Flexible vs. Robust Process Design

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Abstract

- We investigate the design and selection of production processes under conditions of stochastic market preferences. In response to an evolving marketplace, a producer can respond by selecting different degrees of process flexibility. We model the evolution of market preferences and policies for process selection as a Markov Decision Process and find optimal process adoption policies. In addition to optimal strategies, we define two alternative adoption strategies. A “perfectly flexible” policy is defined as instantly matching process capabilities to changes in market preferences, while a “robust” policy is defined as selecting and employing only a single invariant process technology. Simulation experiments and numerical examples demonstrate when a flexible process strategy is preferred to a robust strategy, and vice versa.
Research Approach

• Investigate the design and selection of production processes under conditions of stochastic market preferences.

  – In response to an evolving marketplace, a producer can respond by selecting different degrees of process flexibility.
  – We model the evolution of market preferences and policies for process selection as a Markov Decision Process and find optimal process adoption policies.
Research Objectives

• In addition to determining optimal strategies, we define two alternative adoption strategies.
  – A “perfectly flexible” policy is defined as instantly matching process capabilities to changes in market preferences,
  – A “robust” policy is defined as selecting and employing only a single invariant process technology.

• Simulation experiments and numerical examples demonstrate when a flexible process strategy is preferred to a robust strategy, and vice versa.
Problem Statement

• Problem
  – *Determine the value of perfect flexibility for process design conversions when market evolution is stochastic*

• Perfect Flexibility:
  – Defined as the increase in profit that can be obtained by responding instantly to changes in market preferences through process design conversion, compared to a “robust” policy of keeping one process design throughout the planning horizon.
• Assumptions
  – Time can be discretized (i.e., months, quarters, years)
  – Markets
    • can be modeled as discrete scenarios
    • markets move between scenarios as a Markov process
  – Technologies
    • can be modeled as discrete option bundles
  – Costs
    • The costs associated with market/technology pairs can be estimated
Prior Research

  - Optimal Acquisition of Automated Flexible Manufacturing Processes
- Gupta, Gerchak and Buzacott, *IJPE* (1992)
  - The Optimal Mix of Flexible and Dedicated Manufacturing Capacities: Hedging Against Demand Uncertainty
- Paraskevopoulos, Karakitsos and Rustem, *MS* (1991)
  - Robust Capacity Planning Under Uncertainty
- de Groote,
  - Flexibility and Marketing/Manufacturing Coordination *IPJE* (1994)
• Upton *MS* (1997)
  – Process Range in Manufacturing: An Empirical Study of Flexibility
  – Flexibility vs. Efficiency? A Case Study of Model Changeovers in the Toyota Production System
• Anupindi and Tayur *OR* (1998)
  – Managing Stochastic Multiproduct Systems: Model, Measures, and Analysis
• Rajagopalan, Singh and Morton, *MS* (1998)
  – Capacity Expansion and Replacement in Growing Markets with Uncertain Technological Breakthroughs
• Monahan and Smunt, *JOM* (2001)
  – Processes with Nearly Sequential Routings: Comparative Analysis
• Rajagopalan *MS* (2002)
  – Make to Order or Make to Stock: Model and Application
• Milner and Kouvelis *MS* (2002)
  – On the Complementary Value of Accurate Demand Information and Production and Supplier Flexibility
• Graves and Tomlin *MS* (2003)
  – Process Flexibility in Supply Chains
• Kourpas and Smunt, working paper
  – An Entropy Measure of Flow Dominance for Describing Manufacturing System Performance
Solution Methodology

• Stochastic dynamic programming

• MAPPS
  – Market Preferences and Process Selection
A Simple Example

Market Requirements

Low Demand  Medium Demand  High Demand

Low Volume

Job Shop

Medium Volume

Batch Shop

Flex Shop

High Volume

Flow Shop

Marketing Scenarios

- Discrete market scenarios or states $\mathbb{M} = \{1, \ldots, M\}$
- Market state $m \in \mathbb{M}$ defined by pertinent market variables (product type, product mix, demand levels, etc.)
- Scenarios highly dependent on specific characteristics of the market under study.
- Model market change as an $M \times M$ transition matrix $\Phi$.
- Element $\varphi_{ij} \in \Phi$ represents the probability that the market will evolve to from state $i$ to $j$ in one period.
Market Scenarios for Example

- Three possible scenarios
  1. low demand, high product variability, price not a large factor
  2. medium demand, moderate product variability, lower prices
  3. high demand, low product variability, low prices required
Market Scenarios for Example

- Three possible scenarios
  1. **low mix**, high product variability, price not a large factor
  2. **medium mix**, moderate product variability, lower prices
  3. **high mix**, low product variability, low prices required
- Market scenario transition matrix $\Phi$ for random market progression:

<table>
<thead>
<tr>
<th>Preference</th>
<th>High Mix</th>
<th>Med Mix</th>
<th>Low Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>High Mix</td>
<td>0.80</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Med Mix</td>
<td>0.10</td>
<td>0.80</td>
<td>0.10</td>
</tr>
<tr>
<td>Low Mix</td>
<td>0.10</td>
<td>0.10</td>
<td>0.80</td>
</tr>
</tbody>
</table>
Market Progression Scenarios

- **Random Mix** market preferences
- Progression from **Low Mix to High Mix** market preferences
- Progression from **High Mix to Low Mix** market preferences
Technology Options

• Assume set of technological options $\mathbf{T} = \{1, ..., T\}$
• Option $t \in \mathbf{T}$ defined by important attributes (e.g., equipment descriptions, process capabilities, tolerances, capacity)
• Availability of technological scenarios modeled using $T \times T$ technological possibility matrix $\Theta$
• Element $\theta_{ij} \in \Theta$ represents the probability that technology $j$ will be available in the next period $h+1$
• If option $t \in \mathbf{T}$ has been available in the past, it will always be available in the future.
Technology Options for Example

- **Four technology options:**
  1. **Job shop** – low volumes, high product variation, high cost
  2. **Batch shop** – medium volumes and variation, moderate cost
  3. **Flow shop** – high volumes, low product variation, low cost
  4. **Flexible shop** – moderate/high volume, high product variation, moderate cost
Technology Options for Example

• Four technology options:
  1. **Job shop** – low volumes, high product variation, high cost
  2. **Batch shop** – medium volumes and variation, moderate cost
  3. **Flow shop** – high volumes, low product variation, low cost
  4. **Flexible shop** – moderate/high volume, high product variation, low cost

• Technology possibility matrix \( \Theta \)

<table>
<thead>
<tr>
<th></th>
<th>Job Shop</th>
<th>Batch Shop</th>
<th>Flow Shop</th>
<th>Flexible Shop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job Shop</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Batch Shop</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Flow Shop</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Flexible Shop</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Economic Structure

- Revenues modeled as $M \times T$ matrix $R$
  - element $r_{mt}$ is expected period revenues with market scenario $m$ and technology option $t$.

- Production costs represented as $M \times T$ matrix $K$
  - element $k_{mt}$ represents expected period production costs when the market is in state $m$ and technology is in state $t$.

- Technology switching costs modeled as $T \times T$ matrix $C$
  - element $c_{ij}$ is cost of switching from option $i$ to $j$.

- Single period operating profit $\pi$ is $\pi = r_{mt} - k_{mt} - c_{tt}$.
Dynamic Programming Solution

• In period \( h \in H \), state of system is uniquely defined by market scenario \( m \in M \) and technology option \( t \in T \).
• Expected profits \( \Pi_h \) for remaining periods \( \{h, h+1, \ldots, H\} \) are found by the recursive relationship

\[
\Pi_h(m, t) = \max_{t'} \left\{ (r_{mt} - k_{mt} - c_{tt'}) + \omega_{tt'}^{h+1} \sum_{m'} \varphi_{mm'} \Pi_{h+1}(m', t') \right\}
\]

\( m' \in M, \ t' \in T \)
• Optimal solution is technology the set of \( t \in T \) that maximize \( \Pi_0 \) given \( h \) and \( m \).
Revenue Costs for Example

- **Revenue matrix** $R$

<table>
<thead>
<tr>
<th>Market \ Tech</th>
<th>Job Shop</th>
<th>Batch Shop</th>
<th>Flow Shop</th>
<th>Flex Shop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>1,500</td>
<td>1,250</td>
<td>1,000</td>
<td>1,400</td>
</tr>
<tr>
<td>High Mix</td>
<td>1,250</td>
<td>1,500</td>
<td>1,250</td>
<td>1,400</td>
</tr>
<tr>
<td>Med Mix</td>
<td>1,000</td>
<td>1,250</td>
<td>1,500</td>
<td>1,400</td>
</tr>
<tr>
<td>Low Mix</td>
<td>1,000</td>
<td>1,250</td>
<td>1,500</td>
<td>1,400</td>
</tr>
</tbody>
</table>
Production Costs for Example

- Production cost matrix $K$

<table>
<thead>
<tr>
<th>Market \ Tech</th>
<th>Job Shop</th>
<th>Batch Shop</th>
<th>Flow Shop</th>
<th>Flex Shop</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Mix</td>
<td>500</td>
<td>750</td>
<td>1,000</td>
<td>600</td>
</tr>
<tr>
<td>Med Mix</td>
<td>750</td>
<td>500</td>
<td>750</td>
<td>600</td>
</tr>
<tr>
<td>Low Mix</td>
<td>1,000</td>
<td>750</td>
<td>500</td>
<td>600</td>
</tr>
</tbody>
</table>
Switching Costs for Example

- **Technology switching cost matrix A**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Job Shop</th>
<th>Batch Shop</th>
<th>Flow Shop</th>
<th>Flex Shop</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>1,000</td>
<td>2,000</td>
<td>3,000</td>
<td>4,000</td>
</tr>
<tr>
<td>Job Shop</td>
<td>0</td>
<td>1,000</td>
<td>2,000</td>
<td>3,000</td>
</tr>
<tr>
<td>Batch Shop</td>
<td>1,000</td>
<td>0</td>
<td>1,000</td>
<td>2,000</td>
</tr>
<tr>
<td>Flow Shop</td>
<td>2,000</td>
<td>1,000</td>
<td>0</td>
<td>1,000</td>
</tr>
<tr>
<td>Flex Shop</td>
<td>3,000</td>
<td>2,000</td>
<td>1,000</td>
<td>0</td>
</tr>
</tbody>
</table>
Experimental Results
## Optimal Strategy $D^*$ (fragment)

<table>
<thead>
<tr>
<th>Market Preference</th>
<th>Current Technology</th>
<th>Period 10</th>
<th>Period 11</th>
<th>Period 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Mix</td>
<td>Job Shop</td>
<td>Job Shop</td>
<td>Job Shop</td>
<td>Job Shop</td>
</tr>
<tr>
<td>Low Mix</td>
<td>Batch</td>
<td>Batch</td>
<td>Batch</td>
<td>Batch</td>
</tr>
<tr>
<td>Low Mix</td>
<td>Flow</td>
<td>Batch</td>
<td>Batch</td>
<td>Batch</td>
</tr>
<tr>
<td>Low Mix</td>
<td>Flexible</td>
<td>Flexible</td>
<td>Flexible</td>
<td>Flexible</td>
</tr>
<tr>
<td>Med Mix</td>
<td>Job Shop</td>
<td>Batch</td>
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<td>Flow</td>
<td>Batch</td>
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<td>Flexible</td>
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<td>Flow</td>
</tr>
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<td>Batch</td>
<td>Batch</td>
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<td>High Mix</td>
<td>Flow</td>
<td>Flow</td>
<td>Flow</td>
<td>Flow</td>
</tr>
<tr>
<td>High Mix</td>
<td>Flexible</td>
<td>Flexible</td>
<td>Flexible</td>
<td>Flexible</td>
</tr>
</tbody>
</table>
Sample Result – Random Market

Single Simulation Run

Period

Market Mix Preference

Low Mix

Optimal & Flexible Strategies

Robust Strategy

Optimal Strategy

Flexible Strategy

Process Selection

Flexible

Flow

Batch

Job

Start

High Mix

Med Mix
Average Result – Random Market

Average of 100 simulation runs

- **Market Mix Preference**
  - High Mix
  - Med Mix
  - Low Mix

- **Process Selection**
  - Flexible Strategy
  - Optimal Strategy
  - Robust Strategy

- **Flexible Strategy**

- **Period**
  

- **Start**
- **Batch**
- **Flow**

- **Flexible**
Avg Result – High to Low Market

Average of 100 simulation runs

Market Mix Preference

- Low Mix
- Med Mix
- High Mix

Process Selection
- Flow
- Batch
- Job
- Start

Flexible Strategy
Optimal Strategy
Robust Strategy

Period
Avg Result – Low to High Market

Average of 100 simulation runs

---

**Market Mix Preference**

- Low Mix
- Med Mix
- High Mix

**Process Selection**

- Flexible
- Flow
- Batch
- Job
- Start

**Optimal Strategy**

**Flexible Strategy**

**Robust Strategy**

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**Period**

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Conclusions

• Trajectory of market evolution significantly impacts optimal and robust polices
• Relative value of flexibility varies significantly with market evolution
  – Even though value of perfect flexibility does not vary
• Perfect Flexibility and Robust policies form bounds on profitability
• Bounds provide useful information on the benefits of increased flexibility
Future Work

• Incorporate stochastic technological innovation
  – We assume fixed technologies

• Incorporate stochastic market demand
  – We assume fixed demand levels

• **Goal:** Develop a more complete means to better model interaction of markets, processes, and technology
More Information

• Working paper available
  – http://Leeds.Colorado.edu/faculty/Lawrence/MAPPS