Powering the circular economy with maximum metal recovery from printed circuit boards by machine learning and robust optimisation

Waqar Muhammad Ashraf[1], Prashant Ram Jadhao[2], Ramdayal Panda[2], Kamal Kishore Pant[3], Vivek Dua[1]

[1]The Sargent Centre for Process Systems Engineering, Department of Chemical Engineering, University College London, UK
[2] Department of Chemical Engineering, Indian Institute of Technology, Delhi, India
[3] Department of Chemical Engineering, Indian Institute of Technology, Roorkee, India

UCL

Problem Statement

- ✓ Waste Printed Circuit Boards (WPCBs) cause environmental pollution [1]
- ✓ Current chemical solvents-based metal recovery is harmful for human operators and hazardous to the environment [2]
- ✓ Metal recovery is limited to trial-and-error experimental exploration
- ✓ Machine Learning (ML) and Robust Optimisation (RO) is rarely explored

Objectives

- ✓ Innovating environmental-friendly solvents for metal recovery
- ✓ Leveraging ML & RO for process optimisation to maximise metal recovery from WPCB

Method

- ✓ The design space of process variables are : **NH_3 conc.** (g/L) : 50 – 100, **$(NH_4)_2SO_4$ conc**. (g/L) : 100 – 200, **H_2O_2 conc**. (M) : 0 – 1 M, **Time** (h): 1 – 4, **L/S ratio** (mL/g): 10 – 30, **Temp.** (°C): 40 – 100, **Stirring speed** (rpm): 300 – 900
- ✓ Artificial neural network (ANN) models are trained to predict **Cu** (%) and **Ni** (%) recovery
- ✓ Rigorous hyperparameters tuning is carried out to achieve the robust and generalize performance of ANN models
- ✓ Partial derivative-based % significance order of process conditions is as follows [3]: $\% \, Significance = \frac{\sigma^2_{y_i|x_i}}{\sum_{i=1}^{c} \sigma^2_{y_i|x_i}} \times 100$

  $\sigma^2_{y_i|x_i}$ is square of the sensitivity values produced due to x_i
- ✓ Multi-objective function: $f(x)$: $max\ [a\ f_{Cu}(x) + \ b\ f_{Ni}(x)]$

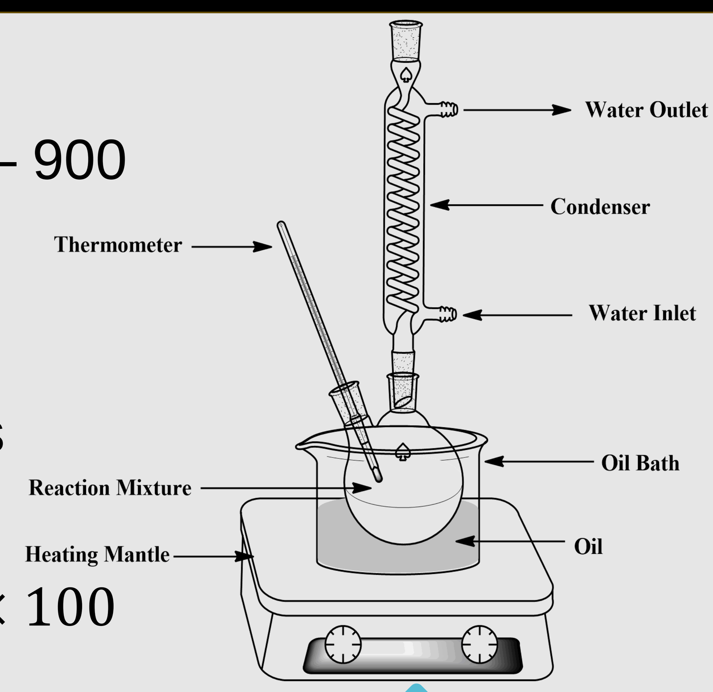
  subject to: $h(x) = 0$

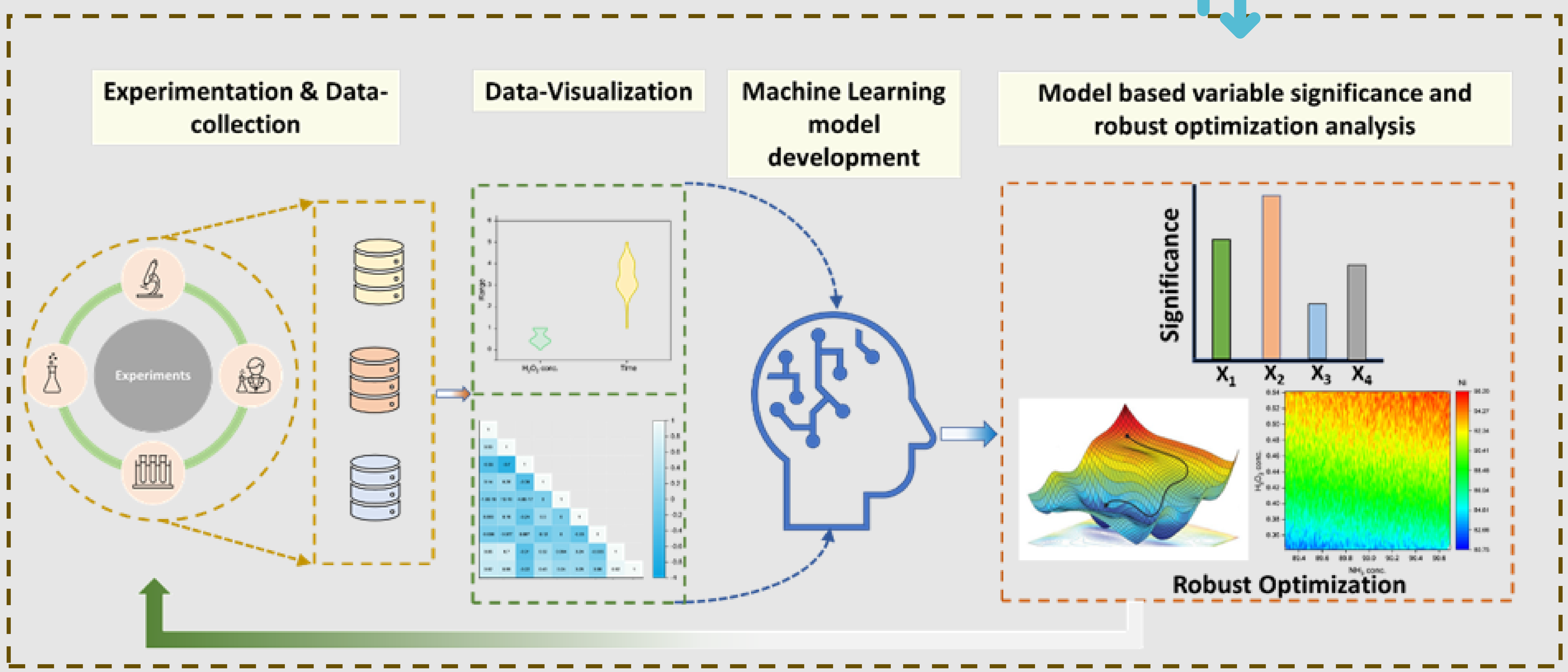
  $x = x_1, x_2, \ldots, x_n,\ \ x \in X \subseteq R^n$ and $x^L \leq x \leq x^U$
- ✓ Mean function response is computed using Monte Carlo simulations as [4]:

$$F(x) = \frac{\sum_{k=1}^{H} f(x+\delta_k)}{H}$$

- ✓ The estimated solution is robust if:

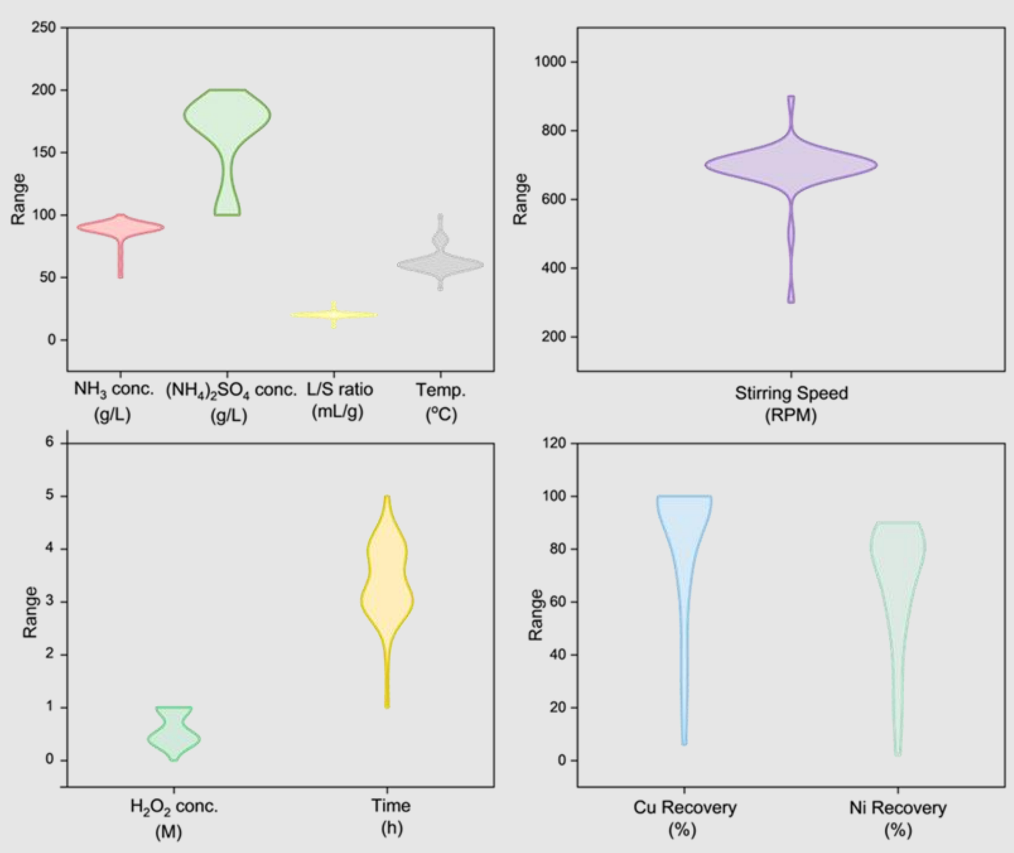
$$V(x) = \frac{\|F(x) - f(x)\|}{\|f(x)\|} < \varepsilon$$

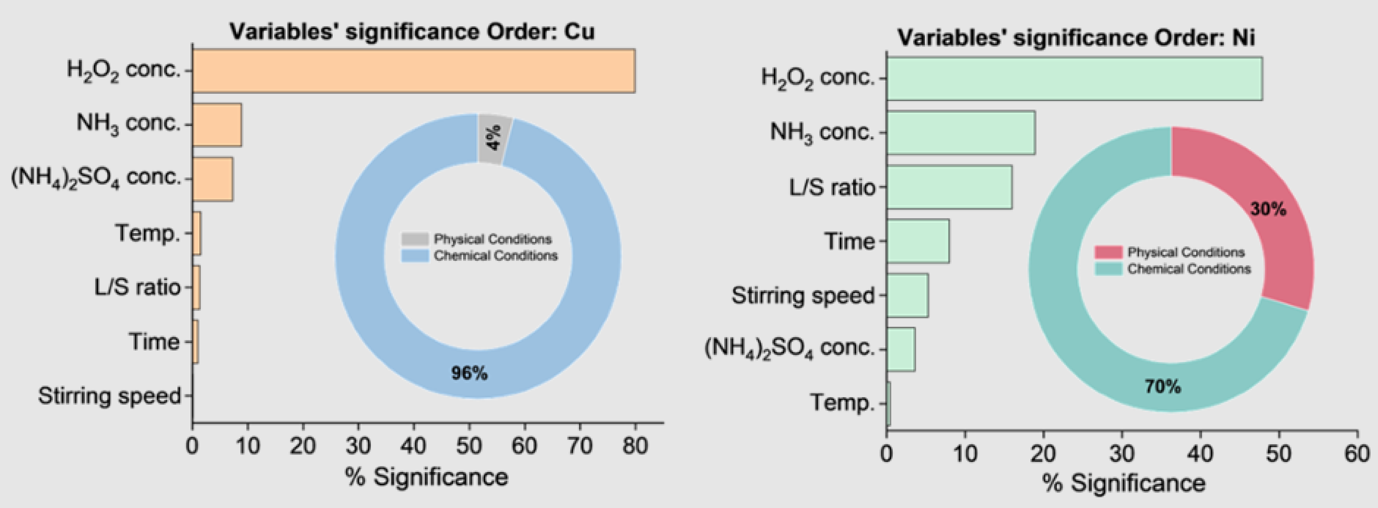




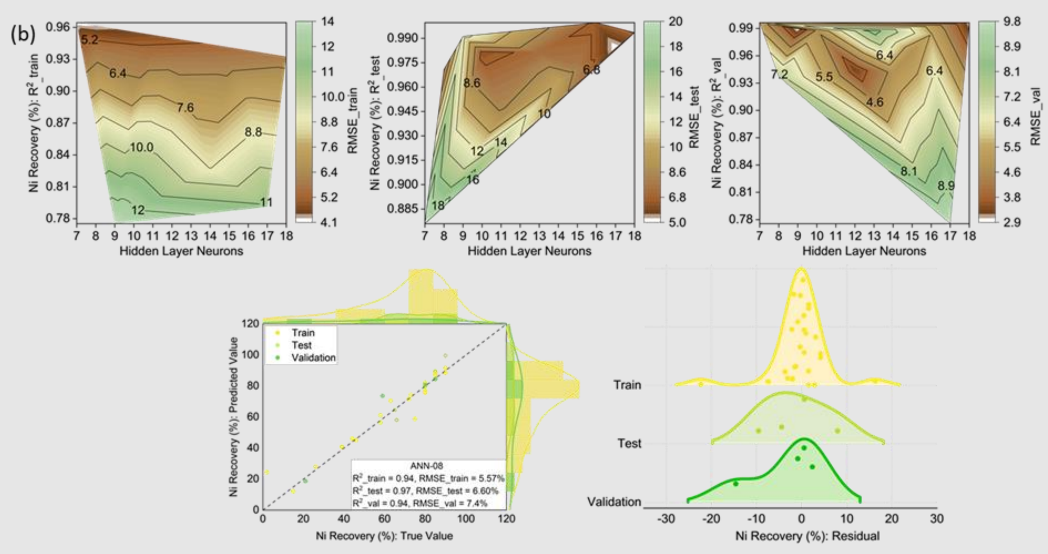
Results

Experimental Data-Collection & Visualization

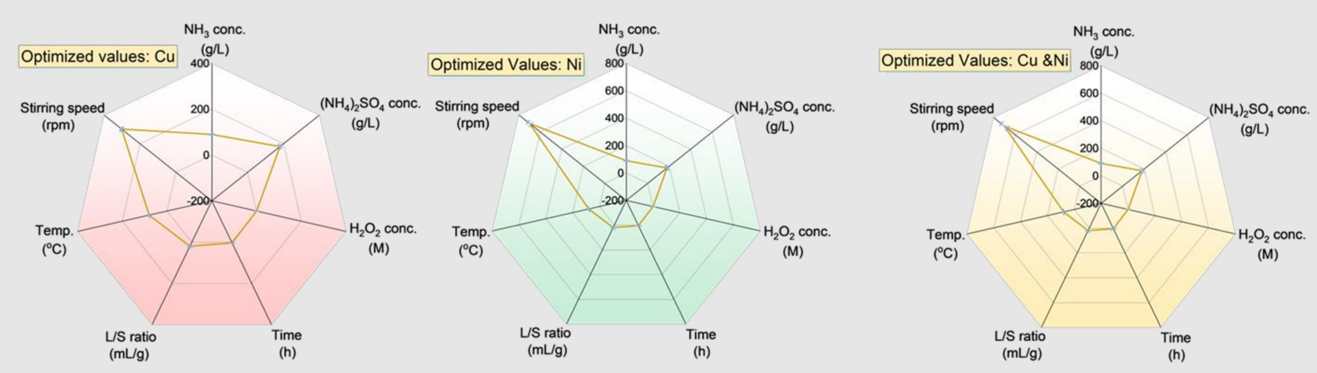


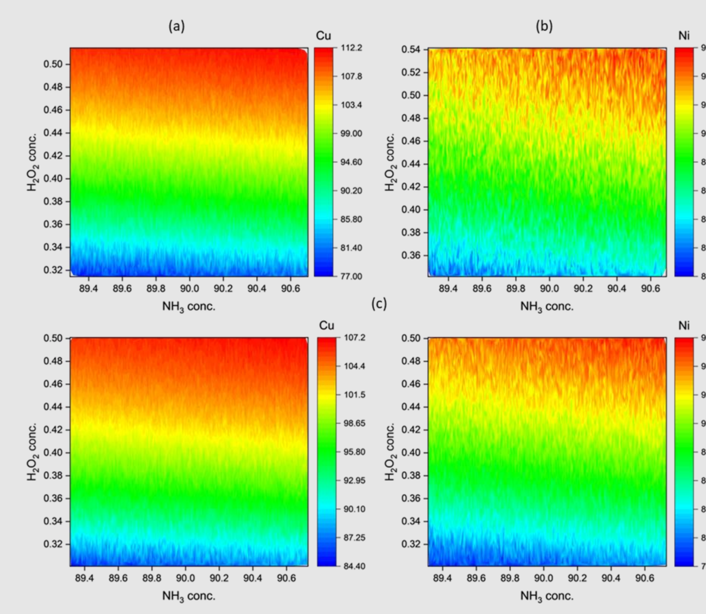


ANN model development & Feature Importance



Separate & combined recovery of Cu & Ni





Solution Robustness Investigation

Conclusions & Future Work

- ✓ ANN models for Cu & Ni are trained with accuracy more than 90%
- ✓ **H_2O_2 conc.** and **NH_3 conc.** are the two most significant variables affecting metal recovery from WPCBs
- ✓ 100% Cu and 90% Ni are recovered from WPCBs
- ✓ 15.2 g and 62.6 g equivalent reduction in CO_2 are estimated for Cu and Ni recovery from 10 g
- ✓ The future work will make the digital platform hosting the metal recovery models to estimate the process design conditions

References

[1] Rajesh, R., D. Kanakadhurga, and N. Prabaharan, Electronic waste: A critical assessment on the unimaginable growing pollutant, legislations and environmental impacts. Environmental Challenges, 2022. 7: p. 100507

[2] Jadhao, P.R., et al., A sustainable route for the recovery of metals from waste printed circuit boards using methanesulfonic acid. Journal of Environmental Management, 2023. 335: p. 117581

[3] Ashraf, Waqar Muhammad, and Vivek Dua. "Artificial intelligence driven smart operation of large industrial complexes supporting the net-zero goal: Coal power plants." Digital Chemical Engineering 8 (2023): 100119.

[4] Mirjalili, S., A. Lewis, and J.S. Dong, Confidence-based robust optimisation using multi-objective meta-heuristics. Swarm and Evolutionary Computation, 2018. 43: p. 109-126

Sargent Centre for Process Systems Engineering

Acknowledgements

The authors acknowledge the funding received for the project, "E-waste recycling: Development of green and sustainable technology for recovery of metals from electronic waste" from the UCL-IIT Delhi Strategic Partner Fund, award number MFIRP179.