Introduction to Technical Cost Modeling Concepts and Illustrations

Materials Systems Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts
Why Is Cost Important?

- A measure of resource consumption
  - How much is required to do (e.g., produce) something?
  - Resources themselves are sometimes hard to define and measure
  - Cost is a useful shorthand

- Therefore, cost is usually a key **decision variable**
  - Reduces the issue of resources to a common metric
  - Actually measured in terms of a real thing - cash
  - Can also be a measure of a real amount (like a bank account balance!)

- Key uses of cost
  - Establishing cash requirements for an operation/project
  - Estimation of revenue requirements for project success
  - Determining strategies -- ways of acting
    - *Make-buy decisions*
    - *Choice of process, design, technology*
    - *Acquisition/Selling strategies*
What is Cost?

Cost "definitions" a reflection of key assumptions
   Assumptions which may defeat the uses of the cost metric if misunderstood

Examples
   - Operating Cost
   - Overhead Cost
   - Depreciated Cost

Let's start with some formal definitions.......
Cost To The Economist

- Cost is used to define resource constraints on production
- Recall how one finds the marginal conditions for production

\[
\text{maximize } Q = f(X_1, X_2, X_3, \ldots, X_i) \\
\text{subject to a budget constraint } B = \sum (p_i \times X_i)
\]

- Efficiency in production is governed by
  - structure of cost
  - nature of the technology
    (ratio of the marginal products to the marginal costs must be equal for all factors)
Cost In Practice

- Companies rarely juggle marginal products and marginal costs for optimality

- Instead, the day-to-day operational mantra becomes:
  - Maximize output
  - Minimize cost

- In practice, maximizing output means
  "keep the machines/process running"

- In practice, minimizing costs means
  "keep track of everything that is bought and try to find ways to buy less"

- Accounting is the tool for tracking expenses
Cost In Practice - Accounting

- Basic principle: Total all expenditures

- In practice, however, the total is not as useful as specific elements of cost

- Subdivisions of cost developed
  - Recurring (or variable) costs
  - One time (or fixed) costs

- Simplifications introduced to
  - Get the right total cost (thus making it possible to set revenue targets correctly)
  - Indicate which elements of the production process require the most control (because they most clearly influence total costs)
  - Without swamping the decisionmaker with too much information

- Example: Classical accounting practice focused upon Labor as the key cost driver
  - Demonstrations of errors have pointed to need for new estimation methods
  - Use of Activity-based accounting to rectify
Cost Modeling

- Problem:
  - Economist's cost is an abstraction, driven by considerations of optimality
  - Accounting cost depends upon measurement of an existing operation
  - How, then, to use cost as a decision tool when neither the economist's abstraction nor existing accounting information is appropriate?

- Examples:
  - Prediction of the cost of a new process, facility, technology
  - Comparison of alternative designs
  - Evaluation of strategic choices

- A "third way" is required
Needed: A Tool Encompassing the Formality of Economics & the Empiricism of Accounting

- Why?

- Engineering Needs a Cost Tool to Evaluate:
  - State of Technology
  - Current Processing Conditions
  - Value of Research Directions

- Businessman Needs a Cost Tool to Evaluate:
  - Competitiveness of His Operation
  - Strategies for Development
  - Investment Needs and Opportunities

- Decisionmakers Need a Tool That:
  - Limits Assumptions
  - Is Explicit About The Assumptions Made
  - Imposes a Consistent Basis for Comparison & Evaluation
Alternative Approach: Cost Modeling

- Why Modeling Instead of Analysis or Structure or ...?
  - Imposition of Structure
  - Incorporation of Knowledge
  - Inclusion of Technology

- Cost Modeling Has Its Weaknesses, Too
  - Garbage In, Garbage Out
  - Time Consuming to Develop
  - Expensive -- $$$
## Conceptual Basis of Cost Model

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Estimated Parameters</th>
<th>Cost Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part Geometry</td>
<td></td>
<td>Material</td>
</tr>
<tr>
<td>Part Material</td>
<td></td>
<td>Energy</td>
</tr>
<tr>
<td>Production Parameters</td>
<td>![?]</td>
<td>Labor</td>
</tr>
<tr>
<td>Exogenous Parameters</td>
<td></td>
<td>Equipment</td>
</tr>
<tr>
<td></td>
<td>![?]</td>
<td>Tooling</td>
</tr>
<tr>
<td></td>
<td>![?]</td>
<td>Maintenance</td>
</tr>
<tr>
<td></td>
<td>![?]</td>
<td>Overhead Labor</td>
</tr>
<tr>
<td></td>
<td>![?]</td>
<td>Building</td>
</tr>
<tr>
<td></td>
<td>![?]</td>
<td>Capital</td>
</tr>
</tbody>
</table>

Massachusetts Institute of Technology  
Cambridge, Massachusetts

Cost Lecture 1+  
MSL  
Materials Systems Laboratory
Evolution of a Cost Model - Injection Molding

- Conventional Wisdom

\[ Part \ Cost = 2 \times Material \ Cost \]

- What Is Material Cost?

\[ Materials \ Cost = \frac{(Part \ Weight \times Raw \ Material \ Price)}{(1 - Material \ Scrap \ Rate)} \]

- Limited Perspective
  - No Consideration of Technology Improvement
  - Cannot Incorporate Process Improvement
  - Too Much Weight Placed On Material Cost
Evolution of a Cost Model - Injection Molding

- Classical Accounting Perspective

\[ Part Cost = Material Cost + Labor Cost \times Burden Rate \]

- What is Labor Cost?

\[
\begin{align*}
\text{Labor Cost} &= \text{Effective Labor Rate} \times \text{Time To Make A Part} \\
\text{Effective Labor Rate} &= \frac{\text{Labor Wage}}{\text{Labor Productivity}} \\
\text{Time To Make A Part} &= \text{Cycle Time} \\
\text{Cycle Time} &= f(\text{Material, Geometry, Technology, }...) \\
\end{align*}
\]

Note that a Technological Element (Cycle Time), A Production Element (Productivity) and a Factor Price (Wage Rate) Have Been Introduced

- What is Burden Rate??? - Accounting Construct
Burden Rate

- Concept Introduced By The Accounting Perspective on Cost Estimation
- Based on the Assumption that Physical Plant Must Be Bought To "Maintain" Labor
- Therefore, All Other Costs Of A Plant Operation Are Summed, Then Divided By Total Labor Hours To Get A "Burden" Rate
- Includes: Machines, Tooling, Utilities, Buildings, Support Staff, Maintenance
- Can Also Include: Research, Sales, Management, etc.
- However, Can Estimate Most Of These Elements From Process Considerations
Injection Molding -- Elements of Burden

- Tooling Cost
- Machine Cost -- Press and Auxiliary Equipment
- Machine Maintenance
- Building
- Support Labor
- Energy Consumption
- Opportunity Cost of Capital/Cost of Money
- Each of These Can Be Estimated Directly, Based Upon Engineering, Economic and Processing Considerations!
Time As A Critical Parameter - Engineering & Practice Driven

- Time To Process a Part - Underlies Almost All Cost Factors
- Directly Effects Key Production Parameters
  - Variable Costs:
    - Labor
    - Energy
  - Fixed Costs
    - Number of Machines
    - Number of Tools
- Total Production Time Available -- Critical To Capital Cost Allocations
  - Number of Shifts
  - Number of Days
  - Productive Hours in a Shift

### Example of Differences
In Time of Equipment Use

<table>
<thead>
<tr>
<th></th>
<th>US</th>
<th>Korea</th>
</tr>
</thead>
<tbody>
<tr>
<td>days/shift</td>
<td>240.0</td>
<td>320.0</td>
</tr>
<tr>
<td>shifts/day</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>hrs/shift</td>
<td>6.4</td>
<td>6.4</td>
</tr>
<tr>
<td>total hrs/yr</td>
<td>3,000.0</td>
<td>4,100.0</td>
</tr>
</tbody>
</table>

33% Better Capital Utilization In Korea
# Processing Time/Rate Critical to Cost

<table>
<thead>
<tr>
<th>Inputs</th>
<th>+</th>
<th>Estimated Parameters</th>
<th>Cost Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part Geometry</td>
<td></td>
<td></td>
<td>Material</td>
</tr>
<tr>
<td>Part Material</td>
<td></td>
<td></td>
<td>Energy</td>
</tr>
<tr>
<td>Production Parameters</td>
<td></td>
<td></td>
<td>Labor</td>
</tr>
<tr>
<td>Exogenous Parameters</td>
<td></td>
<td></td>
<td>Equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tooling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Overhead Labor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Building</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Capital</td>
</tr>
</tbody>
</table>

**Time to Process**
Processing Time/Rate Critical to Cost

<table>
<thead>
<tr>
<th>Inputs</th>
<th>+</th>
<th>Estimated Parameters</th>
<th>Cost Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part Geometry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Part Material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production Parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exogenous Parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Material
- Energy
- Labor
- Equipment
- Tooling
- Maintenance
- Overhead Labor
- Building
- Capital

Time to Process

Number of Tools

Number of Machines
Processing Time and Its Relationship with Capital Costs

- Number of Machines/Production Lines
  \[
  \text{Number of lines} = \frac{\text{Cycle Time} \times \text{Annual Production Volume}}{\text{Available Production Time} \times \text{# of Cavities}}
  \]
  (rounded up to the next integer value)

- Number of Tools
  \[
  \text{# of Tools} = \text{# of Lines}
  \]

- Lifetime of Tools
  \[
  \text{Tool Life (yrs)} = \frac{\text{Tool Life (cycles)} \times \text{# of cavities}}{\text{Annual Production}}
  \]

- Critical Accounting Assumption -- Dedication
Dedicated/Non-Dedicated Equipment Assumption

- If a piece of capital equipment is used to manufacture more than one product in a year, the cost of the part should reflect this.

- Typically, cost is scaped according to the fraction of total operating time required to produce the targeted production.

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

- Note: This term is substituted for the number of lines term when equipment is assumed not dedicated.

- But - Tooling is ALWAYS dedicated.
Amortization of Capital Costs

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

- Simple Annuity Calculation:

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

- 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.
Processing Time/Rate - Critical To Cost

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Estimated Parameters</th>
<th>Cost Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part Geometry</td>
<td>Time to Process</td>
<td>Material</td>
</tr>
<tr>
<td>Part Material</td>
<td>Number of Tools</td>
<td>Energy</td>
</tr>
<tr>
<td>Production Parameters</td>
<td>Number of Machines</td>
<td>Labor</td>
</tr>
<tr>
<td>Exogenous Parameters</td>
<td>Building Space</td>
<td>Equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tooling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Overhead Labor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Building</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Capital</td>
</tr>
</tbody>
</table>

Massachusetts Institute of Technology
Cambridge, Massachusetts
Time To Process A Part - Engineering Parameter

- Use Combination of Engineering and Theoretical Approaches

- Cooling Time - Theoretical Determination

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

- Filling Time - Function of Shot Size - Function of Part Weight

- Mold Cycle - Function of Press Size, But Likely A Small Variation

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

\[ T_{\text{cy}} = 1.35 \times T_{\text{cool}} + 0.0151 \times \text{wgt} + 8.87 \]
Evolution of a Cost Model - Injection Molding

- Equipment and Tooling Cost - Primary Capital Expenditures
- Equipment Size Function of Clamping Force
- Clamping Force Function of Part Geometry and Processing Parameters
- Empirical Relation:
  \[ \text{Clamp Force} = \text{Projected Area} \times N_{\text{cavities}} \times \frac{224}{\sqrt{\text{nominal wall}}} + 172 \]
- Clamp Force Can Them Be Related To Press Cost
Capital Cost Relationships

<table>
<thead>
<tr>
<th>Inputs</th>
<th>+</th>
<th>Estimated Parameters</th>
<th>Cost Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part Geometry</td>
<td></td>
<td>Cost of Tools</td>
<td>Material</td>
</tr>
<tr>
<td>Part Material</td>
<td></td>
<td>Clamping Force</td>
<td>Energy</td>
</tr>
<tr>
<td>Production Parameters</td>
<td></td>
<td>Size of Press</td>
<td>Labor</td>
</tr>
<tr>
<td>Exogenous Parameters</td>
<td></td>
<td></td>
<td>Equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tooling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Overhead Labor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Building</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Capital</td>
</tr>
</tbody>
</table>

Massachusetts Institute of Technology
Cambridge, Massachusetts
Correlation Between Press Cost and Tonnage

Cost = 368.82 \times \text{tonnage} + 14831
Evolution of a Cost Model - Injection Molding

- Tooling Cost Estimation Extremely Difficult To Do Reliably

- Process Tooling Is Usually
  - Customized
  - Made By Hand
  - Without Consistent Specification
  - Without Consistent Lifetime
  - Subject to Multiple Revisions

- Nevertheless, Some Guidelines Can Be Established
  - Physical Size of the Tool
  - Complexity of the Machining Required
  - Special Treatments of Surfaces
  - Actions, Other Features
Tooling Cost Regression Estimates

\[ \text{ToolCost} = 10174 + 6.61 \times \text{wgt} + 16150 \times \text{action} + 12.7 \times \text{parea} \]
Industry Practice Parameters

- Operating Hours & Labor Productivity
- Building Space Requirements and Land Cost
- Amount of Auxiliary Equipment
- Amount of Overhead Labor
- Cost of Capital
Elimination of Burden - Example

- Injection Molding Machine Size - Function of Molding Pressure
- Molding Pressure - Function of Resin Being Molded and Part Geometry
- Strong Linear Correlation Between Press Tonnage and Press Cost
- Amortize Machine Cost and Divide By Annual Production Rate
- If Not Dedicated to Single Part Production, Scale Cost By Operating Fraction
Model Results - Cost Estimate

- Capital
- Overhead
- Maintenance
- Building
- Tooling
- Machine
- Labor
- Utilities
- Material

Cost Lecture 1+

Massachusetts Institute of Technology
Cambridge, Massachusetts
Model Results - Sensitivity to Production Volume

![Graph showing the relationship between Part Cost and Annual Production Volume in thousands. The graph indicates a decreasing trend in Part Cost as the Annual Production Volume increases.]
Model Results - Sensitivity to Cycle Time
Technical Cost Modeling - Summary

- Systematic Erosion of Complex Problem of Cost Estimation
- Reduction To Set of Simpler Analyses or Explicit Assumptions
- Can Incorporate Engineering Knowledge, Economic Assumptions and Processing Practice, Within A Consistent Framework For Analysis
- Yields Detailed Results -- With All Assumptions Presented and Explicit
- Can Be Readily Customized To Specific Situations