Capacity Planning

Chapter 6
What is Capacity?

Capacity

The maximum rate of output of a process or a system.
What is Capacity Management?

Capacity management

Capacity planning (long-term)
- Economies and diseconomies of scale
- Capacity timing and sizing strategies
- Systematic approach to capacity decisions

Constraint management (short-term)
- Theory of constraints
- Identification and management of bottlenecks
- Product mix decisions using bottlenecks
- Managing constraints in a line process
Measures of Capacity and Utilization

- Output measures
- Input measures
- Utilization

\[
\text{Utilization} = \frac{\text{Average output rate}}{\text{Maximum capacity}} \times 100\%
\]
Measures of Capacity

• Use Output Measures when:
  – Process has high volume and the firm makes a small number of standardized products

• Using Input Measures when:
  – Product variety and process divergence is high
  – The product or service mix is changing
  – Productivity rates are expected to change
  – Significant learning effects are expected
Economies and Diseconomies of Scale

• Economies of scale
  – Spreading fixed costs
  – Reducing construction costs
  – Cutting costs of purchased materials
  – Finding process advantages

• Diseconomies of scale
  – Complexity
  – Loss of focus
  – Inefficiencies
Economies and Diseconomies of Scale

The graph illustrates the relationship between output rate (patients per week) and average unit cost (dollars per patient) for hospitals of different sizes.

- **Economies of Scale**: Costs decrease as the output rate increases, with a minimum cost at an intermediate output rate.
- **Diseconomies of Scale**: Costs increase as the output rate continues to increase beyond the optimal point.

The graph shows that a 500-bed hospital experiences economies of scale, while a 250-bed and a 750-bed hospital experience diseconomies of scale.

Copyright ©2013 Pearson Education, Inc. publishing as Prentice Hall
Sizing Capacity Cushions

- Capacity cushions – the amount of reserve capacity a process uses to handle sudden changes

Capacity cushion = $100\% - \text{Average Utilization rate (\%)}$

- Capacity cushions vary with industry
- Capital intensive industries prefer cushions as small as 5 percent, while hotel industry can live with 30 to 40 percent cushion
Capacity Timing and Sizing

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Forecast of capacity required</th>
<th>Planned unused capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>Time between increments</td>
<td></td>
</tr>
</tbody>
</table>

(a) Expansionist strategy
Capacity Timing and Sizing

(b) Wait-and-see strategy

Planned use of short-term options
Forecast of capacity required
Capacity increment
Time between increments
A Systematic Approach to Long-Term Capacity Decisions

1. Estimate future capacity requirements
2. Identify gaps by comparing requirements with available capacity
3. Develop alternative plans for reducing the gaps
4. Evaluate each alternative, both qualitatively and quantitatively, and make a final choice
Step 1 - Estimate Capacity Requirements

For one service or product processed at one operation with a one year time period, the capacity requirement, $M$, is

\[ M = \frac{Dp}{N[1 - (C/100)]} \]

where

- $D = \text{demand forecast for the year (number of customers served or units produced)}$
- $p = \text{processing time (in hours per customer served or unit produced)}$
- $N = \text{total number of hours per year during which the process operates}$
- $C = \text{desired capacity cushion (expressed as a percent)}$
Step 1 - Estimate Capacity Requirements

Setup times may be required if multiple products are produced

Capacity requirement = \frac{\text{Processing and setup hours required for year’s demand, summed over all services or products}}{\text{Hours available from a single capacity unit per year, after deducting desired cushion}}

\[ M = \frac{[Dp + (D/Q)s]_{\text{product 1}} + [Dp + (D/Q)s]_{\text{product 2}} + \ldots + [Dp + (D/Q)s]_{\text{product n}}}{N[1 - (C/100)]]} \]

where
\[ Q = \text{number of units in each lot} \]
\[ s = \text{setup time (in hours) per lot} \]
Example 6.1

A copy center in an office building prepares bound reports for two clients. The center makes multiple copies (the lot size) of each report. The processing time to run, collate, and bind each copy depends on, among other factors, the number of pages. The center operates 250 days per year, with one 8-hour shift. Management believes that a capacity cushion of 15 percent (beyond the allowance built into time standards) is best. It currently has three copy machines. Based on the following information, determine how many machines are needed at the copy center.

<table>
<thead>
<tr>
<th>Item</th>
<th>Client X</th>
<th>Client Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual demand forecast (copies)</td>
<td>2,000</td>
<td>6,000</td>
</tr>
<tr>
<td>Standard processing time (hour/copy)</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Average lot size (copies per report)</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Standard setup time (hours)</td>
<td>0.25</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Copyright ©2013 Pearson Education, Inc. publishing as Prentice Hall
Example 6.1

\[ M = \frac{[Dp + (D/Q)s]_{\text{product 1}} + [Dp + (D/Q)s]_{\text{product 1}} + \ldots + [Dp + (D/Q)s]_{\text{product } n}}{N[1 - (C/100)]} \]

\[ = \frac{[2,000(0.5) + (2,000/20)(0.25)]_{\text{client X}} + [6,000(0.7) + (6,000/30)(0.40)]_{\text{client Y}}}{[(250 \text{ day/year})(1 \text{ shift/day})(8 \text{ hours/shift})][1.0 - (15/100)]} \]

\[ = \frac{5,305}{1,700} = 3.12 \]

Rounding up to the next integer gives a requirement of four machines.
Application Problem 6.1

You have been asked to put together a capacity plan for a critical operation at the Surefoot Sandal Company. Your capacity measure is number of machines. Three products (men’s, women’s, and children’s sandals) are manufactured. The time standards (processing and setup), lot sizes, and demand forecasts are given in the following table. The firm operates two 8-hour shifts, 5 days per week, 50 weeks per year. Experience shows that a capacity cushion of 5 percent is sufficient.

<table>
<thead>
<tr>
<th>Product</th>
<th>Processing (hr/pair)</th>
<th>Setup (hr/pair)</th>
<th>Lot size (pairs/lot)</th>
<th>Demand Forecast (pairs/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men’s sandals</td>
<td>0.05</td>
<td>0.5</td>
<td>240</td>
<td>80,000</td>
</tr>
<tr>
<td>Women’s sandals</td>
<td>0.10</td>
<td>2.2</td>
<td>180</td>
<td>60,000</td>
</tr>
<tr>
<td>Children’s sandals</td>
<td>0.02</td>
<td>3.8</td>
<td>360</td>
<td>120,000</td>
</tr>
</tbody>
</table>

a. How many machines are needed?
b. If the operation currently has two machines, what is the capacity gap?
Application Problem 6.1

a. The number of hours of operation per year, \(N\), is \(N = (2 \text{ shifts/day})(8 \text{ hours/shifts})(250 \text{ days/machine-year}) = 4,000 \text{ hours/machine-year}\)

The number of machines required, \(M\), is the sum of machine-hour requirements for all three products divided by the number of productive hours available for one machine:

\[
M = \frac{[Dp + (D/Q)s]_{\text{men}} + [Dp + (D/Q)s]_{\text{women}} + [Dp + (D/Q)s]_{\text{children}}}{N[1 - (C/100)]}
\]

\[
= \frac{[80,000(0.05) + (80,000/240)0.5] + [60,000(0.10) + (60,000/180)2.2] + [120,000(0.02) + (120,000/360)3.8]}{4,000[1 - (5/100)]}
\]

\[
= \frac{14,567 \text{ hours/year}}{3,800 \text{ hours/machine-year}} = 3.83 \text{ or } 4 \text{ machines}
\]
b. The capacity gap is 1.83 machines (3.83 – 2). Two more machines should be purchased, unless management decides to use short-term options to fill the gap.

The *Capacity Requirements* Solver in OM Explorer confirms these calculations, as Figure 6.5 shows, using only the “Expected” scenario for the demand forecasts.

<table>
<thead>
<tr>
<th>Shifts/Day</th>
<th>2</th>
<th>Components</th>
<th>3</th>
<th>More Components</th>
<th>Fewer Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours/Shift</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Days/Week</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weeks/Year</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cushion (as %)</td>
<td>5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current capacity</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Components</th>
<th>Processing (hr/unit)</th>
<th>Setup (hr/lot)</th>
<th>Lot Size (units/lot)</th>
<th>Demand Forecasts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men’s sandals</td>
<td>0.05</td>
<td>0.5</td>
<td>240</td>
<td>80,000</td>
</tr>
<tr>
<td>Women’s sandals</td>
<td>0.10</td>
<td>2.2</td>
<td>180</td>
<td>60,000</td>
</tr>
<tr>
<td>Children’s sandals</td>
<td>0.02</td>
<td>3.8</td>
<td>360</td>
<td>120,000</td>
</tr>
</tbody>
</table>

Productive hours from one capacity unit for a year 3,800
# Application Problem 6.1

<table>
<thead>
<tr>
<th></th>
<th>Pessimistic</th>
<th></th>
<th>Expected</th>
<th></th>
<th>Optimistic</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Process</td>
<td>Setup</td>
<td>Process</td>
<td>Setup</td>
<td>Process</td>
<td>Setup</td>
</tr>
<tr>
<td>Men’s sandals</td>
<td>0</td>
<td>0.0</td>
<td>4,000</td>
<td>166.7</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Women’s sandals</td>
<td>0</td>
<td>0.0</td>
<td>6,000</td>
<td>733.3</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Children’s sandals</td>
<td>0</td>
<td>0.0</td>
<td>2,400</td>
<td>1,266.7</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Total hours required</td>
<td>0</td>
<td>0.0</td>
<td>12,400</td>
<td>2,166.7</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Total capacity</td>
<td>0.00</td>
<td></td>
<td>3.83</td>
<td></td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>requirements (M)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rounded</td>
<td>0</td>
<td></td>
<td>4</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Scenarios that can be met with current system/capacity:</td>
<td></td>
<td></td>
<td>Pessimistic, Optimistic</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If capacity increased by 0% Expanded current capacity 3,800

|                      |          |          |          |          |            |          |
| Total capacity       | 0.00     |          | 3.83     | 3.83     | 0.00       |          |
| requirements (M)     |          |          |          |          |            |          |
| Rounded              | 0        |          | 4        |          | 0          |          |
| Scenarios that can be met with expanded current capacity: | | | Pessimistic, Optimistic |
Step 2 - Identify Gaps

- Identify gaps between projected capacity requirements ($M$) and current capacity
  - Complicated by multiple operations and resource inputs
Steps 3 and 4 – Develop and Evaluate Alternatives

• Base case is to do nothing and suffer the consequences

• Many different alternatives are possible

• Qualitative concerns include strategic fit and uncertainties.

• Quantitative concerns may include cash flows and other quantitative measures.
Example 6.2

Grandmother’s Chicken Restaurant is experiencing a boom in business. The owner expects to serve 80,000 meals this year. Although the kitchen is operating at 100 percent capacity, the dining room can handle 105,000 diners per year. Forecasted demand for the next five years is 90,000 meals for next year, followed by a 10,000-meal increase in each of the succeeding years. One alternative is to expand both the kitchen and the dining room now, bringing their capacities up to 130,000 meals per year. The initial investment would be $200,000, made at the end of this year (year 0). The average meal is priced at $10, and the before-tax profit margin is 20 percent. The 20 percent figure was arrived at by determining that, for each $10 meal, $8 covers variable costs and the remaining $2 goes to pretax profit.

What are the pretax cash flows from this project for the next five years compared to those of the base case of doing nothing?
Example 6.2

- The base case of doing nothing results in losing all potential sales beyond 80,000 meals.
- With the new capacity, the cash flow would equal the extra meals served by having a 130,000-meal capacity, multiplied by a profit of $2 per meal.
- In year 0, the only cash flow is –$200,000 for the initial investment.
- In year 1, the incremental cash flow is \((90,000 - 80,000)(\$2) = \$20,000\).

Year 2: Demand = 100,000; Cash flow = \((100,000 - 80,000)(\$2) = \$40,000\)
Year 3: Demand = 110,000; Cash flow = \((110,000 - 80,000)(\$2) = \$60,000\)
Year 4: Demand = 120,000; Cash flow = \((120,000 - 80,000)(\$2) = \$80,000\)
Year 5: Demand = 130,000; Cash flow = \((130,000 - 80,000)(\$2) = \$100,000\)
Example 6.2

• The owner should account for the time value of money, applying such techniques as the net present value or internal rate of return methods (see Supplement F, “Financial Analysis,” in MyOMLab).

• For instance, the net present value (NPV) of this project at a discount rate of 10 percent is calculated here, and equals $13,051.76.

\[
NPV = -200,000 + \left[ \frac{20,000}{1.1} \right] + \left[ \frac{40,000}{(1.1)^2} \right] + \left[ \frac{60,000}{(1.1)^3} \right] + \left[ \frac{80,000}{(1.1)^4} \right] + \left[ \frac{100,000}{(1.1)^5} \right]
\]

\[
= -200,000 + 18,181.82 + 33,057.85 + 45,078.89 + 54,641.07 + 62,092.13
\]

\[
= 13,051.76
\]
Application Problem 6.2

The base case for Grandmother’s Chicken Restaurant (see Example 6.2) is to do nothing. The capacity of the kitchen in the base case is 80,000 meals per year. A capacity alternative for Grandmother’s Chicken Restaurant is a two-stage expansion. This alternative expands the kitchen at the end of year 0, raising its capacity from 80,000 meals per year to that of the dining area (105,000 meals per year). If sales in year 1 and 2 live up to expectations, the capacities of both the kitchen and the dining room will be expanded at the end of year 3 to 130,000 meals per year. This upgraded capacity level should suffice up through year 5. The initial investment would be $80,000 at the end of year 0, and an additional investment of $170,000 at the end of year 3. The pretax profit is $2 per meal. What are the pretax cash flows for this alternative through year 5, compared with the base case?
Application Problem 6.2

• The following table shows the cash inflows and outflows.
• Year 3 cash flow:
  – The cash inflow from sales is $50,000 rather than $60,000.
  – The increase in sales over the base is 25,000 meals (105,000 – 10,000) instead of 30,000 meals (110,000 – 80,000)
  – A cash outflow of $170,000 occurs at the end of year 3, when the second-stage expansion occurs.
• The net cash flow for year 3 is $50,000 – $170,000 = –$120,000
## Application Problem 6.2

### CASH FLOWS FOR TWO-STAGE EXPANSION AT GRANDMOTHER’S CHICKEN RESTAURANT

<table>
<thead>
<tr>
<th>Year</th>
<th>Projected Demand (meals/yr)</th>
<th>Projected Capacity (meals/yr)</th>
<th>Calculation of Incremental Cash Flow Compared to Base Case (80,000 meals/yr)</th>
<th>Cash Inflow (outflow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>80,000</td>
<td>80,000</td>
<td>Increase kitchen capacity to 105,000 meals = $-80,000</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>90,000</td>
<td>105,000</td>
<td>90,000 – 80,000 = (10,000 meals)($2/meal) = $20,000</td>
<td>$20,000</td>
</tr>
<tr>
<td>2</td>
<td>100,000</td>
<td>105,000</td>
<td>100,000 – 80,000 = (20,000 meals)($2/meal) = $40,000</td>
<td>$40,000</td>
</tr>
<tr>
<td>3</td>
<td>110,000</td>
<td>105,000</td>
<td>105,000 – 80,000 = (25,000 meals)($2/meal) = $50,000</td>
<td>$50,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Increase total capacity to 130,000 meals = $-170,000</td>
<td>$-170,000</td>
</tr>
<tr>
<td>4</td>
<td>120,000</td>
<td>130,000</td>
<td>120,000 – 80,000 = (40,000 meals)($2/meal) = $80,000</td>
<td>$80,000</td>
</tr>
<tr>
<td>5</td>
<td>130,000</td>
<td>130,000</td>
<td>130,000 – 80,000 = (50,000 meals)($2/meal) = $100,000</td>
<td>$100,000</td>
</tr>
</tbody>
</table>
Application Problem 6.2

For comparison purposes, the NPV of this project at a discount rate of 10 percent is calculated as follows, and equals negative $2,184.90.

\[
\text{NPV} = -\frac{20,000}{1.1} + \frac{40,000}{(1.1)^2} - \frac{120,000}{(1.1)^3} + \frac{80,000}{(1.1)^4} + \frac{100,000}{(1.1)^5}
\]

\[
= -80,000 + 18,181.82 + 33,057.85 - 90,157.77 + 54,641.07 + 62,092.13
\]

\[
= -2,184.90
\]

- On a purely monetary basis, a single-stage expansion seems to be a better alternative than this two-stage expansion.
- However, other qualitative factors as mentioned earlier must be considered as well.
Tools for Capacity Planning

• Waiting-line models
  – Useful in high customer-contact processes

• Simulation
  – Useful when models are too complex for waiting-line analysis

• Decision trees
  – Useful when demand is uncertain and sequential decisions are involved
Waiting Line Models

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
<th>Minutes</th>
<th>Seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-Server Model</td>
<td></td>
<td>Average server utilization</td>
<td>.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arrival rate (lambda)</td>
<td>3</td>
<td>Average number in the line (Lq)</td>
<td>.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Service rate (mu)</td>
<td>6</td>
<td>Average number in the system (L)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of servers</td>
<td>1</td>
<td>Average time in the line (Wq)</td>
<td>.17</td>
<td>10</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average time in the system (W)</td>
<td>.33</td>
<td>20</td>
<td>1200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>k</th>
<th>Prob (num in sys = k)</th>
<th>Prob (num in sys &lt;= k)</th>
<th>Prob (num in sys &gt; k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>.5</td>
<td>.5</td>
<td>.5</td>
</tr>
<tr>
<td>1</td>
<td>.25</td>
<td>.75</td>
<td>.25</td>
</tr>
<tr>
<td>2</td>
<td>.13</td>
<td>.88</td>
<td>.13</td>
</tr>
<tr>
<td>3</td>
<td>.06</td>
<td>.94</td>
<td>.06</td>
</tr>
<tr>
<td>4</td>
<td>.03</td>
<td>.97</td>
<td>.03</td>
</tr>
<tr>
<td>5</td>
<td>.02</td>
<td>.98</td>
<td>.02</td>
</tr>
<tr>
<td>6</td>
<td>.01</td>
<td>1</td>
<td>.01</td>
</tr>
<tr>
<td>7</td>
<td>.0</td>
<td>1</td>
<td>.0</td>
</tr>
</tbody>
</table>
Decision Trees

1. Small expansion
   - Low demand [0.40] $70,000
   - High demand [0.60] $135,000

2. Large expansion
   - Low demand [0.40] $40,000
   - High demand [0.60] $220,000

Don’t expand $90,000
Expand $135,000

Copyright © 2013 Pearson Education, Inc. Publishing as Prentice Hall.