Fundamentals of Process-Based Cost Modeling

3.56 Special Session One
Session Goal & Outline

- Goal:
  Understand the basic steps necessary to create a process-based cost model used to educate strategic technology choices

- Topics Covered
  - Define Question to be Answered
  - Identify Relevant Cost Elements
  - Relate What is Known to Cost
    - Identify What is Known
    - Establish Contributing Factors
    - Determine Required Factor Quantity
    - Determine Price of Allocation
  - Understand Uncertain Characteristics
Review of Process-Based Cost Model (PBCM)

- Objective
  - Map from Process Description to Operation Cost

- Purpose
  - Inform decisions amongst technology alternatives BEFORE operations are in place
  - et al. ....

**Process Description**
- Part Description
- Material Properties
- Economic Characteristics
- Operation Variables

PBCM

**Operation Costs**
Creating a PBCM: Overview

- Models are created by decomposing problem from cost backwards
  - Determine what characteristics, $l_1$, effect cost
  - Determine what characteristics, $l_2$, effect $l_1$ ... and so on until...
  - Determine how process description effect $l_n$

★ Model works from inputs to costs <-> Modeler works from costs to inputs
Cost Modeling: Nomenclature, Notation, & Necessities

- **Operation Cost**
  - Cost is generally measured as one of two rates
    - $C^u$ per unit
    - $C^t$ per time period
  - The denominator of the cost rate will be referred to as its **basis**

- **Cost Element**
  - Cost elements are the distinct categories of cost which together sum to the Total Operation Cost
    - e.g. *Materials Cost, Direct Labor Cost, Energy Cost*

- **Factor**
  - Any product of service, required to produce, for which money must be spent
Creating a PBCM: Critical Steps

1. Define Question to be Answered

2. Identify Relevant Cost Elements

3. Relate What is Known to Cost
   - Identify What is Known
   - Establish Contributing Factors
   - Determine Required Factor Quantity
   - Determine Price of Allocation

4. Understand Uncertain Characteristics
Creating a PBCM: Step One

1. Define Question to be Answered
   - Cost of What?
   - Cost to Whom?
   - Cost When?
   - Cost Varying How?
   - Cost Compared to What?
     ▶ *Relative to Other Options*
     ▶ *Absolute Measure of Operation*

★ More than any physical measure cost is fully dependent on context
   - Cost estimation requires exhaustive definition of context
Creating a PBCM: Step Two

2. Identify Relevant Costs
   - Pertinent to Decision
   - Necessary for Completeness / Credibility

<table>
<thead>
<tr>
<th>Common Elements of Manufacturing Cost</th>
<th>Common Relevant Cost Elements</th>
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Exclude Unimportant Elements

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Creating a PBCM: Step Three - *The Real Deal*

3. Relate Costs to What is Known

- What will You Know?
  - *Engineering principles underlying process*
  - *Factor prices*
  - *Design Concept*
  - *Design Specifications***

- General Form of Relationship

\[
C^X = \sum_{i}^X c_i
\]

\[
c_i^X = \sum_{f}^X (Q_f^X \times P_f^X)
\]

- \( i = \text{Cost Element}, \quad f = \text{Factor} \)
Step Three - *Identify Factors*

3. Relate Costs to What is Known

\[ c_i^x = \sum_{\text{all } f} (Q_f^x \times P_f^x) \]

A. Describe Factors which Contribute to Each Cost Element

- **Fixed:**
  - *Electricity*
  - *Laborers*

- **Variable:**
  - *Resin used*

- **Design Dependent:**
  - *Inj. Molding Press Clamping Force = f(Part Size, Number of Cavities)*

★ Whenever feasible, forecast type of factor used based on design specs
Step Three - *Understand Quantity & Price*

3. Relate Costs to What is Known

\[ c_i^X = \sum_{all \ f} (Q_f^X \times P_f^X) \]

B. Relate Quantity to Process & Design
   - *Quantity of Factor f required to produce the number of parts for the basis u*

C. Relate Factor Price to Process & Design
   - *Price allocated to use a unit of Factor f for the basis u*

★ Basis u should be chosen to facilitate calculating Q and P
Variable vs. Fixed Costs

3. Relate Costs to What is Known

\[ c_i^t = \sum_{all \ f} (q_f^t \times p_f^t) \]

- **Per period** element cost form two categories
  - Variable Cost
    - Those directly proportional to production volume in that period
  - Fixed Cost
    - (Obviously) Those little influenced by production volume

- This behavior influences convenient basis for cost
  - Variable
    - Calculate Per Unit
  - Fixed
    - Calculate Per Period
Modeling Specific Cost Elements

- Case Study: Polymer Injection Molding (PIM)
  - Conceptually simple process
    1. Melt polymer feedstock
    2. Inject into mold
    3. Cool
    4. Remove Part
PIM Example - Material Cost

- Variable Cost:
- Factor Required: Polymer Pellets
  - Factor Type: Design Dependent
- \( Q_f = (\text{Material in Part}) + (\text{Other material used}) \)
  - (Part Volume) x (Density)
  - (Mass of Part)
  - Scrapped Parts
  - Delivery Material
  - Finishing Scrap
  - Reusable Material
- \( P_f = \) Price of Polymer Pellets

\[ c_{\text{matl}} = Q_f \times P_f \]
PIM Example - Labor Cost

- Variable Cost

- Factor Required: Polymer Industry Labor
  - Factor Type: Fixed

- $Q_f = \frac{\text{Laborers per Line}}{\text{Parts per Line}} \times (\text{Time To Make A Part} + \text{Other Time})$

  - $\# \text{Cavities in Mold}$
  - $\text{Cycle Time}$
  - Maintenance
  - Breaks
  - General Inefficiency

- $\text{Cycle Time} = f(\text{Material, Geometry, Technology, ...})$

- $P_f = \text{Total Labor Wage}$
Injection Molding Cycle Time

**Cycle Steps**

1. Open Mold
2. Advance Injector
3. Fill
4. Pack
5. Retract Injector
6. Melt next load
7. Open Mold

Cooling

Clamp

Force
Cycle Time - Engineering Parameter

- Use Combination of Engineering and Theoretical Approaches
  - Cycle Time = (Filling Time) + (Cooling Time) + (Cycle Reset)

- Cooling Time - Theoretical Determination

\[
\text{Cooling Time} = \frac{\rho \, d^2 \, c_p}{\kappa} \ln \left[ \frac{8 \times (T_{\text{Melt}} - T_{\text{Mold}})}{\pi^2 \times (T_{\text{Eject}} - T_{\text{Mold}})} \right]
\]

- Filling Time - Function of Shot Size - Function of Part Weight
- Mold Cycle - Function of Press Size, But Likely Only Weakly

★ Cannot Expect Perfect Match To Theory, So Try To Correlate
Cooling Time, Part Weight and Cycle Time Correlation

\[ T_{\text{cyc}} = 1.35 \times T_{\text{cool}} + 0.0151 \times \text{wgt} + 8.87 \]
PIM Example - Equipment Cost

- Fixed Cost (calculate on per time period basis)

- Factor Required: Injection Molding Machine
  - Factor Type: Design Dependent
  - Machine Type = f(Part Geometry)

- \( Q_f = \) Number of Lines Required

- \( P_f = \) Price \( \times \) Fraction Allocated to each Period

\[ \text{Capital Recovery Factor} \]

★ ... However, this is not good enough!
Evolution of a Cost Model - Injection Molding

- Equipment Size $\Rightarrow$
  Function of Clamping Force

- Clamping Force $\Rightarrow$
  Function of Part Geometry and Processing Parameters

- Empirical Relation:

  \[
  \text{Clamp Force} = \text{Projected Area} \times N_{\text{cavities}} \times \frac{224}{\sqrt{\text{Wall Thick.}}} + 172
  \]

★ Clamp Force Can Then Be Related To Press Cost
Correlation Between Press Cost and Tonnage

Cost = 368.82 \times \text{tonnage} + 14831

Machine Cost (thousand $)

Press Tonnage
Processing Time and Its Relationship with Capital Costs

- Number of Machines/Production Lines

\[
\text{Number of lines} = \frac{\text{Cycle Time} \times \text{Annual Production Volume}}{\text{Available Production Time} \times \text{# of Cavities}}
\]

(If dedicated, rounded up to the next integer value)

- Critical Accounting Issue -- Dedication
  - Will lines be fully dedicated to producing only this product?
  - Only impacts lines not fully utilized
Cost Modeling Important Concepts

- Break down problem as much as possible
- Relevant cost elements vary with question and context
- Clearly identify cost elements considered
- Calculate element cost with convenient basis
  - Variable $\iff$ Per Unit
  - Fixed $\iff$ Per Period
- Be careful of spurious precision
Amortization of Capital Costs

- Capital Costs Must Be Annualized / Amortized to Account for Financing Costs or Opportunity Costs

- Simple Annuity Calculation:

  \[
  \text{Annual Cost} = \text{Total Capital Cost} \times \frac{r^n \times (1+r)^n}{(1+r)^n - 1}
  \]

- Note: The period of the annuity/payback is determined by either
  - the accounting lifetime of the capital good (machines, buildings, etc.),
  - the lifetime of the product being produced (tooling) or
  - the physical lifetime of the capital good, whichever is shorter.
Capital Cost Relationships

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<td>Part Material</td>
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