Optimal Design Approaches for Cost-Effective Manufacturing & Deployment of Chemical Process Families with Economies of Numbers

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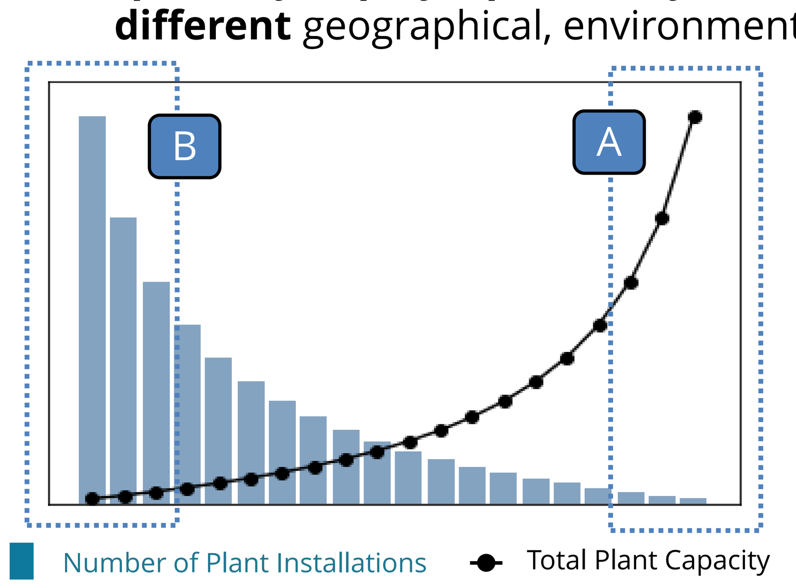
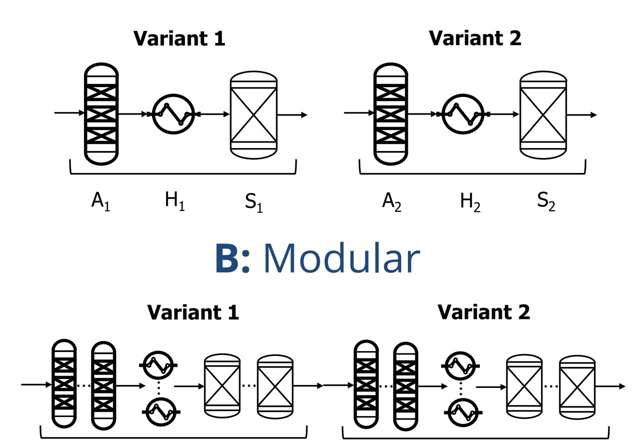
Motivation[1]

Optimally deploy a **process system** across **decentralized sites** with **different** geographical, environmental and operating requirements.

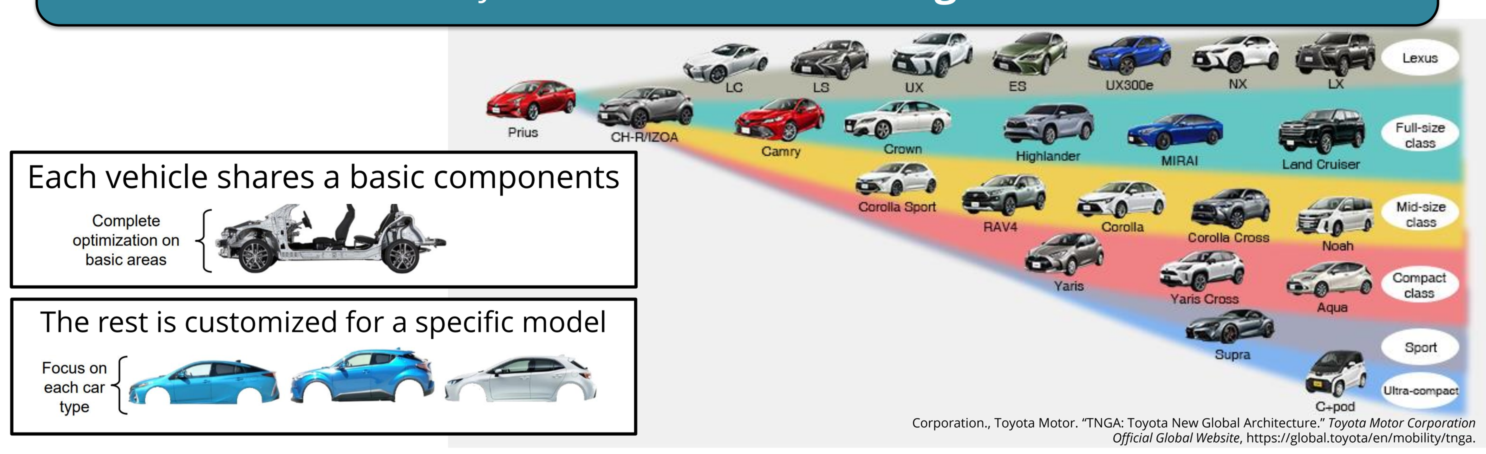


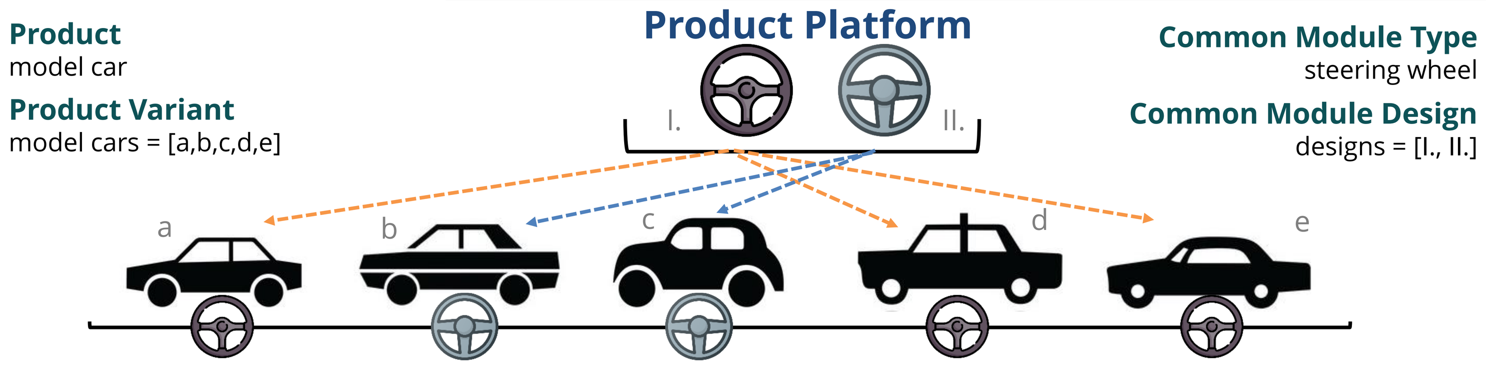


Process Family Design **includes** the **benefits of both**.

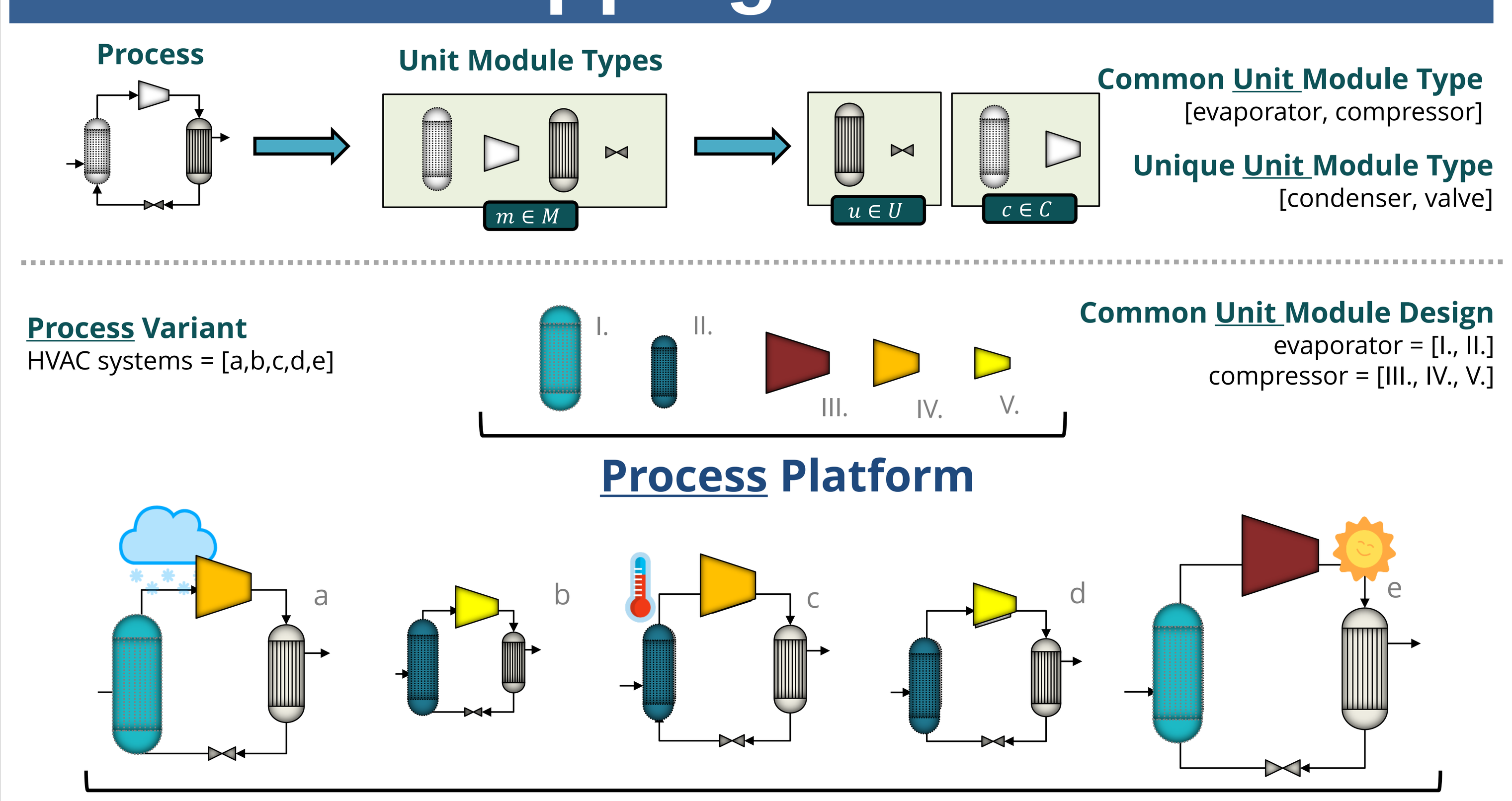
Product Family Design[2]

A **set of products** that **share** one or more **common "element(s)"** yet target a variety of **different market segments**

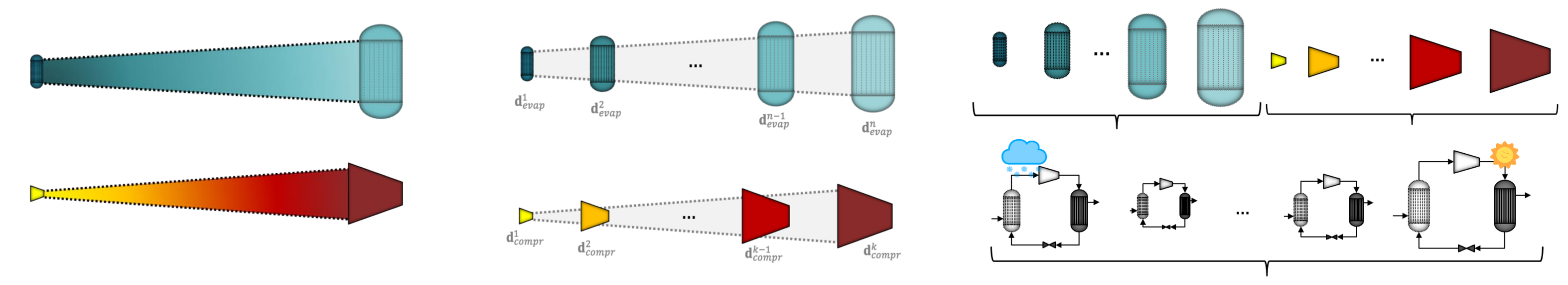




Mapping to PSE



Discretization Approach[3,4]



Given design ranges $\forall c \in C$ → **Discretize** and select **candidate designs** L_c → **Optimize** and **define** the **alternatives** A_v

Decision Variables

(1) which candidate designs $l \in L_c$ are in the platform $\mathcal{P}$? → $z_{c,l}$

(2) which $a \in A_v$ is assigned to each variant $v \in V$? → $x_{v,a}$

$$\min. \sum_{v\in V} w_v \sum_{a\in A_v} p_{v,a} x_{v,a} \quad (1.1)$$

Minimize the total weighted cost of **all variants** in the process family

s.t.

$$\sum_{l\in L_c} z_{c,l} \le M_c \quad \forall c \in C \quad (1.2)$$ → Select units for manufacture

$$\sum_{a\in A_v} x_{v,a} = 1 \quad \forall v \in V \quad (1.3)$$ → Select 1 alternative

$$x_{v,a} \le z_{c,l} \quad \forall v \in V, a \in A_v, (c,l) \in Q_a \quad (1.4)$$ → Alternative *must be* manufactured

$$z_{c,s} \in \{0,1\} \quad \forall c \in C, l \in L_c \quad (1.5)$$

$$0 \le x_{v,a} \le 1 \quad \forall v \in V, a \in A_v \quad (1.6)$$

At optimality, the **solution will converge to binary** under mild assumptions[5]

ReVelle, Charles S., and Ralph W. Swain. "Central facilities location." *Geographical analysis* 2.1 (1970): 30-42.

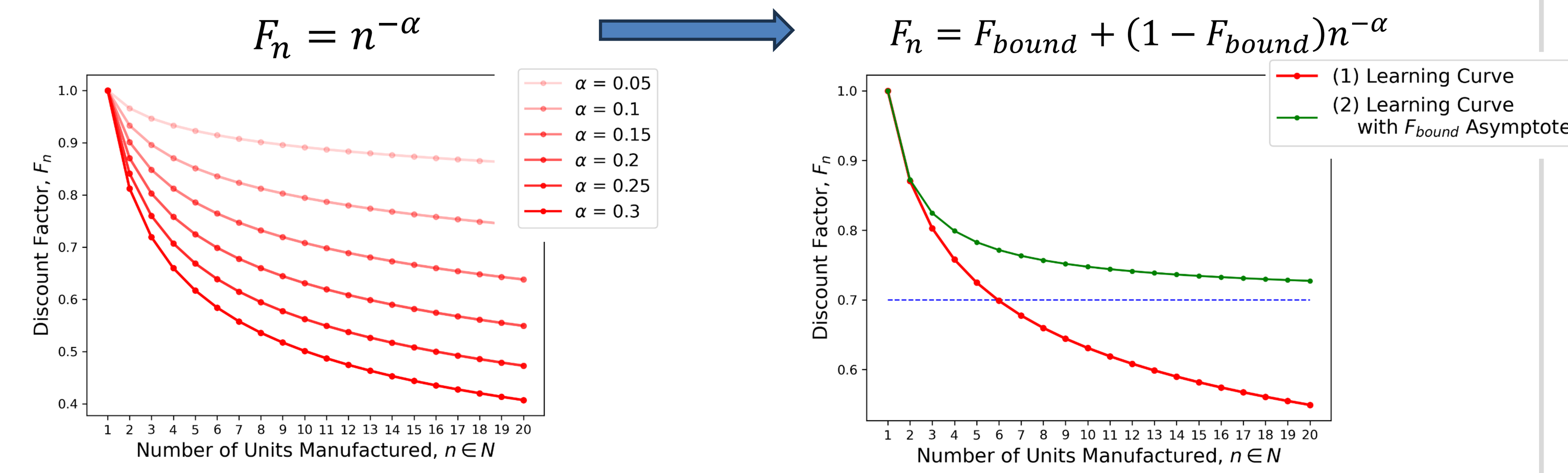
Economies of Numbers[5,6]

Challenge: **(1.2)** requires us to **specify size** of the **platform a priori**.

Approach: Include Economies of Numbers savings *within* formulation

EoN yields **large increases** in **productivity** as organizations **gain experience** in **production**.

$$F_n = n^{-\alpha} \quad \Rightarrow \quad F_n = F_{bound} + (1 - F_{bound}) n^{-\alpha}$$



$$\min. \sum_{v\in V} w_v \sum_{a\in A_v} p_v x_{v,a} - \rho$$

Minimize total weighted cost of every variant **discounted by savings from EoN**

s.t.

$$\sum_{l\in L_c} (1 - y_{c,l,0}) \le M_c \quad \forall c \in C$$

$$\sum_{a\in A_v} x_{v,a} = 1 \quad \forall v \in V$$

$$x_{v,a} \le (1 - y_{c,l,0}) \quad \forall v \in V, a \in A_v, (c,l) \in Q_a$$

$$\sum_{n=0}^{N} y_{c,l,n} = 1 \quad \forall c \in C, l \in L_c$$ → **Decide** integer **number** of unit module type c design l **are manufactured**

$$\sum_{n=0}^{N} n \cdot y_{c,l,n} = \sum_{v\in V} w_v \sum_{a\in A_{v,c,l}} x_{v,a} \quad \forall c \in C, l \in L_c$$ → **Constrain** number of unit module type c design l **manufactured** to **reflect family**

$$\rho = \sum_{c\in C} \sum_{l\in L_c} \sum_{n=0}^{N} n \cdot y_{c,l,n} \cdot (p_{c,l} - \widehat{p_{c,l}}^{\,n})$$ → **Compute** the **total discount** ρ

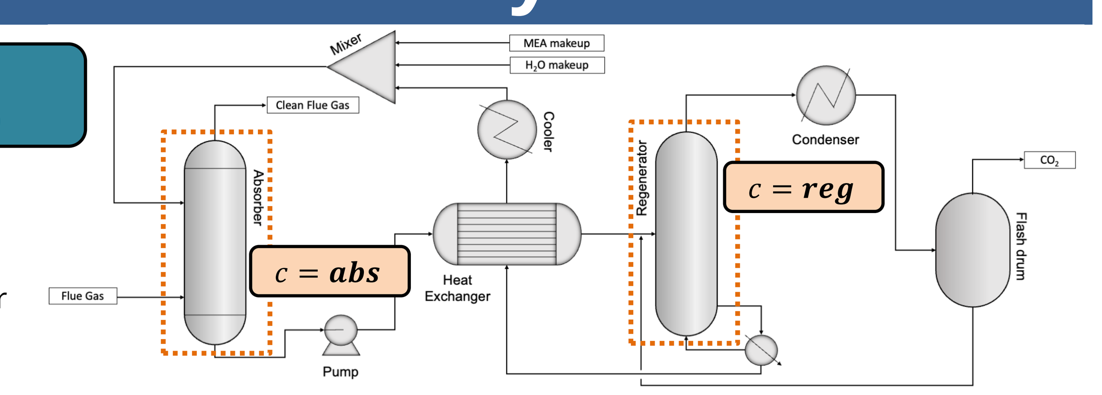
Case Study[7]

Carbon Capture
Monoethanolamine (MEA)

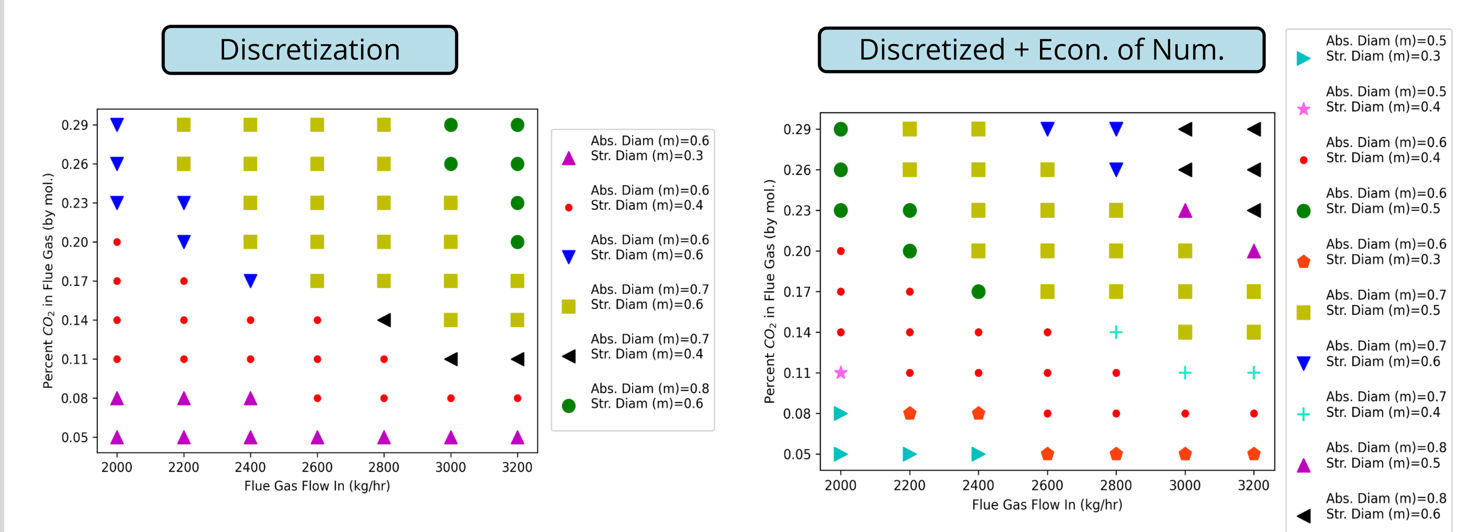
Common Units

1) Diam. of the Absorber
2) Diam. of the Regenerator

$C = [abs, reg]$



Results



Objective: $75.4M | **Objective:** $72.5M

- In the discretization formulation, we need to specify M_c.
- In the EoN formulation, we determine M_c as apart of the optimization.
- $2.38M annual cost savings compared to discretization approach (~3.3%).
- Considering only capital costs, we gain 26.8% annual cost savings.

Conclusions

✓ Reduced manufacturing costs.
  - Economies of numbers (modular concepts at unit level).
  - Economies of scale (customization to design range).

✓ Multiple scalable optimization formulations.

✓ Economies of Numbers formulation adds cost savings and determines size of platform.

✓ Increased annual cost savings using the new approach.

Future Work

❑ Perform a rigorous costing analysis for each design approach.
❑ Incorporate Econ. Of Num. and decomposition for ML Surrogates.
❑ Use the explicit equation oriented system model within formulation.

References

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