Creating a Process-based Cost Model

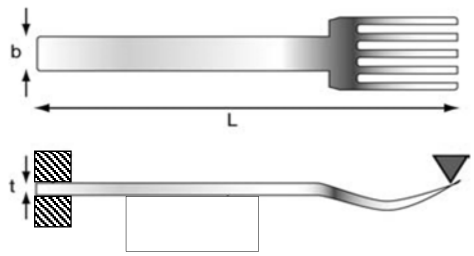
Randolph Kirchain & Frank R. Field III
Materials Systems Laboratory
Massachusetts Institute of Technology

Session Outline

- What is a process-based cost model?
- Examples of Technical Decisions
- Key steps to realizing a model

1. Translation

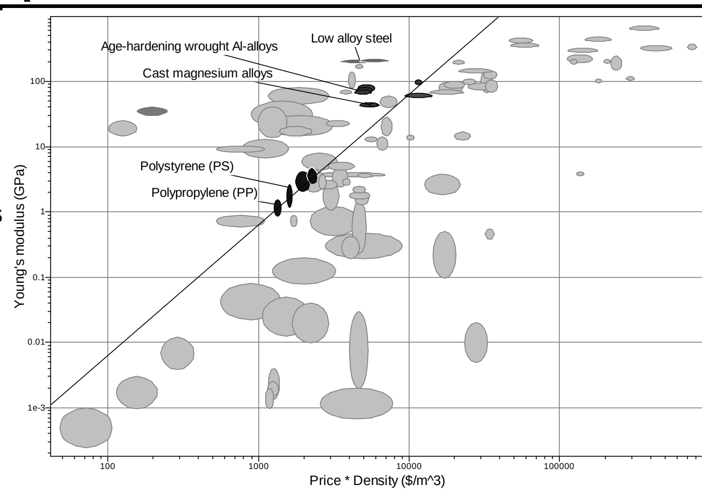
- Function:
  - Eating utensil – support bending loads
- Objective:
  - Minimize cost
- Constraints:
  - Length specified (150 mm)
  - Must not deflect too much
  - Minimum economic batch size of 100,000
- Free variables:
  - Material
  - Shape
  - Process



6. Select materials based on material, shape and process considerations

Final Material Choices

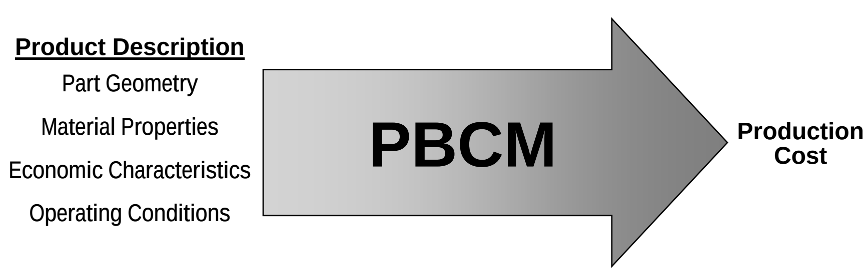
- Al Alloys
- Ferrous Metals
- Mg Alloys
- Thermoplastics
- Thermosets



What is an engineering model?

What is the purpose of creating such models?

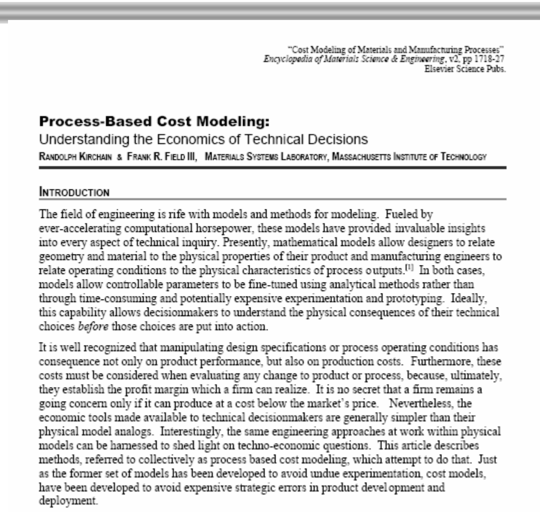
Process-based Cost Modeling (PBCM)



What is a PBCM?

- **Implementation:**
  - **Process Model**
  - **Operations Model**
  - **Financial Model**
- **General:**
  - **Incorporates Technical Information About Process**
    - Builds Cost Up From Technical Detail
  - **Must Be Able To Address Implications Of Change In**
    - Product Design or
    - Process Operation – Incl. Production Volume
- **Remember:**
  - **The Purpose Of A PBCM Is To Inform Technical Decisions**

Please read the supplemental document



"Cost Modeling of Materials and Manufacturing Processes"
Encyclopedia of Materials Science & Engineering, v2, pp 1718-27
Elsevier Science Pubs.

Process-Based Cost Modeling:
Understanding the Economics of Technical Decisions

RANDOLPH KIRCHAIN & FRANK R. FIELD III, MATERIALS SYSTEMS LABORATORY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY

INTRODUCTION

The field of engineering is rife with models and methods for modeling. Fueled by ever-accelerating computational horsepower, these models have provided invaluable insights into every aspect of technical inquiry. Presently, mathematical models allow designers to relate geometry and material to the physical properties of their product and manufacturing engineers to relate operating conditions to the physical characteristics of process outputs.[1] In both cases, models allow controllable parameters to be fine-tuned using analytical methods rather than through time-consuming and potentially expensive experimentation and prototyping. Ideally, this capability allows decisionmakers to understand the physical consequences of their technical choices *before* those choices are put into action.

It is well recognized that manipulating design specifications or process operating conditions has consequence not only on product performance, but also on production costs. Furthermore, these costs must be considered when evaluating any change to product or process, because, ultimately, they establish the profit margin which a firm can realize. It is no secret that a firm remains a going concern only if it can produce at a cost below the market's price. Nevertheless, the economic tools made available to technical decisionmakers are generally simpler than their physical model analogs. Interestingly, the same engineering approaches at work within physical models can be harnessed to shed light on techno-economic questions. This article describes methods, referred to collectively as process based cost modeling, which attempt to do that. Just as the former set of models has been developed to avoid undue experimentation, cost models, have been developed to avoid expensive strategic errors in product development and deployment.

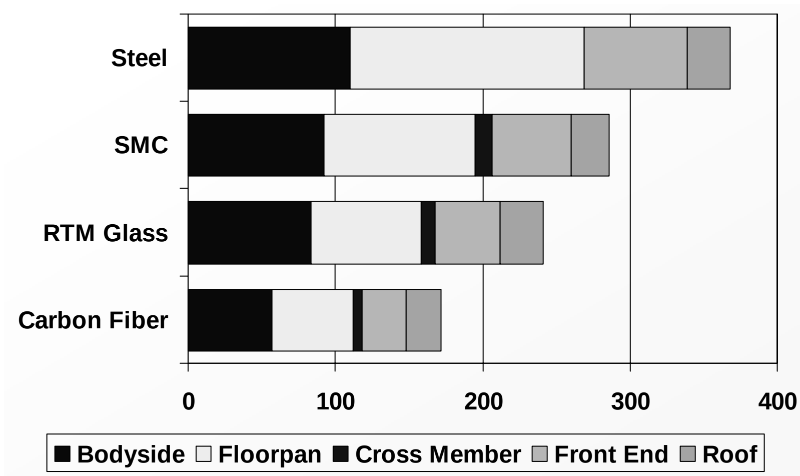
Uses of Cost Models in Technical Decision-making

Case One:
Considering Alternative Structural Materials

- **Steel Baseline**
  - **Honda Odyssey minivan**
  - **Complete Body in White : 148 pieces**
  - **BIW Weight : approx. 370 kg**
- **RTM Glass Composite Intensive Vehicle (CIV)**
  - **Complete Body in White : 8 pieces, plus steel inserts**
  - **BIW Weight : approx. 240 kg**
  - **Baseline design uses glass reinforced composites produced by RTM**
- **Hypothetical Designs**
  - **Carbon fiber or SMC**

From:
Kang, P. J. (1996). *A Technical and Economic Analysis of Structural Composite Use in Automotive Body-In-White Applications.* MS Thesis. Cambridge, Massachusetts Institute of Technology**:** 170.

Comparison of Body Weights
(incl. CIV inserts)



How would you compare these alternatives?

What would you want to know?

What would you NEED to know to calculate this?

Annual Worth Example

- Producing cars is highly capital intensive with a new car factory costing nearly $1 billion dollars
- A new technology has been developed that speeds the assembly of vehicles. It has the following characteristics:
  - Current plant - 30 stations, output = 200k per year
  - Profit = $1000 per vehicle
  - Investment - $250k per station, 30 stations per plant
  - Salvage value $60k per station
  - Maintenance cost - $20k / station / year
  - Improved throughput - 1%
  - Investments replaced after 5 years
  - MARR = 15%

Should you install this tech?

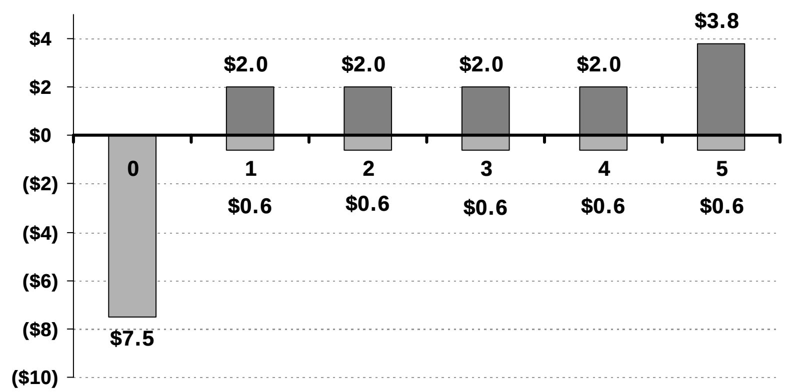
Massachusetts Institute of Technology
Department of Materials Science & Engineering

Evaluating Acceptability:
Annual Worth Method

- **Annual Worth (AW) of a project is the series of equals payments with value equivalent to that project at the MARR**
  - AW = Annual Equivalent Revenues
    - Annual Equivalent Expenses
    - Annual Equivalent Capital Recovery
  - **Capital Recovery**
    = Equivalent uniform annual cost of capital invested
    - Loss in value of the asset
    - Return on invested capital

Massachusetts Institute of Technology
Department of Materials Science & Engineering

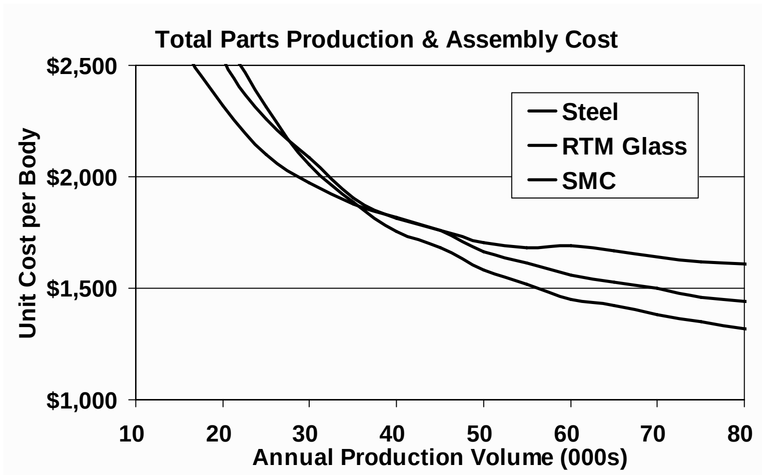
Annual Worth Example (cont)



Uses of Cost Models in Technical Decision-making

- Comparing options
  - Materials
  - Processes
  - Designs
  - Exogenous conditions
- Identifying cost drivers
- Considering hypothetical developments
- Characterizing strategic strengths
- Quantifying necessary performance improvements

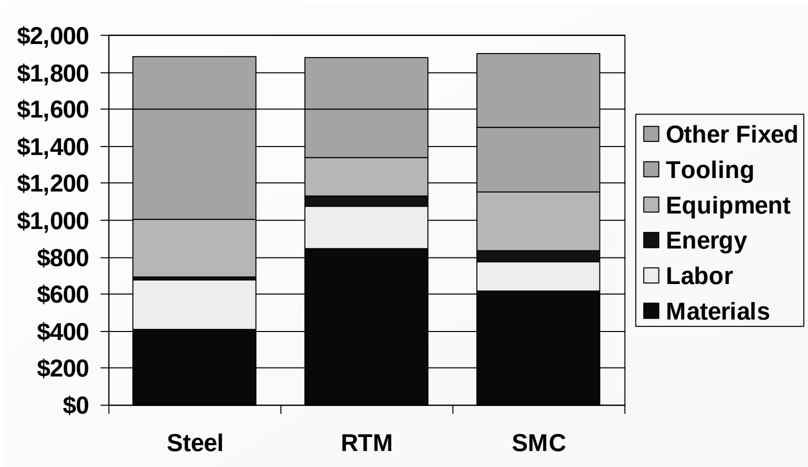
Comparing Manufactured Costs:
Process-based models provide insight into novel options



Uses of Cost Models in Technical Decision-making

- **Comparing options**
  - **Materials**
  - **Processes**
  - **Designs**
  - **Exogenous conditions**
- **Identifying cost drivers**
- **Considering hypothetical developments**
- **Characterizing strategic strengths**
- **Quantifying necessary performance improvements**

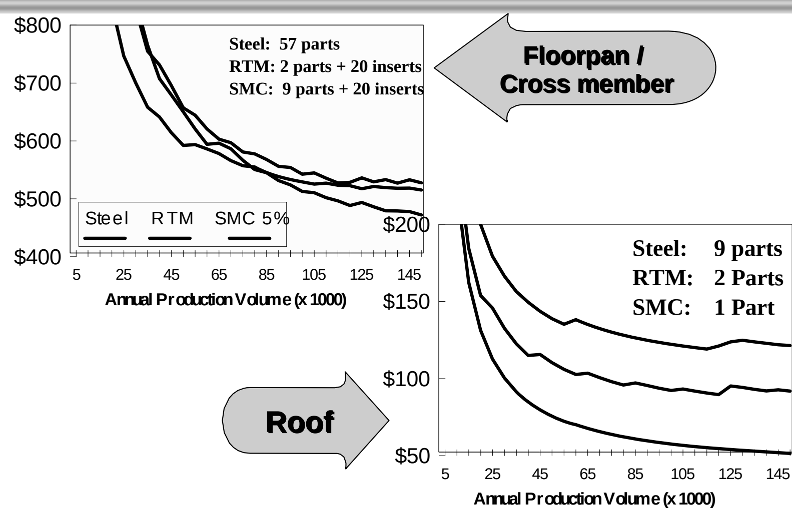
BIW Cost Breakdown at 35,000 parts/year



Uses of Cost Models in Technical Decision-making

- Comparing options
  - Materials
  - Processes
  - Designs
  - Exogenous conditions
- Identifying cost drivers
- Considering hypothetical developments
- Characterizing strategic strengths
- Quantifying necessary performance improvements

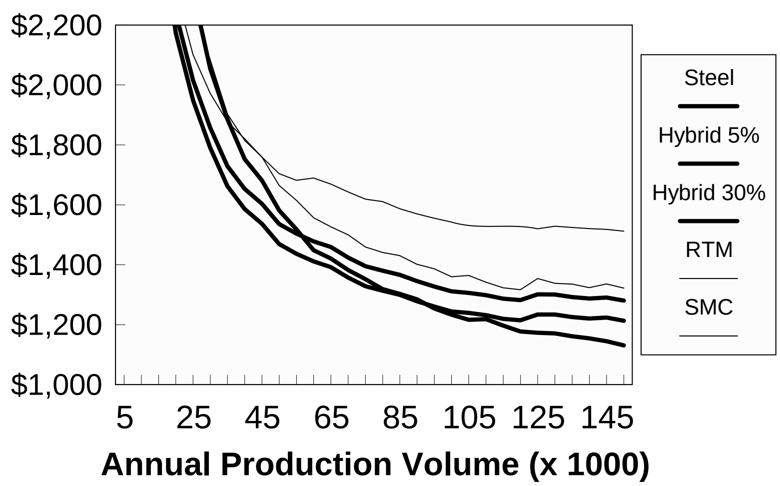
Comparing Cost Performance in Individual Subsystems



Massachusetts Institute of Technology
Department of Materials Science & Engineering

3.080 Econ & Enviro Issues In Materials Selection
Randolph Kirchain

Hybrid Body Scenarios

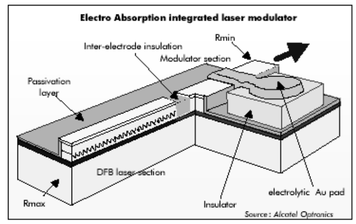


Massachusetts Institute of Technology
Department of Materials Science & Engineering

3.080 Econ & Enviro Issues In Materials Selection
Randolph Kirchain

Case Two: Investigating Early Stage Developments in Optoelectronic Components

- **Initial model development**
  - Integrated DFB laser and electro-absorptive modulator on an InP platform (1550nm)
- **Assessment of Integration (Two Additional Cases)**
  - Monolithically Integrated Laser-Modulator
  - Discrete Devices, Single Package
  - Discrete Packages

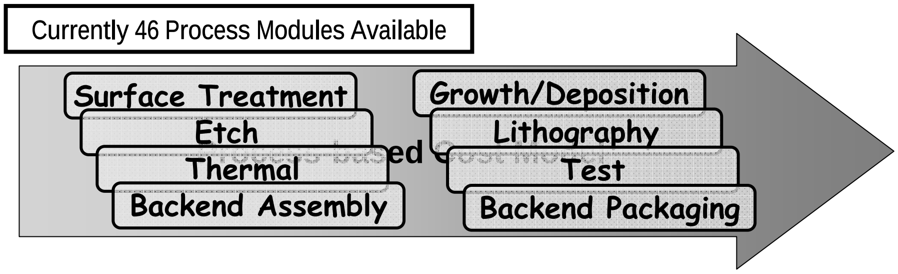


From:
E Fuchs, E Bruce, R Ram, & R Kirchain "Process Based Cost Modeling of Photonics Manufacture: The Cost-Competitiveness of Monolithic Integration of a 1550nm DFB Laser and An Electro-Absorptive Modulator on an InP Platform" in press *Journal of Lightwave Technology*

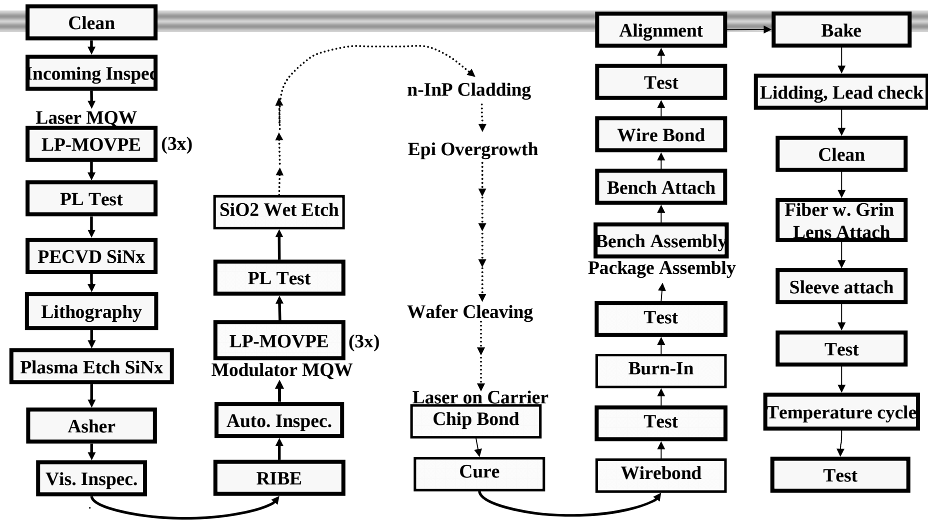
The MIT/CTR Optoelectronics Fabrication Model

- **Mimics production from bare substrate through assembly, packaging, and final test**
- **Provides full flexibility in building a process flow**
- **Captures effect of process derived yields at testing**

Currently 46 Process Modules Available



Process Modules Building Blocks in Product Flow

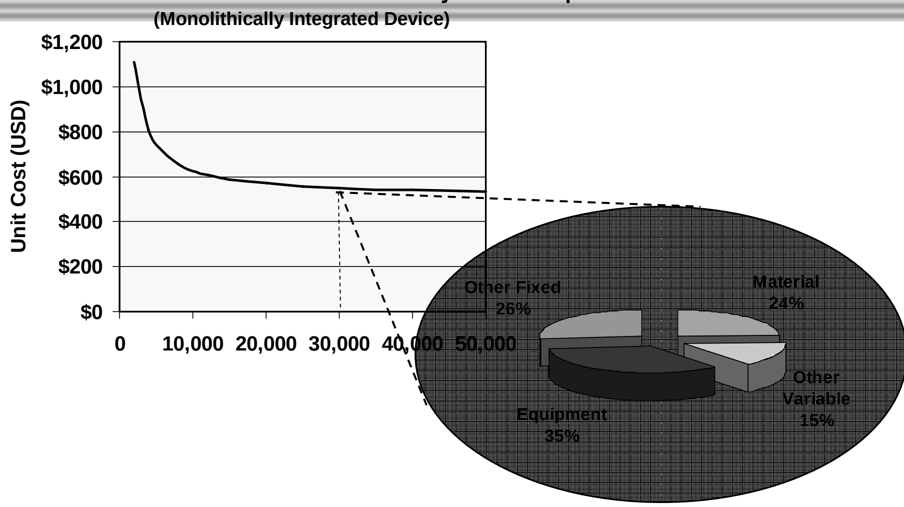


Uses of Cost Models in Technical Decision-making

- Comparing options
  - Materials
  - Processes
  - Designs
  - Exogenous conditions
- Identifying cost drivers
- Considering hypothetical developments
- Characterizing strategic strengths
- Quantifying necessary performance improvements

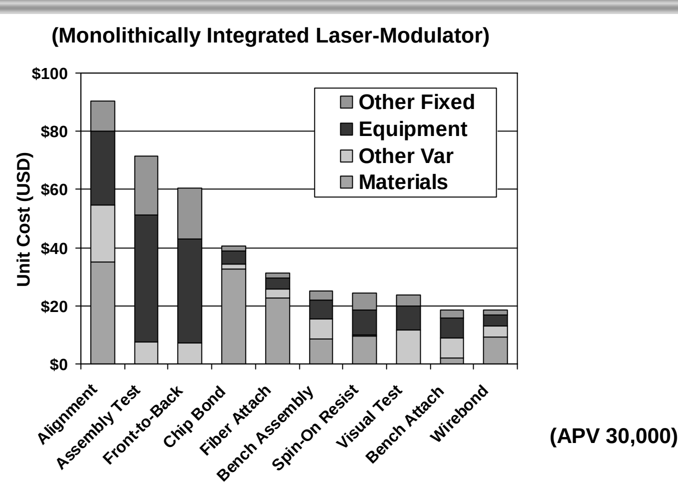
Quantifying Cost-Sensitivity to Scale

Models Derive Cost from Projected Optimal Fab Line



Identifying Key Cost Drivers

Models Provide Unequaled Resolution

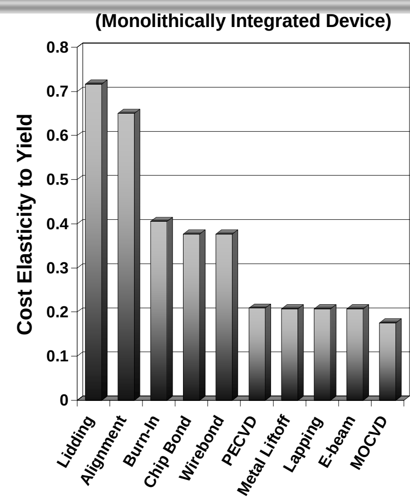


Identifying Opportunities for Improvement:
Unit Cost Elasticity to Yield

- **Yield is key issue for optoelectronics manufacturing cost**
- **What processes provide the most leverage?**
  - **Position in flow**
  - **Embedded yield**
- **Cost elasticity to yield**

$$\frac{\%\Delta Cost}{\%\Delta Yield}$$

  - **Identifies process yield impact on aggregate cost**



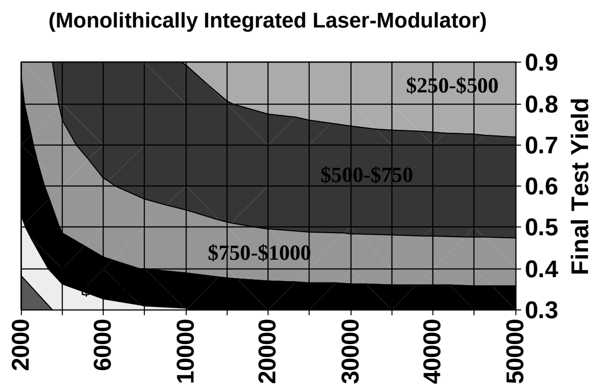
Massachusetts Institute of Technology
Department of Materials Science & Engineering

Uses of Cost Models in Technical Decision-making

- **Comparing options**
  - **Materials**
  - **Processes**
  - **Designs**
  - **Exogenous conditions**
- **Identifying cost drivers**
- **Considering hypothetical developments**
- **Characterizing strategic strengths**
- **Quantifying necessary performance improvements**

Massachusetts Institute of Technology
Department of Materials Science & Engineering

Cost Sensitivity to Final Test Yield

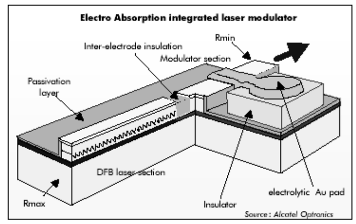


Uses of Cost Models in Technical Decision-making

- Comparing options
  - Materials
  - Processes
  - Designs
  - Exogenous conditions
- Identifying cost drivers
- Considering hypothetical developments
- Characterizing strategic strengths
- Quantifying necessary performance improvements

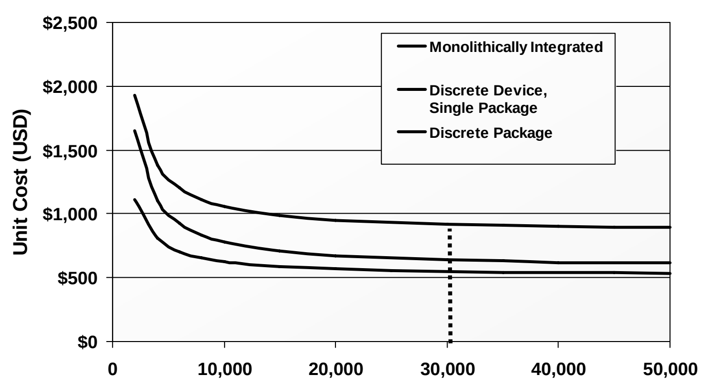
Case Two: Investigating Early Stage Developments in Optoelectronic Components

- **Initial model development is around a well-known case**
  - Integrated DFB laser and electro-absorptive modulator on an InP platform (1550nm)
- **Assessment of Integration (Two Additional Cases)**
  - Monolithically Integrated Laser-Modulator
  - Discrete Devices, Single Package
  - Discrete Packages



From:
E Fuchs, E Bruce, R Ram, & R Kirchain "Process Based Cost Modeling of Photonics Manufacture: The Cost-Competitiveness of Monolithic Integration of a 1550nm DFB Laser and An Electro-Absorptive Modulator on an InP Platform" in press *Journal of Lightwave Technology*

Exploring the Cost-Impact of Integration:
Models Allow Testing of Novel Technologies

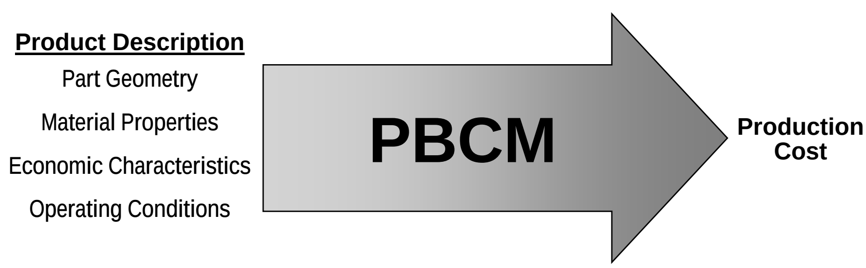


The most competitive alternative is the monolithically integrated laser-modulator.

Session 2

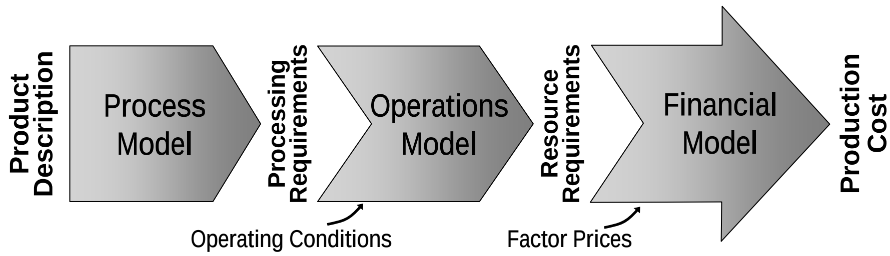
Process-based Cost Modeling (PBCM)

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



Process-based Cost Modeling (PBCM)

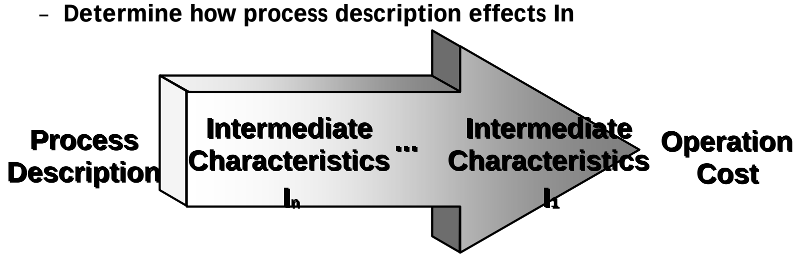
- **PBCM forecasts manufacturing requirements → costs**
  - **Processing requirements**
    - Cycle times, equipment specifications
  - **Resource requirements**
    - Number of tools, equipment, and laborers
- **How do technology changes impact manufacturing cost?**



Creating a PBCM: Overview

- **Models are created by decomposing problem from cost backwards**
  - **Determine what characteristics, I1, effect cost**
  - **Determine what characteristics, I2, effect I1**

    … and so on until…
  - **Determine how process description effects In**



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

Step One:
Define Question

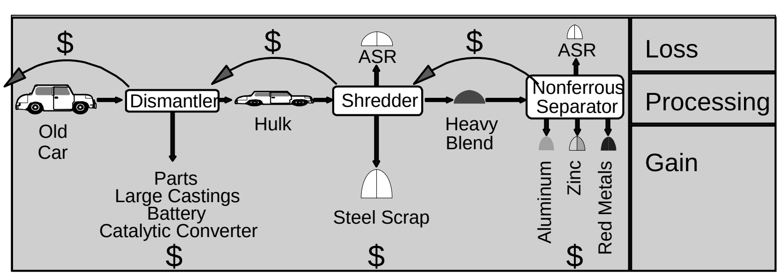
What cost are we going to model?

Step One: Defining your Question

- **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 Context Dependent**
  - **Cost estimation requires exhaustive definition of context**

Examining Automobile Recycling:
Applying Process-based Cost Modeling

- **Models account for:**
  - **Vehicle composition and configuration**
  - **Factor costs and transfer prices**
  - **Recycling practice**
- **Examined questions of:**
  - **Changing vehicle composition**
  - **Alternative recovery technologies**
  - **Imposed recovery targets**



Step Two:
Identify Relevant Costs

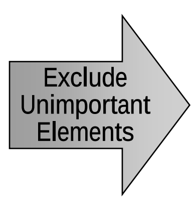
What costs should be considered?

Creating a PBCM: Step Two

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

Elements of Manufacturing Cost

Relevant Elements of Cost



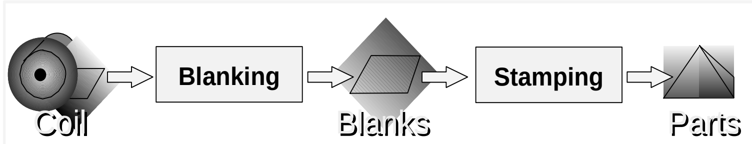
Common Relevant Cost Elements

- **Begin With These, But Always Ask Whether Others Are Important**
  - **Tradeoff Amongst Time, Resources, and Available Knowledge**

Creating A PBCM: Step Three

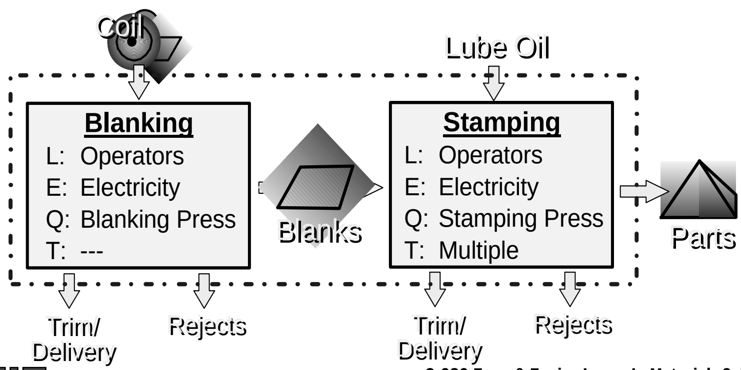
- **Diagram Process Flows**
  - **Draw In Materials Flowing Into AND Out Of**
  - **Catalog For Each Process Step**
    - Equipment
    - Labor
    - Energy

e.g., Sheet Metal Stamping
Forming Between Two Matched Dies



Diagramming Flows Example: Stamping

- Catalog For Each Process Step
  -- *Labor* -- *Energy* -- *Equipment* -- *Tools*



Cost Modeling Challenge

- How much equipment to buy?
- What is the cost of producing your various products?
  ... for your business...

?

Your Business

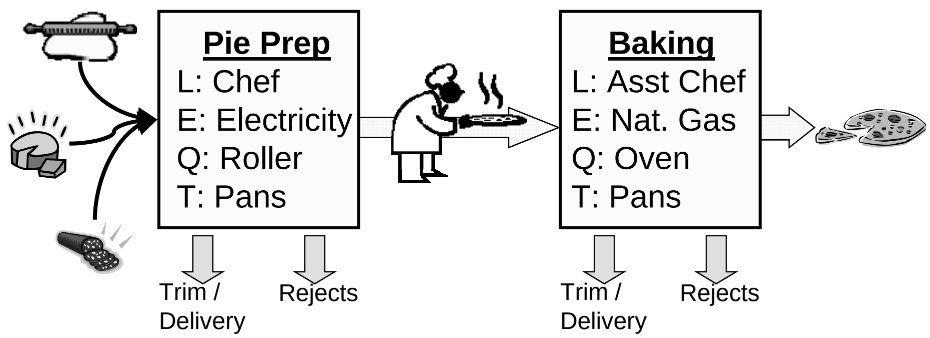
Modeling the Cost of Pizza Manufacture: Defining Scope

?

Diagramming Flows Example: W & P

Catalog For Each Process Step

-- Labor -- Energy -- Equipment -- Tools



Data Collection & Model Development

- **For each resource in your diagram**
  - **How much does a unit cost?**
  - **How many units are required?**
- **Begin data collection early!!!**
  - **Start with low risk sources**
    - Probably smaller firms
  - **End with high value sources**

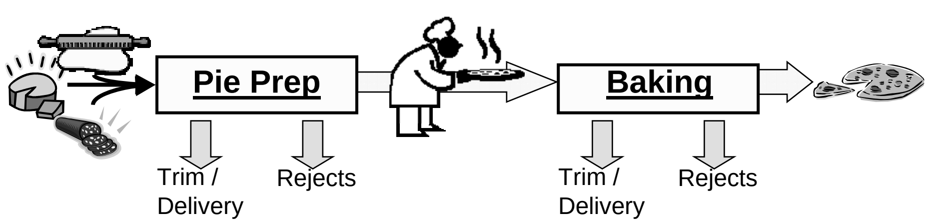
Step Four: Relate Costs to What is Known

- **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**

Step Four Example: Pepperoni Costs

- **Start at the end**
- **Think in terms of annual quantities**



Two Important Quantities

- Production Capacity =
  Qty. 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?

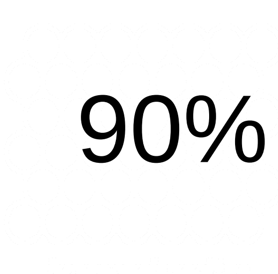
Generally, Both Are Measured In Units Per Year

(e.g., parts / year, kgs / year)

Massachusetts Institute of Technology
Department of Materials Science & Engineering

Slices per Pizza

- General area covering is difficult to solve
  - Solutions for small number of circumscribed circles has been solved
- Approximate:



Massachusetts Institute of Technology
Department of Materials Science & Engineering

Calculating Effective Production Volume: Work Backwards from Final Step

Prepped Pizzas Produced / Year = Good Preps + Rejects

$\text{effective } PV_{Prepping} = PV_{Prepping} + \text{Rejects}$

Can model Rejects as % of total production

$$effPV_{Prep} = PV_{Prep} + R \times effPV_{Prep}$$

$$effPV_{Prep} = \frac{PV_{Prep}}{(1 - R)}$$

But what is PV_{Prep}?

Assume that PV_{Prep} = Total Pizzas Baked / Year (i.e., $effPV_{Baking}$)

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

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

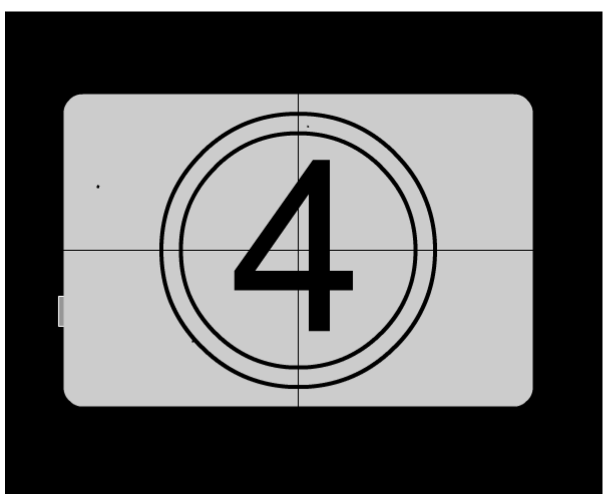
Next Question ...

What is the cost of equipment?

How much equipment to buy?

A Little Intro - http://www.remcousa.com/flash.html

A Little Intro - http://www.remcousa.com/flash.html



Goal: What is Equipment Cost?

- Basic structure is the same:

  How Many? X How Much?

- What modifies this compared to the materials cost discussion?
  - Time value of money
  - Allocation

Key Structuring Constraint -- Time

- Hours of daily operation an operational constant
- To get more than a day's production, you need more resources
- Inverting that calculus can be used to scale/size an operation
- Defines capital requirements

Determining Equipment Requirements: Compare Time Needed With Time Available

- **Time Needed**
  - **To Make Product + To Load/Unload**
  - **Total Number of Pies (effective PV)**
  - **Cycle Loading (Analogous To Multiple Cavities)**
- **Time Available**
  - **Shifts, Days**
  - **Less Breaks, Downtime, Maintenance**

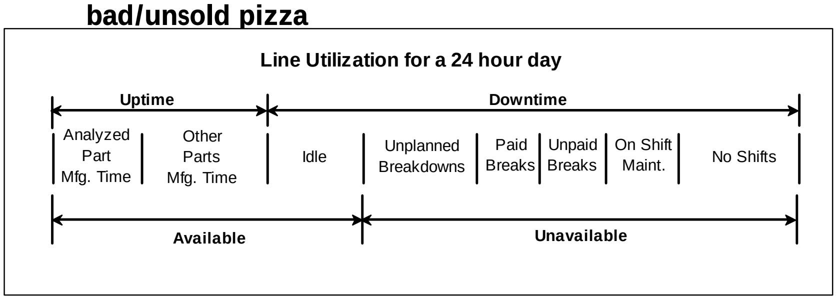
Determining Equipment Requirements: Compare Time Needed With Time Available

- **Minimum equipment requirement:**

$$\frac{\textbf{Annual Required Production Time}}{\textbf{Annual Available Operating Time}}$$

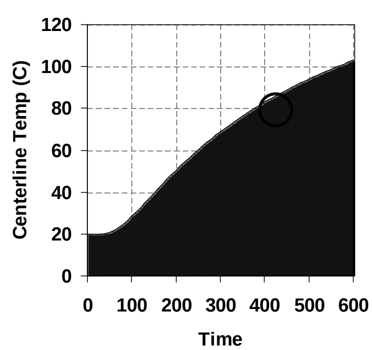
Considerations in Required & Available Time

- Total processing time
  - Processing
  - Load/Unload Time
  - Time spent making bad/unsold pizza
- Other times
  - Downtime Due To Scheduled Breaks
  - Unscheduled Downtime

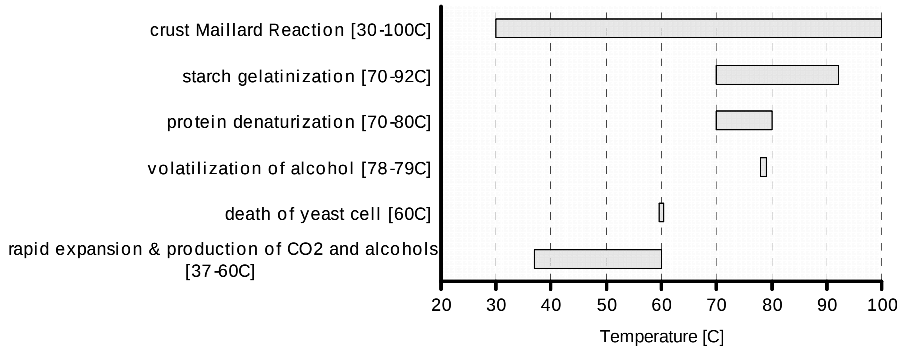


Considering Process Time for W&P

- Assumptions:
  - Initial temp: 20˚C
  - Oven temp: 225˚C
  - α: 7.5E-9
  - Thickness: 10 mm
- How long will it take to cook?
- What's the centerline temperature reach target? ... 80 ˚C



Considering Process Time for W&P Breadmaking: Temperatures



Ref: Oregon State; Nutrition & Food Management (NFM236)
http://oregonstate.edu/instruct/nfm236/bread/index.cfm

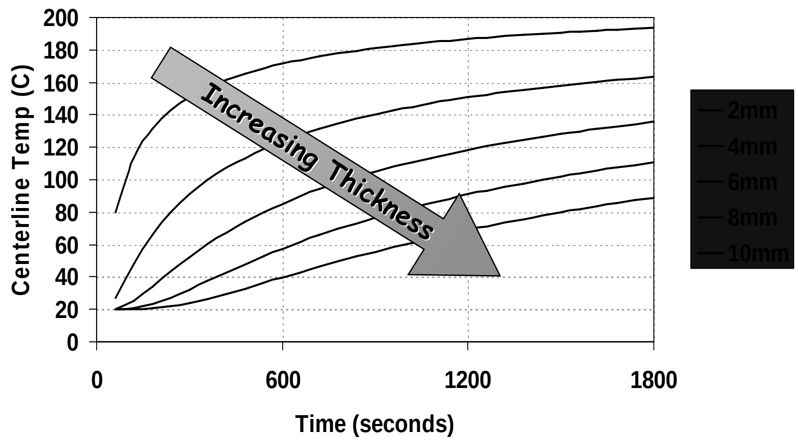
Heat Transfer, Non-Steady State

- **Let's rely on some experts**
  - **Tufts' Gourmet Engineering class, EN43**
  - **Transient Conduction chapter:** **http://www.tufts.edu/as/tampl/lecture_notes/ch4.html**
  - **Assume constant surface temperature:**

$$\frac{T(x,t) - T_{surface}}{Ti - T_{surface}} = \mathrm{erf}\left\{\frac{x}{2\sqrt{\alpha t}}\right\}$$

A relation between time, temperature and position

Time, Temperature and Thickness



Distribution of Capital Costs Over Time

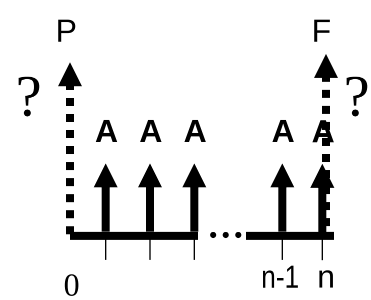
- **Simplicity Is Best At Outset**
  - **Complex capital accounting relies on extra knowledge, usually case specific**
- **Simple amortization -- opportunity cost of capital**
  - **Distributed over goods sold, not made**

Dedicated Capital Or Not?

- Dedicated: Can only be used to make a single good
- Non-dedicated: Can be used to make other goods
  - Note: Just because it can be used doesn't necessarily mean it will be used!

Relating a Uniform Series of Payments to P or F

- Uniform series of payments – often called an *Annuity*
- By convention:
  - P at time 0
  - A at end of period
  - F at end of period



Therefore:
- 1^{st} A, 1 period after P
- Last A, coincident with F

Formulas for N Periods
Finite Series of Equal Payments

a) Future Value (F)

$$= \sum_{i}^{N} A(1+r)^{i}$$

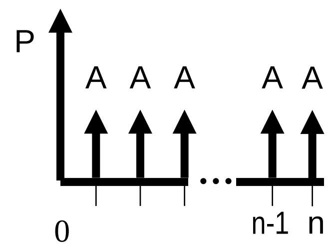
$$= A \frac{[(1+r)^{N} - 1]}{r}$$

b) Payment (A)

$$= P \times r \frac{[(1+r)^{N}]}{[(1+r)^{N} - 1]}$$

$$= P\ (crf)$$

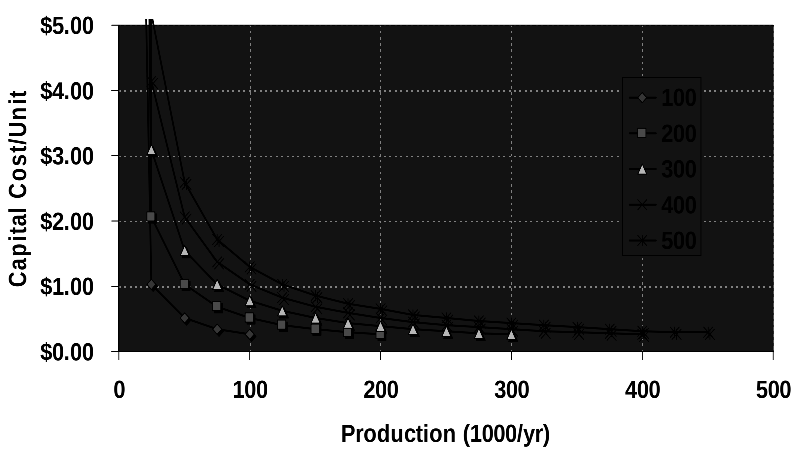
crf = Capital Recovery Factor



Massachusetts Institute of Technology
Department of Materials Science & Engineering

3.080 Econ & Enviro Issues In Materials Selection
Randolph Kirchain

Consequences of Capital Utilization



Massachusetts Institute of Technology
Department of Materials Science & Engineering

3.080 Econ & Enviro Issues In Materials Selection
Randolph Kirchain