Robust Optimization of Critical Mineral Membrane Separations Under Uncertainty

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PROMMIS — Process Optimization and Modeling for Minerals Sustainability

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Diafiltration System Modeling

Membrane technologies are promising low-energy, aqueous processes for critical mineral recovery.

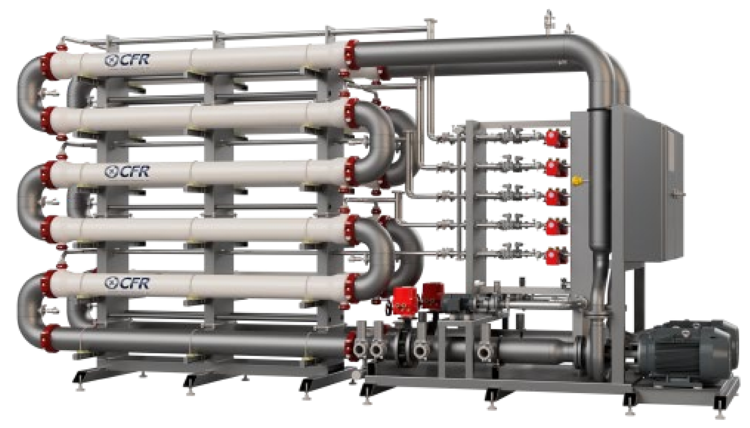
(Interchangeable Li/Co Objectives)

max — Cobalt Recovery
s.t. — Lithium Recovery ≥ Spec

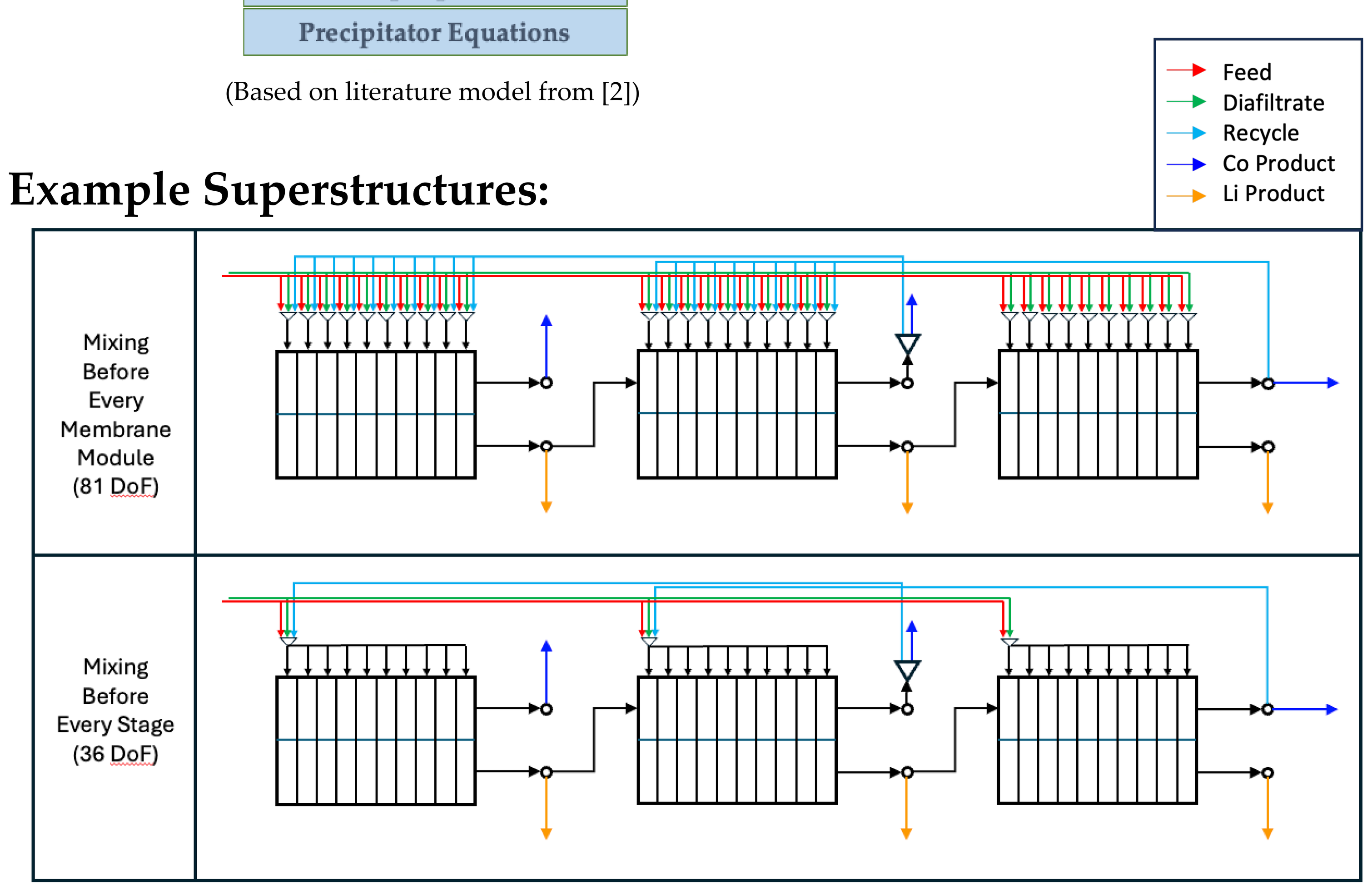
Membrane Model Equations:
- Permeate Mass Balances
- Retentate Mass Balances
- Membrane Performance Equations
- Stage Connectivity Balances
- Flow Rates ≥ 0
- Pump Equations
- Precipitator Equations

(Based on literature model from [2])

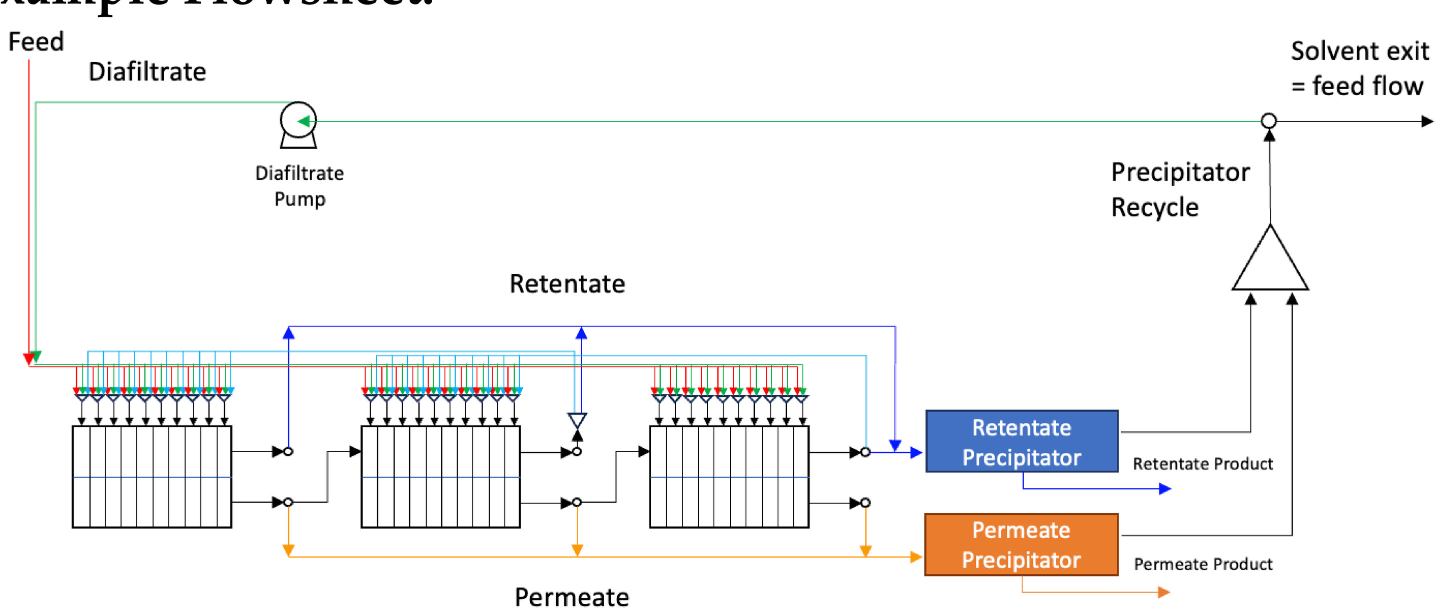
Example Membrane Stage [1]



Example Superstructures:



Example Flowsheet:



Robust Optimization Methods

Membrane processes must be able to perform satisfactorily in light of model uncertainties.

- Membrane performance parameters may have manufacturing variability
- Process inlet stream conditions may be different than expected

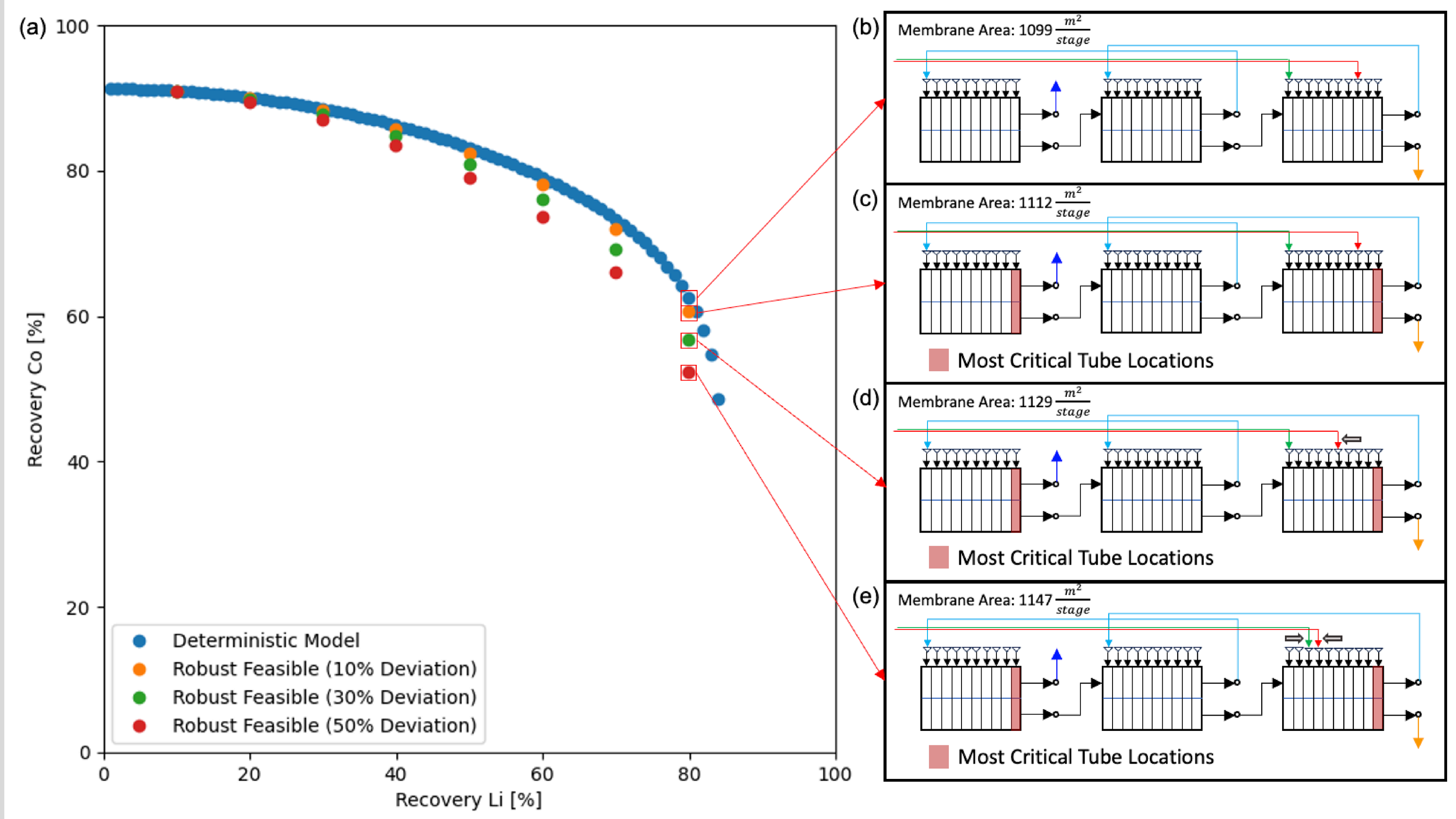
Design & Control Degrees-of-Freedom:

- Membrane area is set during process construction
- Inlet flow rates and locations are adjustable during operation

Pyomo Robust Optimization Solver (PyROS) can obtain robust optimal solutions that are feasible for all realizations of uncertainty[3,4]

Uncertainty in Membrane Performance

Manufacturing variability in membrane sieving may reduce process performance. Robust designs can satisfy recovery requirements under these conditions.

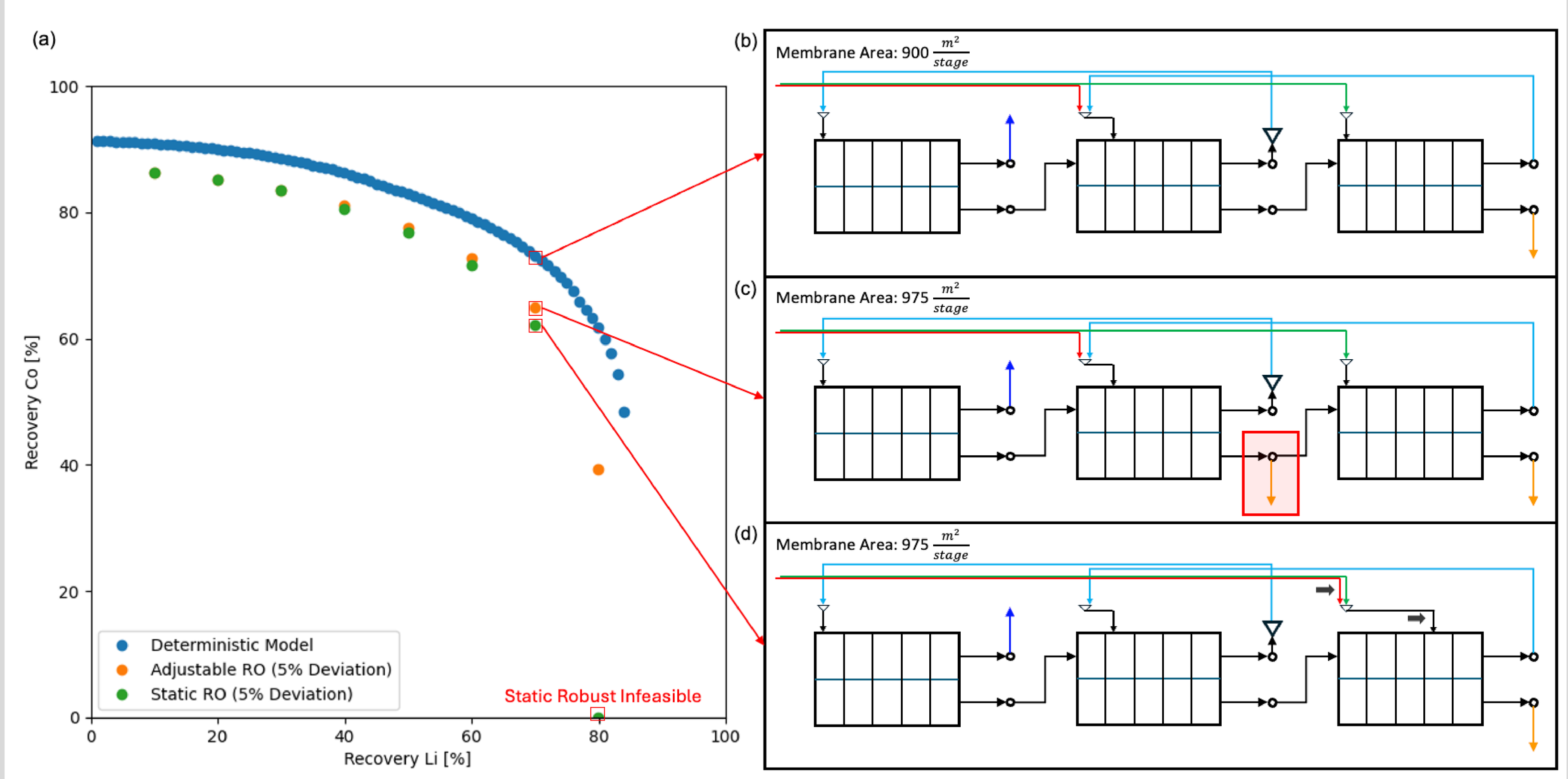


- ➢ As a "cost of robustness", robust optimization with larger uncertainty sets results in worse objectives relative to deterministic solutions

Insights:
- ➢ Increasing membrane area helps to proactively maintain lithium recovery
- ➢ In the worst-case scenario, membrane tube modules right before product streams have high cobalt sieving.
  - — These locations have the highest concentration of solutes and are more vulnerable to loss of product.

Uncertainty in Process Inlet Stream

Uncertainty in the feed flow and quality of raw materials make membrane process design difficult. Adjustable robust optimization takes into account built-in process flexibility and can potentially find better process designs.



- ➢ Static robust optimization assumes all decisions are made during process construction. Adjustable robust optimization assumes some decisions as recourse to react to uncertain scenarios.

Insights:
- ➢ A more flexible process can sustain satisfactory process performance under conditions where static designs fail.
- ➢ Alternative lithium product streams can maintain lithium recoveries with potentially higher cobalt recoveries.

Diafiltration System Costing

Optimization of a costing objective can determine optimal diafiltrate flow rate and yield cost effective designs.

$$\min \; OPEX + \varepsilon\, CAPEX$$

s.t.

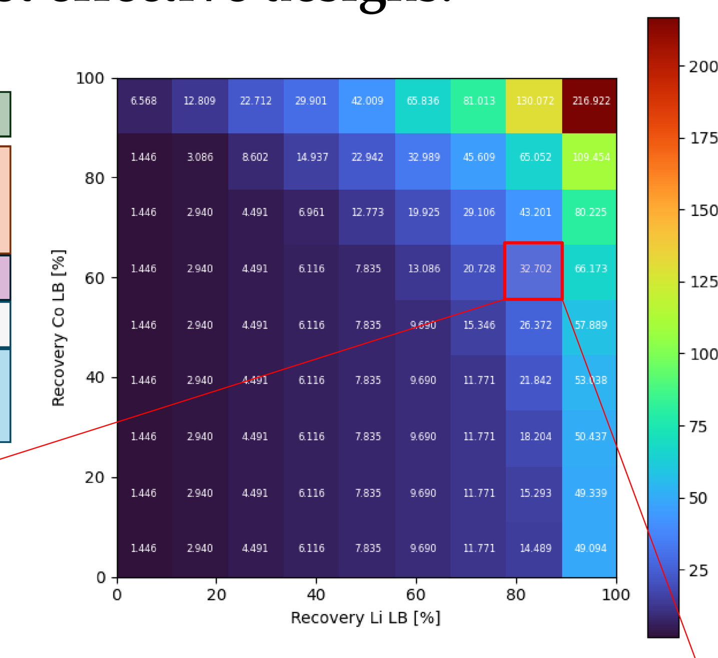
$$OPEX = RR_{memb} c_{memb} A_{memb} + c^{operate}_{pump} p^{operate}$$

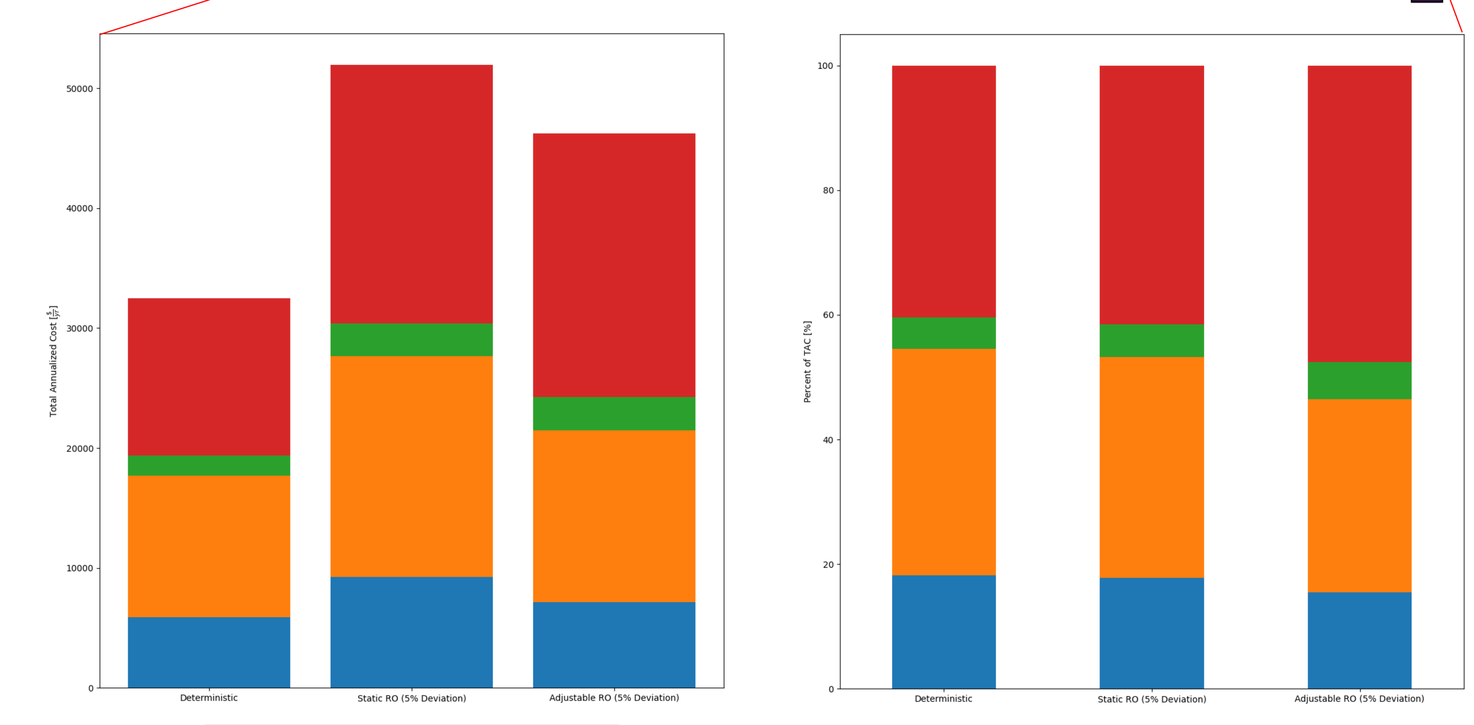
$$CAPEX = c_{memb} A_{memb} + c^{install}_{pump} p^{install}$$

$$Recovery_s \geq Spec_s \quad \forall s \in \{Li, Co\}$$

Membrane Model Equations
Pump Equations
Precipitator Equations

(Costing parameter data from [5-7])





- ➢ Insights from previous case studies still apply with costing model
- ➢ A cost optimal diafiltrate flow balances the cost of increasing flow rate with benefit of improving membrane system performance and flexibility

Conclusions and Future Work

Conclusions:
- ❑ We applied robust optimization methodologies on a Co/Li diafiltration flowsheet to generate optimal designs immune to membrane manufacturing variability and uncertain process feed flow and concentrations.
- ❑ Based on a simple costing model, we showed how robust designs can maintain performance requirements at a slightly higher cost compared to their deterministic counterparts.

Future work:
- ❑ Apply robust optimization on multiperiod membrane models to investigate uncertainty in time-varying raw material inlets and fouling over time.
- ❑ Obtain robust designs using PrOMMiS's high-fidelity costing model.
- ❑ Explore applications with other critical minerals.

Acknowledgements

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