Aggregate Production Planning for Engineer-to-Order Products

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May 2019
Contract Manufacturing

OEM Engineering
Design and Prototype

OEM Factories
In-House Manufacturing

Alternative:
Supply by a contract manufacturer

OEM Factories
Purchase Assembly the Equipment

Sales Channels
Distribute the Equipment

3PL
Provide the Warehouse Solution

Logistics Company
Transportation

CONSUMER

Industry Overview
Benefits of Buying from Contract Manufacturers

- Reduce manufacturing/COGS costs: 51%
- Rely on third parties for manufacturing expertise/core competency: 51%
- Rapid growth/expansion: 28%
- Increase responsiveness/agility: 25%
- Asset reduction (asset-lite strategy): 18%
- Product design expertise: 17%
- Regional/local expansion: 14%
- Other: 6%
Machinery Parts Contract Manufacturer

ZY Machining and Distributions, Ltd

Sponsor Company Overview

Revenue Center
Major Customer

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Product
ETO Products: Increasing Share – Decreasing Profit Margin

Contract manufacturing industry is becoming more competitive with the market leaning towards ETO products.

### Share of ETO orders

- 2014: 55%
- 2015: 64%
- 2016: 69%
- 2017: 69%
- 2018: 75%

### Profit margin for ETO products

- 2014: 28%
- 2015: 26%
- 2016: 25%
- 2017: 24%
- 2018: 19%
Problem Statement

Production Cost Increased

WHY?

- Isolated, inaccurate planning and production process uncertainty
- Actual production schedule doesn't stick to initial plan
- Increased Costs
  - Labor resources
  - Short-notice outsourcing
  - WIP inventory holding
  - Penalties for late deliveries
Feasible Production Plan for ETO Products

Under Process Uncertainty with Minimum Cost
Methodology Outline

- **Deterministic APP LP Model**
- **Initial Analysis**
  - Cost drivers
  - Total expected costs
- **Process Map**
- **Analysis Setting**
  - Production planning options
  - Scenarios of different production times
- **Further Analysis**
  - Buffer capacity
  - Shadow price analysis
- **Deliverables**
  - Resources Change Recommendation
  - Aggregate Production Plan
Stage 2:  
Variable production cost: \( P_{12t} C_{12}^{P} L_{i2} \)  
Labor cost: \( W_{2t} C_{2}^{W} + O_{2t} C_{2}^{ov} \)  
Inventory holding cost: \( I_{i2t} C_{i2}^{ln} \)

Stage 3 Alternative: Outsource cost: \( U_{i3t} C_{i3}^{U} \)

Stage 3:  
Variable production cost: \( P_{i3t} C_{i3}^{P} L_{i3} \)  
Labor cost: \( W_{3t} C_{3}^{W} + O_{3t} C_{3}^{ov} \)  
Inventory holding cost: \( I_{i3t} C_{i3}^{ln} \)

Stage 4:  
Variable production cost: \( P_{i4t} C_{i4}^{P} L_{i4} \)  
Labor cost: \( W_{4t} C_{4}^{W} + O_{4t} C_{4}^{ov} \)  
Inventory holding cost: \( I_{i4t} C_{i4}^{ln} \)

Stage 4 Alternative: Outsource cost: \( U_{i4t} C_{i4}^{U} \)

Stage 5:  
Variable cost: \( P_{i5t} C_{i5}^{P} L_{i5} \)  
Labor cost: \( W_{5t} C_{5}^{W} + O_{5t} C_{5}^{ov} \)  
Inventory holding cost: \( I_{i5t} C_{i5}^{ln} \)  
Backorder penalty: \( B_{i5t} C_{Pen}^{P} \)
Deterministic APP LP Model

Methodology

Minimize costs

- WIP inventory holding
- FG holding before shipment
- Overtime hours
- Hiring
- In-house production
- Outsourcing

Meet the shipment date
/ Incur Penalties

Additional Model Characteristics:
- Multiple production stages
- Multi-product model
- Multi-period model
- ETO products
  - no stock
  - deterministic demand = order
### Three Model Options

**New Employees Hiring**

**Option 1:**
(Both in-house and outsourcing)

**Option 2:**
(In-house regular hours only)

**Option 3:**
(Emergency response without planning)

**Overtime Hours**

- **Option 1:** ✓
- **Option 2:** ✗
- **Option 3:** ✓

**Outsourcing**

- **Option 1:** ✓
- **Option 2:** ✗
- **Option 3:** ✓
Multiple Scenarios

Methodology

Scenarios

Base Scenario (1)  Improvement Scenarios (4)  Disruption Scenarios (11)

Uniform distribution for the 16 scenarios
Analysis Plan

Methodology

STAGE 01
- Run Model under 3 options and all scenarios
- Identify the cost drivers
- Compare costs for different production planning options

STAGE 02
- Conduct shadow price analysis
- Calculate final production plan using buffer capacity
Data Input

- Capacity Constraint
- Costs
- Demand
Option 2 is the most expensive:
1. Outsourcing is cheaper for some product/stages
2. Employees can’t be fired
3. Not enough capacities to produce on-time → penalties

Option 1 achieved a cost reduction of 11.9% compared to Option 3.

<table>
<thead>
<tr>
<th>Model Option</th>
<th>Option 1, ¥</th>
<th>Option 3, ¥</th>
<th>Cost Change, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Expected Cost</td>
<td>714,247</td>
<td>810,364</td>
<td>-11.86%</td>
</tr>
</tbody>
</table>

Total Expected Costs (for All Scenarios) under the Three Model Options
Shadow Price Analysis

**Workforce**
- Stage 3: Excessive labor
- Stage 5: the most constraint

Workforce re-allocation:
0.52% total expected cost reduction without headcount increase

**Equipment**
- Stage 3: the only constrained stage

Adding 1 equipment unit gives only 0.18% total expected cost reduction while investments required
A single plan for execution:

We add buffer capacity to the base plan until production cost is equal to the total expected cost.

7% capacity buffer is required for the data provided (for 4.3% additional cost vs base scenario).
Recommendation for the Sponsor Company

1. **APP LP MODEL**
   Use the model with hiring, outsourcing, and overtime hours

2. **BUFFER CAPACITY**
   Add 7% buffer capacity across all stages to the base scenario

3. **EMPLOYEES**
   Remove 1 employee at stage 3 and add 1 employee at stage 5.

**12.3% COST SAVINGS**
General Recommendations for the Company

01. Model Utilization
02. Lay-off Option
03. Buffer Capacity
04. Total Expected Cost
05. Shadow Price Analysis
06. Model Replicability
THANK YOU!

Questions?

Cheng Cheng

Liz Shafir
APP LP Model

Min \[ z = \sum_i \sum_s \sum_t \left( p_{ist} L_{ist} c_{ist}^{p} + l_{ist} c_{ist}^{l} + u_{ist} c_{ist}^{u} \right) + \sum_s \sum_t \left( w_{st} c_{st}^{w} + o_{st} c_{st}^{ov} \right) + \sum_i \sum_t \left( b_{it} c_{i}^{pen} \right) \]

\[ \forall i, \forall s, \forall t \in \{1 \ldots T\} \] (1)

\[ \sum_t \left( p_{ist} L_{ist} - (hw_{st} + o_{st}) * z \right) \leq 0 \]

\[ \forall s, \forall t \in \{1 \ldots T\} \] (2)

\[ \sum_t \left( p_{ist} L_{ist} - \left( p_{s}^{\text{Max}} \right) * 24 * 6 \right) * z \leq 0 \]

\[ \forall s, \forall t \in \{1 \ldots T\} \] (3)

\[ W_{st} - W_{st-1} - A_{st} = 0 \]

\[ \forall s, \forall t \in \{1 \ldots T\} \] (4)

\[ O_{st} - O_{st}^{\text{Max}} W_{st} * z \leq 0 \]

\[ \forall s, \forall t \in \{1 \ldots T\} \] (5)

\[ U_{ist} - U_{ist}^{\text{Max}} \leq 0 \]

\[ \forall i, \forall s, \forall t \] (6)

\[ l_{ist-1} - l_{ist} + p_{ist} + u_{ist} - (p_{is+1 \cdot t} + u_{is+1 \cdot t}) = 0 \]

\[ \forall i, \forall s \in \{1 \ldots s - 1\}, \forall t \in \{1 \ldots T\} \] (7)

\[ l_{ist-1} - l_{ist} + p_{ist} + u_{ist} - d_{it} - b_{it-1} + b_{it} = 0 \]

\[ \forall i, \forall s \in \{1 \ldots T\} \] (8)

\[ A_{st} W_{st} l_{ist} P_{ist} U_{ist} O_{st} B_{it} \geq 0 \]

\[ \forall i, \forall s, \forall t \] (9)

\[ 0 < z < 1 \]

\[ \forall i, \forall s, \forall t \] (10)

Indices:
- \( i \) – product, 1<i<N
- \( s \) – production stage, 1<s<S
- \( t \) – time period, 0<t<T

Decision variables:
- \( A_{st} \) – employees to hire at start of period t, stage s
- \( W_{st} \) – employees in the end of period t, stage s
- \( O_{st} \) – overtime hours to work in period t, stage s
- \( I_{ist} \) – units of inventory, product i, end of period t, stage s
- \( P_{ist} \) – units to produce internally, period t, stage s, product i
- \( U_{ist} \) – units to outsource, period t, stage s, product i
- \( B_{it} \) – units of backlog by product by week

Input data:
- \( D_{it} \) – demand for product i period t, units
- \( L_{ist} \) – production time for stage s product i, hours/unit
- \( W_{s \cdot 0} \) – workforce at week 0 stage s, # of employees
- \( H \) – working hours, hours/person/week
- \( O_{st}^{\text{Max}} \) – max hours of overtime, hours/person/week
- \( U_{ist}^{\text{Max}} \) – max outsourcing product i stage s, units/week
- \( P_{s}^{\text{Max}} \) – production equipment by stage, units
- \( I_{s \cdot 0} \) – inventory at week 0 product i stage s, units
- \( C_{p}^{e} \) – production cost for product i stage s, \( \$/\text{hour} \)
- \( C_{ov}^{s} \) – cost of overtime hour for stage s, \( \$/\text{hour} \)
- \( C_{w}^{e} \) – cost of employee for stage s, \( \$/\text{person/week} \)
- \( C_{in}^{s} \) – inventory holding cost product i stage s, \( \$/\text{unit/week} \)
- \( C_{o}^{s} \) – outsource cost product i stage s, \( \$/\text{unit} \)
- \( C_{\text{Pen}}^{e} \) – late delivery penalty product i, \( \$/\text{unit/week} \)
1) Calculation buffer capacity by every production stage based on scenarios probability derived from historical data (needs to be collected)

2) Adding buffer capacity size to the objective function of the LP model

3) Adding more constraints and inputs to the model
### Aggregate Production Plan (extract)

#### In-House Production Plan Example for the Base Scenario

<table>
<thead>
<tr>
<th>Product-Stage</th>
<th>Week 9</th>
<th>Week 10</th>
<th>Week 11</th>
<th>Week 12</th>
<th>Week 13</th>
<th>Week 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product 8, Stage 2</td>
<td>0</td>
<td>0</td>
<td>13.1</td>
<td>4.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Product 8, Stage 3</td>
<td>1.1</td>
<td>18.1</td>
<td>27.2</td>
<td>16.1</td>
<td>17.5</td>
<td>0</td>
</tr>
<tr>
<td>Product 8, Stage 4</td>
<td>0</td>
<td>0</td>
<td>46.4</td>
<td>0</td>
<td>33.6</td>
<td>0</td>
</tr>
<tr>
<td>Product 8, Stage 5</td>
<td>0</td>
<td>0</td>
<td>46.4</td>
<td>0</td>
<td>33.6</td>
<td>0</td>
</tr>
</tbody>
</table>

#### Inventories Level for Work-in-Progress Materials for the Base Scenario

<table>
<thead>
<tr>
<th>Product-Stage</th>
<th>Week 9</th>
<th>Week 10</th>
<th>Week 11</th>
<th>Week 12</th>
<th>Week 13</th>
<th>Week 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product 8, Stage 2</td>
<td>61.4</td>
<td>43.2</td>
<td>29.1</td>
<td>17.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Product 8, Stage 3</td>
<td>1.1</td>
<td>19.2</td>
<td>0</td>
<td>16.1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Product 8, Stage 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Product 8, Stage 5</td>
<td>0</td>
<td>0</td>
<td>46.4</td>
<td>46.4</td>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

#### Overtime Hours Planned for the Base Scenario

<table>
<thead>
<tr>
<th>Stage</th>
<th>Week 9</th>
<th>Week 10</th>
<th>Week 11</th>
<th>Week 12</th>
<th>Week 13</th>
<th>Week 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Stage 2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Stage 3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Stage 4</td>
<td>0</td>
<td>0</td>
<td>45.6</td>
<td>86.2</td>
<td>43.9</td>
<td>0</td>
</tr>
</tbody>
</table>
Extreme Scenarios Cost Breakdown

**Scenario 6**
- Option 1: Hiring, Overtime and Outsource Allowed
  - Total Cost = ¥ 895,161
- Option 2: No Overtime, Outsource but Hiring Allowed
  - Total Cost = ¥ 1,494,430
- Option 3: Overtime and Outsource Allowed, No Hiring
  - Total Cost = ¥ 1,609,120

**Scenario 7**
- Option 1: Hiring, Overtime and Outsource Allowed
  - Total Cost = ¥ 822,813
- Option 2: None of Overtime, Outsource or Hiring Allowed
  - Total Cost = ¥ 1,530,375
- Option 3: Overtime and Outsource Allowed, No Hiring
  - Total Cost = ¥ 856,347