GLOBAL EDITION

Operations Management

Processes and Supply Chains

THIRTEENTH EDITION

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PROCESSES AND SUPPLY CHAINS

Thirteenth Edition

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What to do when M is not an integer depends on the situation. For example, it is impossible to buy a fractional machine. In this case, round up the fractional part, unless it is cost efficient to use short-term options, such as overtime or stockouts, to cover any shortfalls. If, instead, the capacity unit is the number of employees at a process, a value of 23.6 may be achieved using just 23 employees and a modest use of overtime (equivalent to having 60 percent of another full-time person). Here, the fractional value should be retained as useful information.

Example 5.1 shows how to calculate capacity requirements using input measures of capacity.

EXAMPLE 5.1 Estimating Capacity Requirements When Using Input Measures

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 table of information, determine how many machines are needed at the copy center.

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

SOLUTION

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

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

$$= \frac{5{,}305}{1{,}700} = \mathbf{3.12}$$

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

DECISION POINT

The copy center's capacity is being stretched and no longer has the desired 15 percent capacity cushion with the existing three machines. Not wanting customer service to suffer, management decided to use overtime as a short-term solution to handle past-due orders. If demand continues at the current level or grows, it will acquire a fourth machine.

Step 2: Identify Gaps

capacity gap

Positive or negative difference between projected demand and current capacity.

A **capacity gap** is any difference (positive or negative) between projected capacity requirements (M) and current capacity. Complications arise when multiple operations and several resource inputs are involved. Expanding the capacity of some operations may increase overall capacity. However, as we will learn later in Chapter 6, "Constraint Management," if one operation is more constrained than others, total process capacity can be expanded only if the capacity of the constrained operation is expanded.

Step 3: Develop Alternatives

base case

The act of doing nothing and losing orders from any demand that exceeds current capacity, or incur costs because capacity is too large.

The next step is to develop alternative plans to cope with projected gaps. One alternative, called the **base case**, is to do nothing and simply lose orders from any demand that exceeds current capacity or incur costs because capacity is too large. Other alternatives if expected demand exceeds current capacity are various timing and sizing options for adding new capacity, including the expansionist and wait-and-see strategies illustrated in Figure 5.2. Additional possibilities include expanding at a different location and using short-term options, such as overtime, temporary workers, and subcontracting. Alternatives for reducing capacity include the closing of plants or warehouses, laying off employees, or reducing the days or hours of operation.

Step 4: Evaluate the Alternatives

In this final step, the manager evaluates each alternative, both qualitatively and quantitatively.

Qualitative Concerns Qualitatively, the manager looks at how each alternative fits the overall capacity strategy and other aspects of the business not covered by the financial analysis. Of particular concern might be uncertainties about demand, competitive reaction, technological change, and cost estimates. Some of these factors cannot be quantified and must be assessed on the basis of judgment and experience. Others can be quantified, and the manager can analyze each alternative by using different assumptions about the future. One set of assumptions could represent a worst case, in which demand is less, competition is greater, and construction costs are higher than expected. Another set of assumptions could represent the most optimistic view of the future. This type of "what-if" analysis allows the manager to get an idea of each alternative's implications before making a final choice. Qualitative factors would tend to dominate when a business is trying to enter new markets or change the focus of its business strategy.

Quantitative Concerns Quantitatively, the manager estimates the change in cash flows for each alternative over the forecast time horizon compared to the base case. **Cash flow** is the difference between the flows of funds into and out of an organization over a period of time, including revenues, costs, and changes in assets and liabilities. The manager is concerned here only with calculating the cash flows attributable to the project. Example 5.2 shows how cash flow is used to evaluate capacity alternatives.

cash flow

The difference between the flows of funds into and out of an organization over a period of time, including revenues, costs, and changes in assets and liabilities.

EXAMPLE 5.2 Evaluating the Alternatives

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 5 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 5 years compared to those of the base case of doing nothing?

Online Resource

Tutor 4.2 in OM Explorer provides a new example to practice projecting cash flows for capacity decisions.

Atstock Productions/Shutterstock

SOLUTION

Recall that 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 90,000-meal demand will be completely satisfied by the expanded capacity, so the incremental cash flow is (90,000 − 80,000)($2) = $20,000. For subsequent years, the figures are as follows:

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

If the new capacity were smaller than the expected demand in any year, we would subtract the base case capacity from the new capacity (rather than the demand). 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 online Supplement F, "Financial Analysis"). 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.

$$\begin{aligned} NPV &= -200{,}000 + [20{,}000/1.1] + [40{,}000/(1.1)^2] + [60{,}000/(1.1)^3] + [80{,}000/(1.1)^4] + [100{,}000/(1.1)^5] \\ &= -\$200{,}000 + \$18{,}181.82 + \$33{,}057.85 + \$45{,}078.89 + \$54{,}641.07 + \$62{,}092.13 \\ &= \mathbf{\$13{,}051.76} \end{aligned}$$

DECISION POINT

Before deciding on this capacity alternative, the owner should also examine the qualitative concerns, such as future location of competitors. In addition, the homey atmosphere of the restaurant may be lost with expansion. Furthermore, other alternatives should be considered (see Solved Problem 2).

Tools for Capacity Planning

Capacity planning requires demand forecasts for an extended period of time. Unfortunately, forecast accuracy declines as the forecasting horizon lengthens. In addition, anticipating what competitors will do increases the uncertainty of demand forecasts. Demand during any period of time may not be evenly distributed; peaks and valleys of demand may (and often do) occur within the time period. These realities necessitate the use of capacity cushions. In this section, we introduce three tools that deal more formally with demand uncertainty and variability: (1) waiting-line models, (2) simulation, and (3) decision trees. Waiting-line models and simulation account for the random, independent behavior of many customers, in terms of both their time of arrival and their processing needs. Decision trees allow anticipation of events, such as competitors' actions, which requires a sequence of decisions regarding capacities.

Managerial Practice 5.1 shows how PacifiCorp used sophisticated optimization and simulation tools to evaluate different alternatives for long-term capacity planning, including balancing demand and supply of energy from multiple sources.

MANAGERIAL PRACTICE 5.1 Capacity Planning at PacifiCorp

Energy demand in the United States is volatile, making it difficult to predict, while power generation facilities age over time and eventually need to be replaced. Therefore, one of the key decisions for utility companies is planning for the best capacity resource portfolio that is both cost effective and compliant with local government regulations. Capacity decision making in utility companies follows a standardized guideline known as Integrated Resource Planning (IRP). The IRP concept started in the late 1980s between state governments and local utility companies in response to the oil price fluctuations and the introduction of low-cost nuclear energy. An integrated resource plan is a long-term capacity plan for utilities to meet the growing forecasted annual energy demand. Extra capacity cushions are built into the plan to deal with peak demands while meeting the varying state requirements regarding planning horizons, frequency of plan updates, resources to be considered, and stakeholder involvement.

Natalie Behring/Bloomberg via Getty Images

A grid operator works at the PacifiCorp Transmissions Grid Operations center in Portland, Oregon, U.S. PacifiCorp, a unit of Warren Buffett's Berkshire Hathaway Energy that operates the largest transmission system in the western United States, and delivers power to customers in Oregon, Washington, California, Utah, Wyoming, and Idaho. The utility is the second-largest owner of wind generation, behind only another Berkshire subsidiary.

PacifiCorp is a utility company that is a subsidiary of Berkshire Hathaway Energy, and currently operates one of the largest privately held transmission systems in the United States, serving the Western Energy Imbalance Market in multiple states such as Oregon, Washington, California, Idaho, Utah, and Wyoming. Headquartered in Portland, Oregon, PacifiCorp's two business units, Pacific Power and Rocky Mountain Power, serve a combined market of over 1.6 million residential customers, 202,000 commercial customers, and 37,000 industrial and irrigation customers. The service area is 143,000 square miles, and transmission lines add up to 16,500 miles along with 64,000 miles of distribution lines and 900 substations. To prepare for future customer needs, PacifiCorp evaluates a 20-year study period for capacity planning, but mainly focuses on the first 10 years in its assessment of capacity requirements. In the planning horizon of 2011–2020, PacifiCorp forecasted that system peak load will grow at 2.1% per year, and that general energy needs will grow by 1.8% per year. The current capacity was estimated to fall short right from the first year (2011) of the forecast by 326 MW. This deficit was predicted to grow to 3,852 MW by 2020. PacifiCorp has set up plans to introduce additional measures such as demand-side management initiatives (reducing electricity use by promoting saving campaigns, or by implementing efficient load management systems such as smart grid technology), renewable energy, and market purchases. Yet the initial projection of shortfall in the available long-term capacity was significant.

On the basis of these plans, PacifiCorp developed the 2020 capacity mix portfolio using a comprehensive model called System Optimizer. The System Optimizer allows PacifiCorp to determine when and how much to expand resource capacity, run cost simulations on various resource portfolios, and assess the risks. Altogether, PacifiCorp defined 67 input scenarios for the portfolio development. Each scenario was based on alternative transmission configurations, varying carbon dioxide emission control costs and regulation types, natural gas prices, and renewable resource policies. A subsequent sensitivity analysis examined additional incremental costs for coal plants, alternative load forecasts, renewable generation costs and incentives, and demand-side management resource availability. The best resource portfolios were chosen on the basis of the risk-adjusted total cost, 10-year customer rating impact, carbon dioxide emissions, supply reliability, resource diversity, and uncertainty risk from the regulatory policy change. The chosen portfolio showed a capacity mix of 62.5 percent traditional thermal resources, 13 percent of demand-side management initiatives, and 2.6 percent of renewables. Because the sophisticated simulation model at PacifiCorp can comprehensively evaluate the impact of efficiency-improving demand-side management practices on capacity, the company can make more accurate decisions on whether to add additional resources to its portfolio. This increased precision in capacity estimation saved PacifiCorp from investing in an additional 2,500 MW of supply-side resources, which would have been costly.

Still, the usefulness of the capacity optimization model developed by PacifiCorp is only as good as the input assumptions. For example, the changing political environment is pressing on PacifiCorp to reduce the reliance on fossil fuels, even as it still operates 17 thermal electric facilities that generate electricity from coal, natural gas, or geothermal sources. Even though PacifiCorp's power plants use specialized equipment to control environmental emissions, they are more and more looking toward increasing the proportion of renewable resources in the company's portfolio. Factoring the environmental and compliance pressures into the capacity decision model would be the next challenge that PacifiCorp has to meet.[2]

Waiting-Line Models

Waiting-line models often are useful in capacity planning, such as selecting an appropriate capacity cushion for a high-customer-contact process. Waiting lines tend to develop in front of a work center, such as an airport ticket counter, a machine center, or a central computer. The reason is that the arrival time between jobs or customers varies, and the processing time may vary from one customer to the next. Waiting-line models use probability distributions to provide estimates of average customer wait time, average length of waiting lines, and utilization of the work center. Managers can use this information to choose the most cost-effective capacity, balancing customer service and the cost of adding capacity.

Supplement B, "Waiting Lines," follows this chapter and provides a fuller treatment of these models. It introduces formulas for estimating important characteristics of a waiting line, such as average customer waiting time and average facility utilization for different facility designs. For example, a facility might be designed to have one or multiple lines at each operation and to route customers through one or multiple operations. Given the estimating capability of these formulas and cost estimates for waiting and idle time, managers can select cost-effective designs and capacity levels that also provide the desired level of customer service.

Figure 5.3 shows output from POM for Windows for waiting lines. A professor meeting students during office hours has students arriving on average every 20 minutes (three per hour) and can address their questions in 10 minutes (6 per hour). The professor's utilization is 50 percent; therefore the capacity cushion is 50 percent. With that large a capacity cushion, you might expect that students would experience little or no waiting time. However, the output shows that the probability of having two or more students in line, prob(num in sys > 1), is 0.25. This probability might be surprisingly high, given the large capacity cushion.

k	Prob (num in sys = k)	Prob (num in sys <= k)	Prob (num in sys >k)
0	.5	.5	.5
1	.25	.75	.25
2	.13	.88	.13
3	.06	.94	.06
4	.03	.97	.03
5	.02	.98	.02
6	.01	1	.01
7	.0	1	.0

FIGURE 5.3 POM for Windows Output for Waiting Lines during Office Hours

Simulation

More complex waiting-line problems must be analyzed with simulation. It can identify the process's bottlenecks and appropriate capacity cushions, even for complex processes with random demand patterns and predictable surges in demand during a typical day. The SimQuick simulation package available online allows you to build dynamic models and systems. Other simulation packages can be found with Extend, Simprocess, ProModel, and Witness.

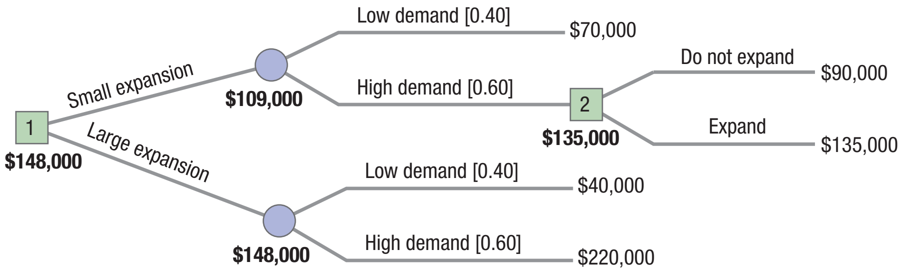
[2] *Sources:* Rachel Wilson and Bruce Biewald, "Best Practices in Electric Utility Integrated Resource Planning," *Synapse Energy Economics, Inc.* (June, 2013); PacifiCorp, "Integrated Resource Plan: Volume 1," http://pacificorp.com/irp (March, 2011); U.S. Department of Energy, "What Is the Smart Grid?" https://www.smartgrid.gov/the_smart_grid/smart_grid.html; https://en.wikipedia.org/wiki/PacifiCorp (June 27, 2020); https://www.pacificorp.com/energy/thermal.html#:~:text=PacifiCorp%20operates%2017%20thermal%20electric%20facilities%20that%20generate, and %20comply%20with%20all%20state%20and%20federal%20requirements (June 27, 2020).

Decision Trees

A decision tree can be particularly valuable for evaluating different capacity expansion alternatives when demand is uncertain and sequential decisions are involved (see Supplement A, "Decision Making"). For example, the owner of Grandmother's Chicken Restaurant (see Example 5.2) may expand the restaurant now, only to discover in year 4 that demand growth is much higher than forecasted. In that case, she needs to decide whether to expand further. In terms of construction costs and downtime, expanding twice is likely to be much more expensive than building a larger facility from the outset. However, making a large expansion now, when demand growth is low, means poor facility utilization. Much depends on the demand.

Figure 5.4 shows a decision tree for this view of the problem, with new information provided. Demand growth can be either low or high, with probabilities of 0.40 and 0.60, respectively. The initial expansion in year 1 (square node 1) can either be small or large. The second decision node (square node 2), whether to expand at a later date, is reached only if the initial expansion is small and demand turns out to be high. If demand is high and if the initial expansion was small, a decision must be made about a second expansion in year 4. Payoffs for each branch of the tree are estimated. For example, if the initial expansion is large, the financial benefit is either $40,000 or $220,000, depending on whether demand is low or high. Weighting these payoffs by the probabilities yields an expected value of $148,000. This expected payoff is higher than the $109,000 payoff for the small initial expansion, so the better choice is to make a large expansion in year 1.

FIGURE 5.4 ▶
A Decision Tree for Capacity Expansion



LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
5.1 Define long-term capacity and its relationship with economies and diseconomies of scale.	Review the section "Measures of Capacity and Utilization" and understand why and how capacity measured in high-volume processes is different from its measurement in low-volume, flexible processes. Also see the section on "Economies of Scale" and "Diseconomies of Scale". Figure 5.1 illustrates the relationship between average unit cost and output rate, and shows different output ranges over which economies and diseconomies of scale can occur.	
5.2 Understand the main differences between the expansionist and wait-and-see capacity timing and sizing strategies.	The section "Capacity Timing and Sizing Strategies" and Figure 5.2 differentiate between the expansionist and wait-and-see strategies. Understand the notion of capacity cushions, and how they link to other decisions in the firm.	
5.3 Identify a systematic four-step approach for determining long-term capacity requirements and associated cash flows.	The section "A Systematic Approach to Long-Term Capacity Decisions" shows you how capacity requirements can be estimated for both input-based and output-based measures. Focus on how different alternatives can be developed to fill the capacity gaps between requirements and current capacity.	**OM Explorer Solvers:** Capacity Requirements **OM Explorer Tutors:** 5.1: Capacity Requirements; 5.2: Projecting Cash Flows **Online Supplements:** F. Financial Analysis; H. Measuring Output Rates; I. Learning Curve Analysis **Case:** Fitness Plus B
5.4 Describe how the common tools for capacity planning, such as waiting-line models, simulation, and decision trees, assist in capacity decisions.	The section "Tools for Capacity Planning" illustrates several different methods and tools that can be used to arrive at capacity decisions. Read Managerial Practice 5.1 to understand how these tools can actually be used in the real world.	

Key Equations

Planning Long-Term Capacity

1. Utilization, expressed as a percent:

$$\text{Utilization} = \frac{\text{Average output rate}}{\text{Maximum capacity}} \times \mathbf{100\%}$$

Capacity Timing and Sizing Strategies

2. Capacity cushion, C, expressed as a percent:

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

A Systematic Approach to Long-Term Capacity Decisions

3. Capacity requirement for one service or product:

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

4. Capacity requirement for multiple services or products:

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

Key Terms

Solved Problem 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.

	TIME STANDARDS			
Product	**Processing (hr/pair)**	**Setup (hr/pair)**	**Lot Size (pairs/lot)**	**Demand Forecast (pairs/yr)**
Men's sandals	0.05	0.5	240	80,000
Women's sandals	0.10	2.2	180	60,000
Children's sandals	0.02	3.8	360	120,000

a. How many machines are needed?

b. If the operation currently has two machines, what is the capacity gap?

SOLUTION

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