Fundamentals of Process-Based Cost Modeling

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
  – Understand Uncertain Characteristics
Review of Process-Based Cost Model (PBCM)

- **Objective**
  - Map From Process Description To Operation Cost
- **Purpose**
  - Inform Decisions Concerning Technology Alternatives
    BEFORE Operations Are In Place

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

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What is a PBCM?

- **What is a PBCM?**
  - Incorporates Technical Information About Process
  - Builds Cost Up From Technical Detail
  - Must Be Able To Address Cost Implications Of Change In
    - Product Design or
    - Process Operation -- Including Production Volume
- **Remember:**
  - The Purpose Of A Cost Model Is To Inform Technical Decisions
Model Objective

- Operation Cost
  - Cost is generally measured as one of two rates
    \[ \frac{C_t}{t} \text{ per time period} \]
    \[ \frac{C_u}{u} \text{ per unit} \]
  - In Most Cases, Cost Per Unit (e.g., $ / part, $ / kg) Is The First Measure To Use For Comparing Technologies

Creating a PBCM: Overview

- Models are created by decomposing problem from cost backwards
  - Determine what characteristics, \( I_1 \), effect cost
  - Determine what characteristics, \( I_2 \), effect \( I_1 \) ... and so on until...
  - Determine how process description effects \( I_n \)

- Model works from inputs to costs
  - Modeler works from costs to inputs
Creating a PBCM: Critical Steps

- Define Question To Be Answered
- Identify Relevant Cost Elements
- Diagram Process Operations & Material Flows
- Relate Cost To What Is Known
- Understand Uncertain Characteristics

Creating a PBCM: Step One

- Define Question To Be Answered
  - Cost of What?
    - Carefully Understand Processing Boundaries
  - Cost to Whom?
    - Perspective Determines Pertinent Costs
  - Cost Varying How?
    - What Technical Changes Are Being Considered?
  - 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

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

Common Elements of Manufacturing Cost

<table>
<thead>
<tr>
<th>Material</th>
<th>Tooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Overhead</td>
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<tr>
<td>Labor</td>
<td>Building</td>
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Exclude Unimportant Elements

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Common Relevant Cost Elements

- Variable
  - Materials (Raw Materials & Consumables)
  - Labor
  - Energy

- Fixed
  - Equipment (including Maintenance)
  - Tooling
  - Building
  - Overhead

- Begin With These, But Always Ask Whether Others Are Important
  - Tradeoff Amongst Time, Resources, and Available Knowledge
Creating A PBCM: Step Three

- Diagram Process Flows
  - Draw in materials flowing into AND out of
  - Catalog for each process step
    - Equipment
    - Labor
    - Energy
- e.g., Sheet Metal Stamping
  - Forming between two matched dies

Diagramming Flows Example: Stamping

- Catalog for each process step
  - Equipment
  - Labor
  - Energy
Step Four: Relate Costs to What is Known

• Process Involves Four Steps
  – 1. Begin At The Current Endpoint (initially, the costs)
  – 2. Ask: How Can That Quantity Be Broken Down?
    Initially, How Many Do I Need x How Much Does Each Cost
  – 3. Analyze Required Information (i.e. parameters)
    Are Those Parameters Acceptable Endpoints?
    Can I (the model) Derive Them From A Simpler Or More Relevant Set Of Information?
  – 4. If No, Repeat 1 With New Endpoints

• Watch Out For Interdependent Parameters
  e.g. Part Mass & Part Dimensions

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Step Four Example

• Start At The End
  – What Is The End? Costs

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• Pick An Endpoint
  – For Example, Material Cost For Blanking

• How Can That Be Broken Down:
  – How Many Do I Need x How Much Does Each Cost
  – Number of Coils Used x Cost per Coil
Step Four Example (cont.): Material Cost

- Start At The End:
  - How Many Are Needed \( \times \) How Much Does Each Cost
  
  *Think In Terms Of Yearly Quantities*

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Two Important Quantities

- Production Capacity = Quantity of "Good" Parts Capable of Being Produced
  - How much CAN a plant produce

- Production Volume = Quantity of "Good" Parts Produced
  - How much DOES a plant produce

- Generally, Both Are Measured In Units Per Year
  (e.g., parts / year, kgs / year)
Step Four Example: Material Cost (Blanking)

Satisfactory Endpoints

- Production Volume (PV)
- Coil Mass
- Coil Price ($/kg)

Material Cost (Blanking) =
Cost of Coils - Value of Scrap Sold

Tip: Compute costs on annual basis, use PV to convert to unit cost

$ of Coils = How Many X How Much Each Cost
Coils / Year X Unit Price of Coil

Are these satisfactory endpoints? No: Coils / Year, depends on PV Price of Coil, normally prices are appropriate inputs, but this price is depends on the dimensions of the coil

Price of Coil = Mass of Coil X Price of Coil Material ($ / kg)
Satisfactory? Both seem like reasonable inputs

Material Cost Blanking - 2

Coils / Year = f (Blanks per Coil, Number of Blanks Made)
= (Blanks Produced / Year) ÷ (Blanks / Coil)

- Satisfactory? Blanks / Year is dependent on PV
- Need more modeling

Blanks / Coil = f(Usable Area on Coil, Blank dimensions)
- Imagine Rolling Coil Out

# blanks = f( Length_{coil}, Width_{coil}, Unusable Length_{b}, Length_{blank}, Width_{blank} )

Blanks come in many sizes

Delivery Mat'l (unusable)
Material Cost Blanking - 3

- Blanks Produced / Year = Good Blanks + Rejects
- effective PV\text{Blanking} = PV\text{Blanking} + Rejects
  - Can model Rejects as % of total production
- Production Volume (PV)
- Coil Mass
- Coil Price ($/kg)
- L_c, W_c
- Unusable Length
- L_B, W_B
- Reject Rate (R)

- effPV_B = PV_B + R \times effPV_B
- effPV_B = PV_B(1 - R)

- But what is PV_B?
  - Assume that PV_B equals Total Stampings Produced / Year (i.e., effPV_{Stamping})

- effPV_i = effPV_{i+1} (1 - R)

- For last step, substitute PV for effPV_{i+1}

Material Cost Blanking - 4

- Value of Scrap = Quantity of Scrap \times Price of Scrap

- Quantity of Scrap = Mass of Coils Purchased
- Mass of Good Blanks
  - We know Mass of Coils
  - Need Mass of Good Blanks. Know Number of Good Blanks, Need Mass of Blanks
  - Given blank length and width, only need thickness_{Blank}

- Given This Set Of Information We Can Calculate The Annual Material Cost For Blanking
  - Remember, convert unit cost by dividing by PV
Capital Cost

- Capital Cost: One of the so-called "Fixed" Costs
  - "Fixed" in that the firm incurs the cost irrespective of whether ANY products are manufactured
  - Cannot merely acquire more of a fixed cost "factor" on a short time cycle

- Thus, fixed costs must be covered no matter how many units are actually produced

- Typical Capital Costs
  - Machinery, Tools Employed
  - Buildings, Fixed Contracts

Because fixed costs are established at the outset of production (before the first product is made), the cost derives not only from appropriate sizing, but also from the need to distribute the cost over actual production

Thus, a three part problem:
- How much equipment is required?
- How much does that equipment cost?
- How to distribute the cost of that equipment onto the production?
Capital Cost -- How Much Equipment?

• Key Equipment Characteristic: Rate of Production

• Another Name: Cycle Time - Time to make one unit of production

• Given:
  – A rate of production (or cycle time) and
  – A targeted magnitude of output (or annual production)
  The number of machines can be established

• How?

Capital Cost -- How Much Equipment?

• The universal constraint on production: Time!
  – Targeted production volume => desired production rate
  – The amount of equipment derives from the relationship between the technical rate of production and the desired rate of production
  – If you want to exceed the rate of production of a single machine, then you need to buy more machines!

\[
\text{# machines} = \frac{\text{desired rate of production}}{\text{machine rate of production}}
\]
Capital Cost -- How Much Equipment?

• This equation can be expressed other ways:

\[
\text{desired rate of production} \\
\text{# machines} = \frac{\text{machine rate of production}}{\text{Required time to produce target output}} \\
\text{# machines} = \frac{\text{Required time to produce target output}}{\text{Available time to produce target output}}
\]

• Sometimes, one is easier to use than the other
  – Particularly when using cycle time

For example:

• Required Operating Time is
  – Targeted production * Cycle time

• Available Operating Time is
  – Total hours / yr - [Planned + Unplanned downtime]

• Alternatively:
  – Targeted Production Rate:
    . Targeted production / Hours available for production (as above)
  – Machine Production Rate:
    . 1 / Cycle Time

• Generally, the former is easier to explain
Time As Key Modeling Unifier

- The tension between available and necessary time immediately generates a workable structure for interconnection of process elements
- Time to produce underlies many elements of cost, both fixed and variable
  - Directly:
    - Variable: Labor & energy
    - Fixed: Number of machines, dies/tools
  - Indirectly:
    - Fixed: Maintenance, downtime, scheduling

- Almost impossible to avoid consideration of TIME

Engineering Basis For Cycle Time

- While cycle time can be externally set, it frequently increases the power of a model if it can be estimated endogenously

- Engineering analyses, combined with statistical tools, can supply effective tools for estimation

- Other methods, ranging from table lookup to sophisticated modeling tools, can be tied into these cost models
**Injection Molding Cycle Time**

**Cycle Steps**
5. Retract Injector 6. Melt Next Load 7. Open Mold

![Cycle Steps Diagram]

**Cycle Time - Engineering Parameter**

- **Working Model:**
  \[
  \text{Cycle Time} = (\text{Fill Time}) + (\text{Cooling Time}) + (\text{Cycle Reset})
  \]

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

- Filling Time - Varies with Part Weight
- Mold Cycle - Varies with Press Size, But Weakly

*Assume a statistical correlation and estimate*
Cooling Time, Part Weight and Cycle Time Correlation

\[ T_{cyc} = 1.35 \times T_{cool} + 0.0151 \times \text{wgt} + 8.87 \]

Capital Cost --
How much does the equipment cost?

- Equipment costing can be complex
- Knowledge of the process will establish best method for estimation
- Enumeration is always preferable, but frequently may not have enough data to track all appropriate setups
- A case-specific effort
Machine Cost - Injection Molding

- Equipment Size - Function of:
  - Clamping Force
- Clamping Force - 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

\[
\text{Cost} = 368.82 \times \text{tonnage} + 14831
\]
Capital Cost - How To Distribute Cost?

- Many ways to accomplish this -- formally the domain of accountants and tax specialists
- In practice, simple amortization to "annualize" costs a good starting point
  - Assumes that the allocation of capital to machines means that an "opportunity cost" must be covered
  - Alternatively, can be thought of as "paying off a loan"
- Formulas are simple and universally applied
  - Opportunity cost of capital (or interest rate)
  - Time period over which the cost is to be distributed

Important Caveats:
- Conceptual
  - *Opportunity Cost of Capital* is NOT depreciation!
  - *Opportunity Cost of Capital* is NOT profit - although it may be a hurdle rate
- Practical
  - *Select your period appropriately - is it the lifetime of the machine, the product, or the company?*

The formula:

\[
\text{Annualized Cost} = \text{Capital} \times \left[ \frac{r(1 + r)^N}{(1 + r)^N - 1} \right]
\]
Capital Cost - Per Part Calculation

- With the answer to our three questions:
  - How many machines do I need?
  - How much does each machine cost?
  - How do I distribute the cost?

- We can calculate
  - An annual cost of the equipment, assuming an opportunity cost of capital and an amortization period; and
  - A per piece cost of capital, by dividing the annual cost by the number of pieces produced

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 <=> Per Unit
  - Fixed <=> Per Period
- Be careful of spurious precision