A Screening Model to Explore Planning Decisions in Automotive Manufacturing Systems under Demand Uncertainty

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Outline

What am I doing? (Research Question)
- How to design large scale and complex manufacturing systems so that they perform well under demand uncertainty

How am I doing it? (Research method)
- A screening model + an evaluation model
  - Screening model → to identify good decision candidates
  - Evaluation model → to extensively examine decision candidates

How does it work? (Method application)
- Case study in Automotive body assembly system planning

Motivation

- Large complex engineering systems, such as automotive manufacturing systems, are:
  - Capital intensive
  - Require long lead time to develop
  - Difficult to change
  - Demand uncertainty
Motivation(2): Demand Uncertainty

- Macroeconomic Fluctuations
- Shifting Consumer Preferences
- Incorrect Predictions

Motivation

- Large complex engineering systems, such as automotive manufacturing
  - Capital intensive
  - Require long lead time to develop
  - Difficult to change
- Demand uncertainty
  - Macroeconomic change
  - Shifting consumer preference
  - Incorrect prediction, etc.

How to design the systems so that they can perform well under demand uncertainty?

Motivation(3): Multiple sources of flexibility

- System architecture
  - Product to plant allocation (Process flexibility)
  - Capacity
- Technology
  - Tooling Technology
  - Equipment automation
- Operation
  - Shifts selection
  - Overtime operation
  - Inventory

Strategic Planning Decisions
(Strategic Flexibility)

Operational Decisions
(Operational Flexibility)
Research Questions

- For large complex manufacturing systems, given
  - Demand uncertainty
  - Multiple sources of flexibility

- How to design these systems so that they can perform well under uncertainty?
  - What is the impact of considering demand uncertainty on strategic decision making?
  - What is the impact of considering operational flexibility?
  - How to identify good design candidate in a large design space?

Research Scope

- System architecture
  - **Product to plant allocation**
  - **Capacity**
  - Technology
    - Tooling Technology
    - Equipment automation
  - Operation
    - Shifts selection
    - **Overtime operation**
    - Inventory

- Strategic Planning Decisions
  (Strategic Flexibility)

- Operational Decisions
  (Operational Flexibility)

Case study 1: Simple Hypothetical Case

- Objective:
  - To demonstrate the impact of considering demand uncertainty and operational flexibility on system design during planning stage.

- Which product to which plant?
- What capacity should each plant have?
Case study 1: Simple Hypothetical Case

- System under consideration
  - 2 products, 2 plants, 5 years
- Demand
  - Normal distribution
  - Expected values 200k, standard deviation 50k each year for both
  - No correlation
- Investment cost, as a function of
  - Equipment, tool, building, capacity, process flexibility upcharge
- Operating cost:
  - Operating cost during overtime > Operating cost during normal time

Decision Approaches

<table>
<thead>
<tr>
<th>Demand Uncertainty</th>
<th>Operational Flexibility</th>
<th>DA1</th>
<th>DA2</th>
<th>DA3</th>
<th>DA4</th>
</tr>
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<tbody>
<tr>
<td>No</td>
<td>No</td>
<td>DA1</td>
<td>DA2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>DA3</td>
<td>DA4</td>
<td></td>
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</table>

Optimal Decisions under DAs

<table>
<thead>
<tr>
<th>Decision Approach</th>
<th>Considers Demand Uncertainty</th>
<th>Considers Operational Flexibility</th>
<th>Allocation Decision</th>
<th>Capacity Decision</th>
<th>Decision Characteristics</th>
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</thead>
<tbody>
<tr>
<td>DA1</td>
<td>No</td>
<td>No</td>
<td>Product A</td>
<td>Plant 1</td>
<td>200k</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Product B</td>
<td>Plant 2</td>
<td>200k</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S2 (2 Dedicated-200k)</td>
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</tbody>
</table>
Results Evaluation-Simulation Model

Strategic decision candidate

Monte Carlo Simulation (simulate demand uncertainty) (1-5 samples)

Simulation time step (T=1)

Operational Decision Making Module (Linear Programming)

Inner loop

Switch Production of products?

Run Overtime?

Enabled by strategic process flexibility

Enabled by overtime flexibility

Economic outputs for sample i

Outer loop

No

YES

Results Evaluation-VaRG Chart

Results for Case Study 1
Conclusions for Case Study 1

- The impact of considering demand uncertainty:
  - Leads to flexible process design as compared to dedicated process design under deterministic approach
  - As a result, reduces system's risk under demand uncertainty
- The impact of considering overtime flexibility:
  - Enhances the value of strategic process flexibility
  - Reduced investment cost, improved ENPV, min NPV, and max NPV.

Computational Challenge

- Exhaustive search
  - Total number of design alternatives grows exponentially with the number of products and the number of plants
  - i.e. 3 products and 3 plants = 2400 hours
- Stochastic optimization

<table>
<thead>
<tr>
<th># of product</th>
<th># of plant</th>
<th># of variables</th>
<th># of constraints</th>
<th>Computational Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>500</td>
<td>2,000</td>
<td>2 min 46s</td>
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<tr>
<td>2</td>
<td>4</td>
<td>1,000</td>
<td>3,750</td>
<td>&gt;20 hours</td>
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<tr>
<td>3</td>
<td>2</td>
<td>3,750</td>
<td>13,125</td>
<td>13 min 25s</td>
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<tr>
<td>3</td>
<td>3</td>
<td>5,625</td>
<td>18,750</td>
<td>&gt;20 hours</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>7,500</td>
<td>24,375</td>
<td>&gt;20 hours</td>
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Proposed Method: A Screening Model
Screening Model

Allocation Decision Space

Adaptive One Factor At a Time (OFAT)

Capacity Decision Space

Response Surface Methodology (RSM)

Simulation-based Linear Programming (SLP)

Operation Decision Space

Case Study 2:
Auto Body Assembly System Planning

Which product to which plant?
What capacity should each plant have?

S1
S0
S3
S2

INPUT: An allocation plan

OUTPUT: Identified candidate: Allocation & Plant capacity

Schematic Chart of the Screening Model
Case Study 2

- System under consideration
  - 6 products, 3 plants, and 5 years
- Demand
  - Normal distribution
  - Expected values of demands decrease at 4%/year
  - Standard deviation increases 5%/year
  - Demands are correlated
- Investment, as a function of
  - Equipment, tool, building, capacity, flexibility upcharge
  - Flexibility upcharge, as a function of
  - # of styles, # of platforms, difference between platforms
- Operating cost
  - Includes purchased part cost, assembly material and energy, maintenance, labor cost and overhead cost

Case Study 2: Decisions From Different Approaches

<table>
<thead>
<tr>
<th>Decision Approach</th>
<th>Considers Demand Uncertainty?</th>
<th>Considers Operational Flexibility?</th>
<th>Investment</th>
<th>NPV</th>
<th>ENPV</th>
<th>MIN</th>
<th>MAX</th>
<th>Standard Deviation</th>
<th>VaR@5%</th>
<th>VaG@5%</th>
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<tr>
<td>DA1</td>
<td>No</td>
<td>No</td>
<td>$340M</td>
<td>$68M</td>
<td>($10.3M)</td>
<td>$117M</td>
<td>32%</td>
<td>$28M</td>
<td>$98M</td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>No</td>
<td>No</td>
<td>$324M</td>
<td>$65M</td>
<td>($4M)</td>
<td>$102M</td>
<td>29%</td>
<td>$27M</td>
<td>$92M</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>Yes</td>
<td>No</td>
<td>$359M</td>
<td>$91M</td>
<td>$20M</td>
<td>$20M</td>
<td>19%</td>
<td>$60M</td>
<td>$115M</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>Yes</td>
<td>Yes</td>
<td>$346M</td>
<td>$93M</td>
<td>$26M</td>
<td>$118M</td>
<td>16%</td>
<td>$64M</td>
<td>$114M</td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>No</td>
<td>No</td>
<td>$346M</td>
<td>$93M</td>
<td>$26M</td>
<td>$118M</td>
<td>16%</td>
<td>$64M</td>
<td>$114M</td>
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Case Study 2: Results

![Graph showing Value at Risk and Gain Chart]
Conclusions For Case Study 2

- The screening model identified different auto body assembly system designs as compared to traditional practice
  - More flexible processes
  - Fewer plants
- The identified design results in big improvement of performance
  - 47% improved ENPV
  - Reduced downside risks
  - Increased upside gain

Contributions

- A framework to design manufacturing system, which considers
  - Demand uncertainty
  - Multiple sources of flexibility
- An integrated screening model that
  - Considers demand uncertainty and multiple sources of flexibility
  - Adaptively explores design space by integrating OFAT, RSM, and SLP methods
  - Is computationally practical to identify good design candidates
- Application in automotive body assembly systems planning
  - The case study shows screening model leads to system design with a 47% improvement of ENPV and reduced downside risks as compared to traditional practice.

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