnectivity of many modern engineering challenges. Various process-specific factors such as regulatory requirements, complex feedstocks or performance trade-offs may result in larger, more integrated process flow diagrams with expanded boundaries. For example, in membrane separations, where molecular-level permeability and selectivity are at odds, additional potentially larger-sized units may be needed to achieve a desired separation efficiency while maintaining adequate throughput. This interdependency, however, extends even to the societal level.

Although the 17 United Nations Sustainable Development Goals (SDGs) have been established as independent targets, realizing viable solutions to these challenges is a strongly coupled problem; progress on one SDG can potentially aid or negatively impact progress on others[2,3]. Take, for example, the competition between biomass-based feedstocks for biofuels and food for human consumption, where there is a shared need for land and resources, as well as the potential for indirect deleterious consequences of the process such as habitat destruction and soil degradation[1]. In this case, a potential integrated systems boundary could extend well beyond the immediate biomass-to-biofuel process; the optimization could occur across multiple SDGs, with a solution that, for example, replaces the feedstock with one that requires less land, water and nutrients, or is not suitable for food consumption.

Although it is clear that integrated design can greatly accelerate the development of practical solutions, it is not effective if it is applied as an afterthought. As in the case of biomass-based feedstocks, adopting this mindset early in the design allows one to minimize any potential unintended consequences, such as those described above[4]. Other contemporary examples include harmful bisphenol A (BPA) in drinking bottles; persistent per- and polyfluoroalkyl substances (PFAS) in non-stick coatings and membranes; environmental challenges posed by plastic waste; and the recovery of critical components from electronic waste and batteries. Integration of systems-level thinking represents, therefore, a key element that must be considered at earlier stages of the process design.

In this issue of *Nature Chemical Engineering*, we present several examples of systems-oriented thinking applied to process design. A Perspective by Garg and co-workers discusses tandem thermocatalytic and electrocatalytic processes to sustainably convert carbon dioxide into value-added products. An Article by Shang and co-workers presents a photocatalytic process that enables the selective, efficient and scalable extraction of gold from different forms of electronic waste. A Q&A with Kai Qiao highlights the significance of process-level thinking in industrial biochemical engineering. And an Article by Bell and co-workers reports a modular programmable inert-atmosphere Schlenk-line computer for the synthesis of highly reactive compounds.

Our emphasis on systems-level approaches to design continues from a different angle in this issue's Viewpoint that showcases the perspectives of six educators in chemical engineering on the current strengths and areas that need development in the undergraduate curriculum. Over the past several decades, the field boundaries have greatly expanded, and here the design challenge is to incorporate new approaches and topics into a curriculum with a fixed number of course hours. The Viewpoint, although not comprehensive, begins an important discussion that covers topics such as data science and advanced computational methods, electrochemical engineering, and techno-economic and life-cycle assessments.

Finally, to fully embrace the above challenges, future journal issues will feature an Analysis format covering research that proposes, evaluates or optimizes chemical processes over a wide range of scales. This format will be key to assessing economic feasibility, understanding environmental impacts, quantifying design criteria for materials and/or units, and identifying sensitivity and risks associated with key inputs. Through this format, we aim to foster a comprehensive understanding of the complexities involved in the design of chemical processes and systems.

There is a fine art within the field of drawing the line in process design. But we are now at an opportune moment to put these principles into practice.

Published online: 8 February 2024

References

1. Zimmerman, J. B., Anastas, P. T., Erythropel, H. C. & Leitner, W. *Science* **367**, 397–400 (2020).
2. Wu, X. S. et al. *Nat. Sustain.* **5**, 452–459 (2022).
3. Ioannou, I., Galán-Martín, Á., Pérez-Ramírez, J. & Guillén-Gosálbez, G. *Energy Environ. Sci.* **16**, 113–124 (2023).
4. Anastas, P. T. *Trends Chem.* **1**, 145–148 (2019).