MSCI 432 Course Notes
Production and Service Operations Management

Paolo Torres

University of Waterloo

Winter 2021

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1 OPERATIONS MANAGEMENT AND DEMAND FORECASTING (I)

1.1 Operations Management

1.1.1 Basic Premise of Supply and Demand

- As consumers, we decide how much we want to buy and how much we are willing to pay
- Consumers hold the cash and as such are the ultimate decision makers
- This underlies OM as it goes to the heart of the environment in which firms operate

1.1.2 Operations as an Aggregate Function

What is Operations Management?

- OM is the management of activities and resources that create goods and provide services
- Companies use OM to improve efficiency and effectiveness

Why Study Operations Management?

- A large percentage of a company's expenses occur in the OM area
- A large number of all jobs are in the OM area
- Activities in all other areas are interrelated with OM activities

Three Basic Functions:

1. Operations: Create goods and services
2. Finance: Provide funds and the economic analysis of investment proposals
3. Marketing: Assess customer wants and needs and communicate them to others

Types of OM Decisions:

- Design (strategic) decisions that are medium to long term and deal with capital equipment and other physical assets (equipment needs, production capacity, etc.)
- Day-to-day operations involve the everyday decisions such as scheduling, packaging, quality control, and labour requirements

1.1.3 What Operations Managers Do

Defining the Role of the Operations Manager:

- Core (manufacturing)
- Support (maintenance, accounting, HR, purchasing)
- Managerial (general administration)

The Operations Manager's Job:

Management Process	Field of Responsibility
Planning	Capacity, location, make or buy
Organizing	Centralization, specialization, staffing
Controlling	Inventory, quality, motivation
Directing	Scheduling, incentive plans, work orders

Establishing Priorities:

- Pareto Phenomenon: A few factors account for a high percentage of the occurrence of some event(s)
- 80/20 Rule: 80% of problems are caused by 20% of the activities

1.1.4 The Importance of Collaboration

- A clear and comprehensive systems-based approach for issues is in demand
- Coordination between marketing and operations is essential for success
- For example, changing a package form needs to account for inventory costs and order quantities, existing packaging inventories, new equipment needs, plant layout, etc.

1.1.5 Concept of Value Added

- Difference between the cost of goods and the value of outputs
- For services, the cost of services and the value placed on those services by individuals
- Value of output is determined by the prices that consumers are willing to pay for goods

1.1.6 Stakeholder Management

- "Any group or individual who can affect or is affected by the achievement of an organization's objective" (Freeman, 1984)
- Stakeholders may include customers, employees, suppliers, financiers, etc.

1.2 Demand Forecasting

- Underlies strategic planning when it comes to plant or service design
- Essential for budgeting and determining capital requirements for both inputs and projects
- Dictates medium-term operations and affects short-term operations

1.2.1 Forecast Commonalities

1. Rely, to some extent, upon past demand and criteria identified as affecting that demand
2. Forecasts of aggregate demand for similar goods is more accurate than forecasts for individual items within a category
3. Increasing forecast horizons introduces greater uncertainty and reduced reliability

1.2.2 Requirements for a Useful Forecast

1. Forecast should be long enough to make it relevant
2. Limitations on accuracy must be clearly stated
3. Forecasting method should be reliable
4. Operations forecasts should be expressed in units

1.2.3 How it is Done

1. Determine why you are forecasting (who wants it and what will they use it for)
2. Assess and state the required levels of detail and accuracy
3. Establish a forecasting horizon
4. Gather historical data
5. Select a forecasting method
6. Complete the forecast
7. Monitor its accuracy

1.2.4 Judgemental Approaches

- Includes things such as hunches, personal opinions, non-quantitative observations
- Can be tainted by personal bias
- Developed as a non-quantitative analysis of historical data or analysis of subjective data

1.2.5 Quantitative Approaches

- Utilize hard data from the past (untainted from personal bias)
- Time series models (identifies patterns in data and projects these trends into the future)
- Associative models (describes demand in terms of independent causal variables)

1.2.6 Time Series Modeling

- A time-ordered sequence of observations taken at regular intervals over a period of time

- Assumes that future values of the series can be estimated from past values

Data Behaviour:

- Average (level): Horizontal pattern
- Trend: Persistent upward or downward pattern
- Seasonality: Regular wavelike pattern that corresponds with some repeatable event
- Cycles: Lasts more than one year and looks at longer-term patterns
- Irregular Variations: One-time events that tend to skew the data
- Random Variations: Multitude of minor events that combine to affect the data

Methods:

Naïve Method:

- Assumes that the value of the data for the last period will be the value of the next period
- Can be applied to average, trend, and seasonal data

Period	Actual	Change	Naïve Forecast
$t-1$	50		
t	53	$+3$	
$t+1$			$53+3=56$

Averaging Methods:

- Three types: moving average, weighted moving average, and exponential smoothing
- Requires stable data and can handle random variations but not irregular data points

Moving Average Method:

- Average of recent observations are used as the basis for the current forecast
- Choice of the number of data points used for the calculation will affect the sensitivity of the average to the most recent data point

Period	Demand
1	42
2	40
3	43
4	40
5	41

$$F_6 = \frac{43+40+41}{3} = 41.33$$

$$F_7 = \frac{40 + 41 + 39}{3} = 40.00$$

Weighted Moving Average Method:

- Assigns a heavier weight to more recent data points
- Sum of the weights must equal to one

$$F_6 = 0.40(41) + 0.30(40) + 0.20(43) + 0.10(40) = 41.0$$

$$F_7 = 0.40(39) + 0.30(41) + 0.20(40) + 0.10(43) = 40.2$$

Exponential Smoothing:

- Current forecast that is based upon the previous period plus a portion of the difference between the actual outcome in the period and the quantity forecast for that period
- Notation: $F_t = F_{t-1} + \alpha(A_{t-1} - F_{t-1}), where\ 0 < \alpha < 1$
- For example, if previous forecast was 42 units, previous actual demand was 40 units, and $\alpha = 0.10$, the new forecast would be:

$$F_t = 42 + 0.10(40 - 42) = 41.8$$

- Then, if the actual demand turned out to be 43, the next forecast would be:

$$F_{t+1} = 41.8 + 0.10(43 - 41.8) = 41.92$$

Associative Forecasting:

- If I want to predict ridership from a new train station, what data might I look at?

1. Find (predictor) variables associated with ridership at other stations
2. $Associated = correlated = as\ one\ moves\ the\ other\ moves$
3. Create a model that shows the relationship between the predictor variables and the predicted variable (ex. ridership)
4. Technique is regression analysis (ex. Simple linear regression with one variable, multiple regression that can be non-linear)
5. Test the model to see which variables are most useful in predicting ridership (r^2)
6. Use the model to predict ridership, given the values of the predictor variables

Associative Models:

- Predictor Variables (x): Used to predict values of the variable of interest (y) – independent variables
- Linear Regression: Process of finding a straight line that best fits a set of points on a graph – least squares estimation

- Multiple Regression: Models with more than one predictor variables – computations complex, created with computer

Correlation and Excel:

- Correlation Coefficient (r): Measure of strength of the relationship between two variables
  - Ranges from -1 (moves in same direction) to $+1$ (moves in opposite direction)
- r^2 measures proportion of variation in the values of y that is "explained" by the predictor variables in the regression model
  - Ranges from 0 to 1 (higher values means more useful predictors)

Linear Regression Assumptions:

- Predictions are being made only within the range of observed values
- Variations around the line are random and normally distributed

1.2.7 Forecasting Accuracy

- Definition: A judgement or measurement of how accurate the forecast is to actual results from the demand being forecast (or predicted)
- Presence of random variables such as changes in tastes, preferences, and values of consumers make it almost impossible to create a perfect prediction of future demand

Forecasting Error:

$$E_t = A_t - F_t$$

- In words: The error E for period t is simply the difference between the actual demand A and the forecast demand F for the same period
- **Bias:** Sum of forecast errors, if positive then forecasts are underestimating demand, if negative then forecasts are overestimating demand

Three Methods for Measuring Accuracy:

- **Mean Absolute Deviation:** $MAD = \frac{\sum|e|}{n}$
- **Mean Squared Error:** $MSE = \frac{\sum(A_i - F_i)^2}{n}$
- **Mean Absolute Percent Error:** $MAPE = \frac{\sum[\frac{|A_i - F_i|}{A_i} \times 100]}{n}$
  - e is the value of individual forecast errors, n is the number of observations

Calculate MAD, MSE, and MAPE for the following data.

Period	Actual	Forecast	Forecast Error	$(A-F)$ |Error|	Forecast Error^2	$\frac{\lvert\text{Error}\rvert}{\text{Actual}} \times 100$
1	217	215	2	2	4	.92%
2	213	216	−3	3	9	1.41
3	216	215	1	1	1	.46
4	210	214	−4	4	16	1.90
5	213	211	2	2	4	.94
6	219	214	5	5	25	2.28
7	216	217	−1	1	1	.46
8	212	216	−4	4	16	1.89
			−2	22	76	10.26%

d

SOLUTION

Using the numbers shown in the above table,

$$\text{MAD} = \frac{\sum |e|}{n} = \frac{22}{8} = 2.75$$

$$\text{MSE} = \frac{\sum e^2}{n} = \frac{76}{8} = 9.5$$

$$\text{MAPE} = \frac{\sum \left[\frac{|e|}{\text{Actual}} \times 100\right]}{n} = \frac{10.26\%}{8} = 1.28\%$$

1.2.8 Dealing with Control Charts

- Objective: Measure the accuracy of the forecasts within a set of prescribed boundaries
- Control limits "s" based upon the square root of the mean squared error: $s = \sqrt{MSE}$

Solution Process:

1. Setup the required data table and make the necessary calculations
2. Check average forecast error and comment on its proximity to zero
3. Calculate the square root of the forecast errors
4. Determine the 2s control limits
5. Compare forecast errors to the control limits

2 DEMAND FORECASTING (II) AND PRODUCT DESIGN

2.1 Demand Forecasting

2.1.1 Trend Adjusted Forecasts (TAF)

- Slightly more complicated version of exponential smoothing:

$$S_t = TAF_t + \alpha(A_t - TAF_t)$$
$$T_t = T_{t-1} + \beta(S_t - S_{t-1} - T_{t-1})$$
$$TAF_{t+1} = S_t + T_t$$

- S_t: Smoothed series at the end of period t
- T_t: Smoothed trend at the end of period t
- α and β are arbitrary smoothing constants
- A_t is the actual data from period t

Example 4

Cellphone sales of a company over the last 10 weeks are shown below. The data appear to have a linear trend. Determine the equation of the linear trend and predict the sales of cellphones for weeks 11 and 12. Plot the data and trend line.

Week	Unit Sales
1	700
2	724
3	720
4	728
5	740
6	742
7	758
8	750
9	770
10	775

Using the cellphone data from Example 4 (where it was concluded that the data exhibited a linear trend), use trend-adjusted exponential smoothing to prepare forecasts for periods 5 through 11, with α = .4 and β = .3. Use the first four weeks to estimate starting smoothed series and smoothed trend.

SOLUTION

Table 3-1 displays the data again in the Actual column. We will use the average of the first four weeks as the starting smoothed series:

$$S_4 = (700 + 724 + 720 + 728)/4 = 718.$$

t (Week)	A_t (Actual)			
1	700			
2	724	Starting values:		
3	720	$S_4 = (700+724+720+728)/4 = 718$, $T_4 = (728-700)/3 = 9.33$		
4	728	$TAF_5 = 718 + 9.33 = 727.33$		
		$TAF_t + \alpha(A_t - TAF_t) = S_t$	$T_{t-1} + \beta(S_t - S_{t-1} - T_{t-1}) = T_t$	$TAF_{t+1} = S_t + T_t$
5	740	727.33 + .4(740 – 727.33) = 732.40	9.33 + .3(732.40 – 718 – 9.33) = 10.85	743.25
6	742	743.25 + .4(742 – 743.25) = 742.75	10.85 + .3(742.75 – 732.40 – 10.85) = 10.70	753.45
7	758	753.45 + .4(758 – 753.45) = 755.27	10.70 + .3(755.27 – 742.75 – 10.70) = 11.25	766.52
8	750	766.52 + .4(750 – 766.52) = 759.91	11.25 + .3(759.91 – 755.27 – 11.25) = 9.27	769.18
9	770	769.18 + .4(770 – 769.18) = 769.51	9.27 + .3(769.51 – 759.91 – 9.27) = 9.37	778.88
10	775	778.88 + .4(775 – 778.88) = 777.33	9.37 + .3(777.33 – 769.51 – 9.37) = 8.90	786.23

2.1.2 Review of Seasonality

- Seasonal data is defined as data that exhibits a repeating pattern that is tied to some regularly occurring event (summer ice cream sales, winter natural gas sales, etc.)
- Expressed as the amount of deviation from the period average, by using the average over the length of the repeating pattern to calculate an adjustment factor
- Seasonality is measured relative to the trend

Computing Seasonal Relatives:

- Need to identify the trend in the data in order to compare seasonal values to some average
- Decompose data into smaller segments through use of a centered moving average (CMA)
- Number of periods in CMA is equal to the number of "seasons" portrayed in the data
- Example: Quarterly data, use a 4-period CMA

Period	Historical Value	CMA	Seasonal Relative

1	79		$79/76.67 = 1.03$
2	86	76.67	$86/76.67 = 1.12$
3	65		$65/76.67 = 0.85$

Steps in Dealing with Seasonal Data:

1. Write out the given data in table form
2. Calculate the appropriate Centered Moving Average (CMA)
3. Use CMA to calculate seasonal relatives
4. Average and adjust the seasonal relatives to the relevant seasonal data
5. Use the "adjusted" averaged seasonal relatives to de-seasonalize the original data
6. Describe the data (does it exhibits a linear trend, upward or downward)
7. Using calculated (GIVEN) Linear Trend Equation, calculate the forecasts for the periods
8. Re-seasonalize forecast using the average seasonal relatives calculated in Step 4

Below are quarterly data for production of ice cream in Canada from quarter 1 of 2006 to quarter 3 of 2009.[2]

a. Calculate the quarterly relatives using the centred moving average method.

b. Deseasonalize the data, fit an appropriate model, project it four quarters ahead, and reseasonalize to obtain forecasts for ice cream demand for the 4th quarter of 2009 and Q1 to Q3 of 2010.

a.

Quarter		Production (million litres)	CMA_4	CMA_2	Production/CMA_2
2006	1	66			
	2	96			
			79.75		
	3	91		78.875	91/78.876 = 1.154
			78		
	4	66		77.375	66/77.375 = 0.853
			76.75		
2007	1	59		75.875	0.778
			75		
	2	91		74.250	1.226
			73.5		
	3	84		73.000	1.151
			72.5		
	4	60		71.375	0.841
			70.25		
2008	1	55		69.500	0.791
			68.75		
	2	82		66.875	1.226
			65		
	3	78		63.875	1.221
			62.75		
	4	45		59.750	0.753
			56.75		
2009	1	46		54.875	0.838
			53		
	2	58			
	3	63			

	QUARTER				
Year	**1**	**2**	**3**	**4**	**Total**
2006			1.154	0.853	
2007	0.778	1.226	1.151	0.841	
2008	0.791	1.226	1.221	0.753	
2009	0.838				
Average	0.802	1.226	1.175	0.816	4.019
Adjusted	.802(4/4.019)=0.798	1.226(4/4.019)=1.220	1.170	0.812	4.000

b.

Quarter	**Production (million litres)**	**Seasonal Relatives**	**Deseasonalized Production**
2006 1	66	0.798	66/.798=82.707
2	96	1.220	96/1.220=78.689
3	91	1.170	77.778
4	66	0.812	81.281
2007 1	59	0.798	73.935
2	91	1.220	74.590
3	84	1.170	71.795
4	60	0.812	73.892
2008 1	55	0.798	68.922
2	82	1.220	67.213
3	78	1.170	66.667
4	45	0.812	55.419
2009 1	46	0.798	57.644
2	58	1.220	47.541
3	63	1.170	53.846

The deseasonalized data has a (decreasing) linear trend. Therefore, a linear trend is fitted to the deseasonalized data using regression, and its equation is displayed at the top of the chart above.

Using the regression equation, the trend forecasts for periods 16 to 19 (Q4 of 2009 and Q1 to Q3 of 2010) are:

$$Y_{16} = -2.2575(16) + 86.85 = 50.730$$
$$Y_{17} = -2.2575(17) + 86.85 = 48.473$$
$$Y_{18} = -2.2575(18) + 86.85 = 46.215$$
$$Y_{19} = -2.2575(19) + 86.85 = 43.958$$

d

The reseasonalized forecasts for the fourth quarter of 2009 and Q1 to Q3 of 2010 are:

$$F_{16} = 50.730(0.812) = 41.193$$
$$F_{17} = 48.473(0.798) = 38.681$$
$$F_{18} = 46.215(1.220) = 56.382$$
$$F_{19} = 43.958(1.170) = 51.431$$

2.2 Product Design

Product Design:

- Determines the form and function
- Is expensive and time consuming
- Governs the level of product quality and hence the level of customer satisfaction
- Contributes to competitive advantage

2.2.1 Product Design Process

- Product Approval Committee: Management team
- Core Teams: Members from all aspects of the organization
- Phase Reviews: Milestones
- Structural Development: Structured and explicit project management technique

2.2.2 Sequential Steps in New Product Developments

- Idea Generation
- Build a Business Case: Market and Competitive Analysis
- Development: Product attributes we need to meet or exceed customer expectations?
- Testing and Validation
- Launch

2.2.3 Sources of New Product Ideas

- Customers, front-line production workers, suppliers, competitive products, R&D

2.2.4 Key Issues in Product Design

Standardization

- Every consumer receives the same product
- High volumes of the same product reduce costs through economies of scale
- Can reduce the level of variety in product offerings
- May breed a climate of resistance of product improvements and modifications

Design for Mass Customization: Attempts to reach a compromise between the benefits of standardization for the producer and the desire of consumers for variety and customization

Reliability: Ability of a product (or part) to perform for its intended use under normal conditions

Robust Design: Products that can stand up under a wide range of operational environments

Legal and Ethical Issues: Product liability (injuries), ethical issues (sub-standard products)

Design for the Environment: Energy efficient, minimization of waste/packaging, etc.

Concurrent Engineering: Bringing design engineering staff into direct work with others

Computer Assisted Design (CAD): Computerizes design to avoid hand-drawn designs

Design for Manufacturing and Assembly: Ease can be incorporated into the design

Component Commonality: Occurs when a component can be used in multiple products

3 CAPACITY PLANNING AND PROCESS DESIGN/FACILITY LAYOUT

3.1 Strategic Capacity Planning

3.1.1 Overview

- **Capacity:** Upper workload limit that a production unit can accommodate
- **Production Rate:** Measured in terms of the units of production per unit of time
- **Capacity Time Frames:** Long-term (1-5 years), medium-term (next 12 months), short-term (up to 12 weeks)
- **Strategic Capacity Planning:** Systematic determination of facility and equipment needs

Importance of Long-Term Capacity

- Capacity directly impacts the ability of the company to meet future demand
- Effective capacity planning optimizes operating costs
- Capacity decisions have a direct impact on initial capital costs
- Capacity involves long-term commitment of resources
- Capacity can directly affect competitiveness

Measuring Capacity

- Design Capacity: Max amount of output that can be produced under ideal conditions
- Effective Capacity: Amount of output that can realistically be made given delays, etc.
- Efficiency: Ratio of actual output to effective capacity:

$$Efficiency = \frac{Actual\ Output}{Effective\ Capacity}$$

- Utilization: Ratio of actual output to design capacity:

$$Utilization = \frac{Actual\ Output\ (or\ Uptime)}{Design\ Capacity\ (or\ Available\ Time)}$$

Minco produces silica and magnesia (http://www.mincoitc.com). To process silica, eight furnaces are used. Each furnace has 2,200 pounds/hour capacity. Minco works 24 hours a day, 5 days a week. During a typical week, total preventive maintenance is 65 hours and total other downtime is 39 hours. Effective capacity is 1,700,000 pounds and actual production is 1,600,000 pounds per week. Calculate the design capacity, utilization, and efficiency of silica furnaces.

SOLUTION

Available hours per week = 8(24)(5) = 960

Design capacity per week = 2,200(960) = 2,112,000 pounds

Productive hours per week = 960 – 65 – 39 = 856

Utilization = uptime hours/available hours = 856/960 = 0.89 or 89%

Efficiency = actual output rate/effective capacity = 1,600,000/1,700,000 = 0.94 or 94%

Note: Effective capacity = 1,700,000 < utilization × design capacity = .89(2,112,000) = 1,879,680

Factors Influencing Capacity

Facilities and equipment, products, workers, planning and operations, external factors

3.1.2 Effective Capacity Planning

1. Forecast demand for a period of 5 years or more
2. Calculate the capacity required to meet that demand
3. Measure existing in-house capacity and if necessary, begin discussing how additional capacity can be achieved

3.1.3 Focusing on Long-Term Demand

1. Identify the trend as expressed over time (growth, decline, cyclical, stable)
2. Consider forecasting technique (regression, judgemental)

3.1.4 Basic Capacity Requirement Question

1. Have a reasonably accurate forecast of annual demand
2. Know standard run times for each product on its respective machine
3. Know the number of hours worked per day
4. Know the number of workdays per year

A department works one eight-hour shift, 250 days a year. Three new products with the following annual demands are to be produced in the department. There is no excess capacity, so the department needs to buy new machines. Fortunately, there is a type of machine that can produce all three products. The expected processing times per unit are also given below. How many machines are needed?

Product	Annual Demand	Standard Processing Time per Unit (Hr)	Processing Time Needed (Hr)
#1	400	5.0	2,000
#2	300	8.0	2,400
#3	700	2.0	1,400
			5,800

d

SOLUTION

Working one eight-hour shift, 250 days a year provides an annual capacity of 8 × 250 = 2,000 hours per year for each machine. We can see that three of these machines would be needed to handle the required volume:

$$\frac{5{,}800}{2{,}000 \text{ hours/machine}} = 2.90 \text{ machines (round up to 3)}$$

The size of the facility can be determined by summing the area required for machines, inventory, handling material, and the offices required. 15

3.1.5 Major Concerns When Assessing Various Capacity Alternatives

- Design flexibility into system
- Differentiate between new and mature products
- Look at the organization in its entirety
- Prepare to deal with large (chunkier) increases in capacity
- Attempt to smooth out capacity requirements as dictated by consumer demand
- Use of capacity cushions
- Identify the optimal operating level

The first product created by toy company Spin Master, now the third largest toy manufacturer in North America, was Earth Buddy, a grass head.[1] Spin Master was hoping to produce and sell 8,000 Earth Buddies for Mother's Day and had one week to produce them. The Earth Buddy assembly consisted of the following operations: A: fill grass seeds and sawdust in a nylon stocking (average time 90 seconds), B: form ears and nose using elastic bands (average time 48 seconds), C: stick on the eyeglass and eyes (average time 24 seconds; eyeglasses were formed off line), and D: paint the mouth (average time 15 seconds). Finally, Earth Buddies are left to dry overnight and then packed. There are 6 workers doing A, 3 doing B, 2 doing C, and 1 doing D. There is enough space for inventory between operations so that they can work fairly independently. Determine the bottleneck operation and capacity of the "line" for a 40-hour week. Is the line balanced? Can Spin Master meet its production goal?

SOLUTION

	Fill	Form	Eyes	Paint
Time per unit per worker (sec)	90	48	24	15
No. of units per minute per worker	60/90 = 2/3	60/48 = 1.25	60/24 = 2.5	60/15 = 4
Number of workers	6	3	2	1
Capacity per minute	6(2/3) = 4	3(1.25) = 3.75	2(2.5) = 5	4(1) = 4
Capacity per hour	4(60) = 240	3.75(60) = 225 Bottleneck	5(60) = 300	4(60) = 240

d

Line capacity = 225 units per hour. Yes, the line is fairly balanced because capacity per hour for the operations are all close.

Productive hours required to make 8,000 units = 8,000/225 = 35.6 hours.

Yes, Spin Master should be able to meet its target production goal of 8,000 units provided employees work 17
approximately 36 hours (excluding breaks).

3.1.6 Break-Even Analysis

- Focuses on the relationship between costs, revenues, and volumes
- Goal is to determine the quantity at which the alternative capacity arrangement being considered will provide an economic advantage profit

Costs

- Fixed Costs (FC) are independent of volume produced
- Variable Costs (VC) are entirely dependent upon how much is produced
- Assume that variable costs (v) remains constant per unit of output (Q) regardless of the volume produced

$$Total\ Cost\ (TC) = FC + VC$$
$$Variable\ Costs\ (VC) = Q \cdot v$$
$$Total\ Revenue\ (TR) = Q \cdot R$$
$$Profit\ (P) = TR - TC = (Q \cdot R) - (FC + VC) = (Q \cdot R) - FC - Q \cdot v$$
$$P = Q(R - v) - FC$$
$$Q = \frac{P + FC}{R - v} \Rightarrow Q_{BEP} = \frac{FC}{R - v}$$

The management of a large bakery is contemplating making pies, which will require leasing a new equipment for a monthly cost of $6,000. Variable cost will be $2.00 per pie and retail price will be $7.00 each.

a. How many pies must be sold per month in order to break even?
b. What would the profit (loss) be if 1,000 pies are made and sold in a month?
c. How many pies must be sold to realize a profit of $4,000 per month?
d. If demand is expected to be 1,500 pies per month, is this a good investment?

SOLUTION

$FC = \$6{,}000$ per month, $v = \$2$ per pie, $R = \$7$ per pie
d

a. $Q_{BEP} = \frac{FC}{R - v} = \frac{\$6{,}000}{\$7 - \$2} = 1{,}200$ pies/month
b. For $Q = 1{,}000$, $P = Q(R - v) - FC = 1{,}000\ (\$7 - \$2) - \$6{,}000 = -\$1{,}000$ (i.e., loss of $1,000)
c. $P = \$4{,}000$; solve for Q using formula 5-7:

$$Q = \frac{\$4{,}000 + \$6{,}000}{\$7 - \$2} = 2{,}000 \text{ pies}$$

d. Because $1{,}500 > 1{,}200 = Q_{BEP}$, this is a good investment.

3.2 Process Design and Facility Layout

3.2.1 General Overview

Process Design and **Plant Layout** have long-term consequences for a company affecting:

- Long-term feasibility of the company
- Ability of the firm to meet its mission statement
- Morale of the workforce who actually operate the equipment and effectively run the plant
- The ability of the firm to meet its long-term strategic goals

3.2.2 Process Types

Job Shop

- <u>Low volume</u> of highly variable customized goods or services
- Process is intermittent
- Employs <u>skilled workers</u>
- Uses <u>highly flexible equipment</u> that can be used on a wide variety of applications

Batch Processing

- This describes a firm that produces a moderate quantity of a good or service
- Process is intermittent (i.e., by batch scheduled)
- <u>Equipment is not as flexible</u> as it is in a job shop
- <u>Workers are skilled but not as skilled</u> as those in a job shop

Repetitive Process

- Marked by <u>higher volumes</u> of more standardized goods
- <u>Lower skilled workforce – this is changing</u>
- <u>Equipment is not very flexible</u>

Continuous

- <u>High volumes of highly standardized output</u>
- Production is <u>continuous</u> and there is not typically counted
- <u>Low skilled workforce</u>

3.2.3 Process Considerations – Matching Process to Product Type and Volume

- **Focused Factory Concept:** High volume shops that specialize in a particular output
- **Hybridization:** Some organizations have been able to combine volume and specialization in their product offerings

3.2.4 Automation

- Using machinery with sensing and control devices that enable it to operate automatically

- Advantages: Low variability, contrasts to labour, strategy necessary for competitiveness
- Disadvantages: Costly, inflexible, can adversely affect worker morale
- Types: Fixed automation, programmable automation, flexible automation

3.2.5 Process Design

- Determines the form and function of how the production of goods and services take place
- Involves the allocation of resources, the sequencing of activities and control mechanisms

Process: Determine state of inputs, outline objectives (speed, type, cost, quality, dates, etc.)
Conceptualize: $inputs \rightarrow outputs$, assess alternatives, incremental/hierarchical, flow diagram
Select: Establish design of choice, build a prototype (computer model) of the process and test it
Create: Specify machinery, determine labour requirements, design placement and work centers
Implement: Buy equipment, hire and train workers, initiate trial runs

3.2.6 Fail-Safe Service Process

- Customer presence infers that quality and delivery problems are going to have immediate consequences
- This suggests that the service provider has a great incentive to ensure that the process is fail-safe, i.e., not prone to failure or on the positive side, to manage process design

3.2.7 Service Process Design

Service process design involves the direct or indirect involvement of the customer or of something belonging to the customer.

3.2.8 Basic Layout Types

Product (Line): Arranges the process (plant layout) linearly according to the progressive steps by which a product is made.
Process (Functional): Arranges production resources together according to the similarity of function.
Cellular: Layout in which different machines are arranged in a cell that can process items that have similar processing requirements.

3.2.9 Assembly Line Balancing

- Assigning tasks to workstations such that the workstations have approximately equal time requirements
- Cycle time is determined by the desired output rate:

$$Cycle\ Time = \frac{Operating\ Time\ Per\ Day}{Desired\ Output\ Rate}$$

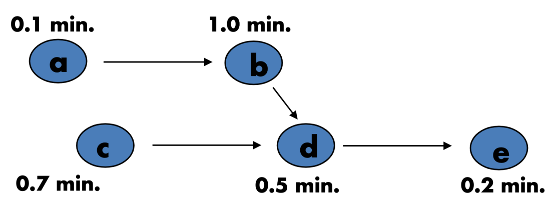
- Number of workstations is determined by the cycle time, the sum of task times, and the ability to bundle activities into appropriately sized workstations:

$$Theoretical\ Number\ of\ Workstations = \frac{Sum\ of\ Task\ Times}{Cycle\ Time}$$

- **Precedence Network:** A diagram that shows the task and their precedence requirements
- **Balancing Rules:** Assign the tasks with the longest time, assign the task with the most followers

A must be done before B, B and C must be done before D, and D must be done before E

Question: Calculate the number of work stations required and the activities done at each work station. Assume a cycle time 0f 1.0 minutes. 'Assign task with the most followers'



Workstation	Time Remaining	Eligible	Assign Task	Revised Time Remaining	Station Idle Time
1	1.0	a, c	a	0.9	
	0.9	c	c	0.2	
	0.2	*none*	–		0.2
2	1.0	b	b	0.0	0.0
3	1.0	d	d	0.5	
	0.5	e	e	0.3	0.3
	0.3	–	–		<u>0.5</u>

Two measures of facility layout effectiveness:

$$Percentage\ Idle\ Time = \left\{\frac{Sum\ of\ Idle\ Times}{Actual\ Number\ of\ Workstations \times Cycle\ Time}\right\} \times 100$$

$$Efficiency\ of\ the\ Line = 100 - Percentage\ Idle\ Time$$

In this example:

$$\%\ idle\ time = \frac{0.5}{3 \times 1.0} \times 100 = 16.7\%$$

$$efficiency = 100\% - 16.7\% = 83.3\%$$

Dealing with Variable Task Times

- Task times vary due to worker fatigue, boredom, mechanical failures, shortages, etc.
- Solutions: Reduce variability in the task time themselves, allow for use of buffer inventories, build some idle time into the process itself, cross training workers

Resolving Bottlenecks

- The task time of the slowest workstation will determine the cycle time for the entire line
- Solutions: Parallelize workstations to decrease process time in half, cross train workers

4 QUALITY MANAGEMENT AND STATISTICAL PROCESS CONTROL

4.1 Quality Management

4.1.1 Quality Overview

- **Quality:** The ability of a product or service to consistently meet or exceed customer expectations
- Evolution: craftsmanship (pre-industrial revolution), division of labour (industrial revolution), quality assurance (1950s), quality management systems (1970s), TQM/continuous improvement (1980s), Six Sigma/statistical tools (today)
- Dimensions: Performance, aesthetics, special features, conformance, reliability, durability, serviceability (example: quality of car)
- Service: Tangibles, convenience, reliability/consistency, responsiveness, time, assurance, courtesy (example: service of car repair)
- Determinants: Product design, process design, production
- Benefits: Improved quality, better reputation, increased market share, higher profitability
- Costs: Failure (defective), appraisal (inspection, testing), prevention (training, planning)

Deming's 14 Steps to Quality:

1. Create constancy of purpose toward improvement
2. Management must adopt the TQM philosophy
3. Cease dependence on inspection
4. Minimize total cost
5. Improve constantly and forever
6. Institute training
7. Institute leadership to act on quality issues
8. Drive out fear
9. Work as a team
10. Eliminate exhortations, and fix the system
11. Eliminate work standards and MBO
12. Remove barriers to pride of workmanship
13. Institute education and self-improvement
14. The transformation is everybody's job

4.1.2 Quality Certifications

- ISO 9001: Set of international standards on quality management and quality assurance, critical to international business
- ISO 14000: Family of standards related to environmental management

4.1.3 Hazard Analysis Critical Control Point (HACCP)

- A quality control system, similar to ISO 9001, designed for food processors
- Main steps: Hazard analysis, determination of the critical control points, creation of the HACCP plan

4.1.4 Problem Solving, Process Improvement, and Quality Tools

- Problem solving: Define problem, collect data, analyze problem, generate potential solutions, choose a solution, implement solution, monitor solution
- PDSA cycle: Plan, do, study, act
- Six Sigma: A business process for improving quality, reducing costs, and increasing customer satisfaction ($\leq 3.4\ defects\ per\ million$)
- Quality tools: Flowcharts, check sheets, histograms, Pareto charts, scatter diagrams, control charts, cause-and-effect diagrams, run charts
- Methods for generating ideas: Brainstorming, quality circles, interviewing, etc.

4.2 Statistical Quality Control

- **Statistical Quality Control:** Uses statistical techniques and sampling to monitor and test the quality of goods and services (acceptance sampling – accept or reject, statistical process control – if process is operating within acceptable limits)
- Inspection: The appraisal of goods/services against standards

4.2.1 Elements of Statistical Process Control (SPC) Process

Statistical Process Control:

- The quality control steps
- Type of variations
- Control charts
- Designing control charts

- Individual unit and moving range charts
- Control charts for attributes
- Using control charts

Types of Variations: Random variation (natural), assignable variation (source can be identified)

4.2.2 Control Charts

Purpose: To monitor process output to distinguish between random and assignable variation

Designing Control Charts:

1. Determine a sample size
2. Obtain 20 to 25 samples
3. Establish and graph preliminary control limits
4. Plot sample statistic values on control chart
5. Are any points outside control limits (CL)?
    a. NO: Assume no assignable cause
    b. YES: Investigate and correct

Control Charts for Variables: Variables generate data that are measured, sample mean/range

Upper and Lower Control Limits for Sample Mean Chart:

$$UCL_{\bar{x}} = \bar{\bar{X}} + z\sigma_{\bar{x}}$$

$$LCL_{\bar{x}} = \bar{\bar{X}} - z\sigma_{\bar{x}}$$

Where:

$$\sigma_x = Standard\ deviation\ of\ sampling\ distribution\ of\ sample\ means = \frac{\sigma}{\sqrt{n}}$$

$$\sigma = Process\ standard\ deviation$$

$$n = Sample\ size$$

$$z = Standard\ normal\ deviate\ (usually\ z = 3)$$

$$\bar{\bar{X}} = Average\ of\ sample\ means\ (grand\ mean)$$

Example:

A quality inspector took five samples, each with four observations, of the length of a part (in cm). She computed the mean of each sample (see table below).

a. Use the following data to obtain Three Sigma (i.e., $z = 3$) control limits for sample mean. Is the process in control?

b. If a new sample has values 12.10, 12.19, 12.12, and 12.14, using the sample mean control chart in part *a*, has the process mean changed (i.e., is there an assignable variation)?

It is known from previous experience that the standard deviation of the process is .02 cm.

Sample

		1	2	3	4	5
	1	12.11	12.15	12.09	12.12	12.09
	2	12.10	12.12	12.09	12.10	12.14
Observation	3	12.11	12.10	12.11	12.08	12.13
	4	12.08	12.11	12.15	12.10	12.12
	$\bar{x}$	12.10	12.12	12.11	12.10	12.12

a. $\bar{\bar{X}} = \frac{12.10+12.12+12.11+12.10+12.12}{5} = 12.11\ cm$

$UCL_{\bar{x}} = 12.11 + 3\left(\frac{0.02}{\sqrt{4}}\right) = 12.14$

$LCL_{\bar{x}} = 12.11 - 3\left(\frac{0.02}{\sqrt{4}}\right) = 12.08$

All 5 sample means fall between the control limits; the process is in control.

b. $\overline{x_6} = \frac{12.10+12.19+12.12+12.14}{4} = 12.1375\ cm$

Because $12.08 < 12.1375 < 12.14$, the process mean has not changed.

Upper and Lower Control Limits Alternate Method:

$$UCL_{\bar{x}} = \bar{\bar{X}} + A_2\bar{R}$$

$$LCL_{\bar{x}} = \bar{\bar{X}} - A_2\bar{R}$$

Where:

$A_2\ can\ be\ obtained\ from\ table\ below$

$\bar{R} = Average\ of\ sample\ ranges$

$Sample\ range = Maximum\ value - minimum\ value\ in\ the\ sample$

$\bar{\bar{X}} = Average\ of\ sample\ means\ (grand\ mean)$

Range Table

Number of Observations in Sample, n	Factor for $\bar{x}$ Charts, A_2	Factors for R-Charts: Lower Control Limit, D_3	Factors for R-Charts: Upper Control Limit, D_4
2	1.88	0	3.27
3	1.02	0	2.57
4	0.73	0	2.28
5	0.58	0	2.11
6	0.48	0	2.00
7	0.42	0.08	1.92
8	0.37	0.14	1.86
9	0.34	0.18	1.82
10	0.31	0.22	1.78
11	0.29	0.26	1.74
12	0.27	0.28	1.72
13	0.25	0.31	1.69
14	0.24	0.33	1.67
15	0.22	0.35	1.65
16	0.21	0.36	1.64
17	0.20	0.38	1.62
18	0.19	0.39	1.61
19	0.19	0.40	1.60
20	0.18	0.41	1.59

Example:

- Twenty samples of $n = 8$ have been taken of the weight of a part. The average of sample ranges for the 20 samples is .016kg, and the average of sample means is 3kg. Determine three sigma control limits for sample mean of this process.

$$\bar{\bar{X}} = 3, \bar{R} = 0.016, A_2 = 0.37 \; (for\ n = 8\ from\ table)$$

$$UCL_{\bar{x}} = \bar{\bar{X}} + A_2\bar{R} = 3 + 0.37(0.016) = 3.006\ kg$$

$$LCL_{\bar{x}} = \bar{\bar{X}} - A_2\bar{R} = 3 - 0.37(0.016) = 2.994\ kg$$

Upper and Lower Control Limits for Sample Range Control Chart:

$$UCL_R = D_4\bar{R}$$

$$LCL_R = D_3\bar{R}$$

Example:

- Twenty-five samples of *n*=10 observations have been taken from a milling process. The average of sample ranges is .01 centimetre. Determine upper and lower control limits for sample range.

$$\bar{R} = 0.01\ cm, D_3 = 0.22, D_4 = 1.78\ (for\ n = 10, from\ table)$$

$$UCL_R = D_4\bar{R} = 1.78(0.01) = 0.0178\ cm$$

$$LCL_R = D_3\bar{R} = 0.22(0.01) = 0.0022\ cm$$

Example:

Calculate sample means, sample ranges, grand mean, and average of sample ranges:

	Observations						
Sample	1	2	3	4	5	Mean	Range
1	10.68	10.69	10.78	10.80	10.71	10.73	0.12
2	10.79	10.86	10.60	10.75	10.78	10.75	0.26
3	10.78	10.67	10.84	10.79	10.72	10.76	0.17
4	10.59	10.73	10.81	10.78	10.73	10.73	0.22
5	10.69	10.71	10.79	10.76	10.67	10.72	0.12
6	10.75	10.71	10.74	10.72	10.61	10.71	0.14
7	10.79	10.71	10.69	10.88	10.60	10.73	0.27
8	10.74	10.78	10.11	10.74	10.75	10.62	0.67
9	10.77	10.77	10.64	10.64	10.73	10.71	0.13
10	10.72	10.67	10.71	10.85	10.71	10.73	0.18
11	10.79	10.82	10.76	10.66	10.71	10.75	0.16
12	10.62	10.80	10.82	10.87	10.73	10.77	0.25
13	10.66	10.82	10.89	10.54	10.75	10.73	0.35
14	10.81	10.75	10.86	10.80	10.70	10.78	0.16
15	10.66	10.68	10.64	10.75	10.73	10.69	0.10
				Averages		**10.73**	**0.22**

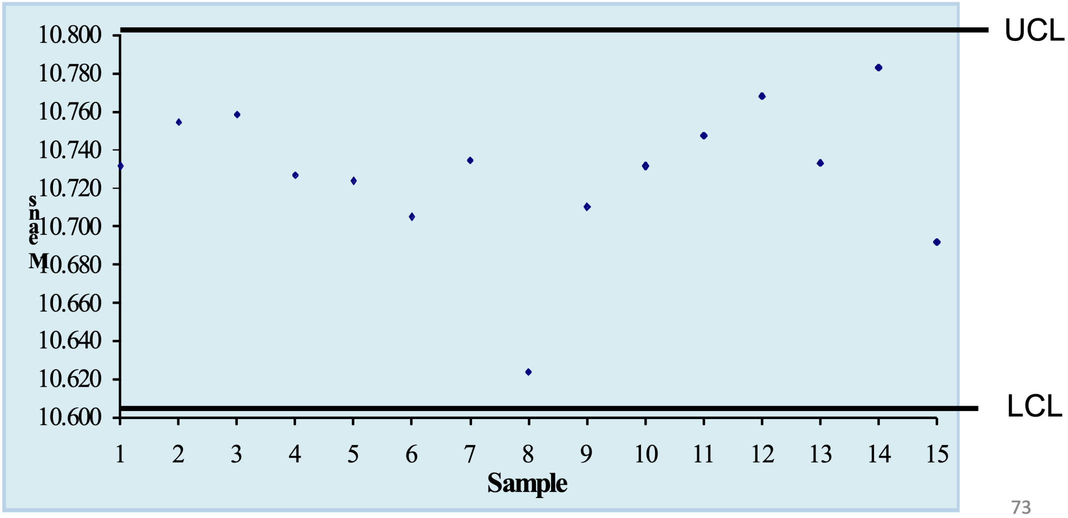
Determine control limits:

$$From\ table, with\ n = 5 \rightarrow A_2 = 0.58$$

$$UCL_{\bar{x}} = \bar{\bar{X}} + A_2\bar{R} = 10.728 + 0.58(0.2204) = 10.856$$

$$LCL_{\bar{x}} = \bar{\bar{X}} - A_2\bar{R} = 10.728 - 0.58(0.2204) = 10.601$$

Create sample mean chart and plot values:

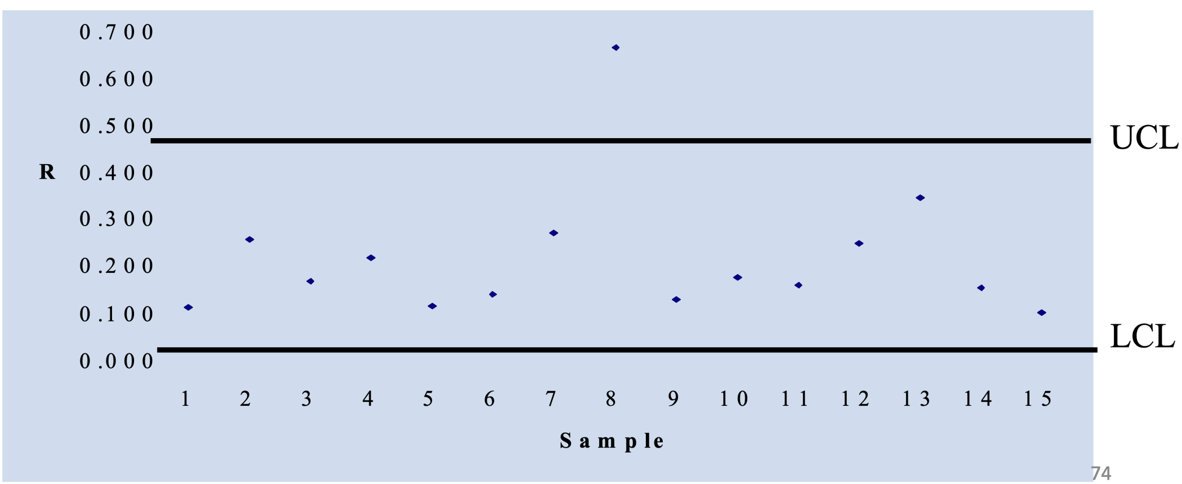


Create sample range chart and plot values:

$$From\ table, with\ n = 5 \rightarrow D_3 = 0, D_4 = 2.11$$

$$UCL_R = D_4\bar{R} = (2.11)(0.2204) = 0.46504$$

$$LCL_R = D_3\bar{R} = (0)(0.2204) = 0$$



5 SUPPLY CHAIN MANAGEMENT (SCM)

5.1 SCM Part 1

5.1.1 SCM

- **Supply Chain:** A sequence of organizations that produce a good or provide a service and get it to the marketplace.
- **Supply Chain Management:** The cooperation, collaboration and coordination of facilities such as manufacturing plants, warehouses, distribution centers; and activities such as production and physical delivery of goods.
- **Value Added:** The creation of a good's value as it moves through production and distribution.

$$Suppliers \rightarrow Manufacturers \rightarrow Distributors \rightarrow Retailers \rightarrow Consumers$$

5.1.2 The Need for SCM and Potential Benefits

Prime Objective of SCM: To get the product to the marketplace as efficiently (i.e., least costly) as possible to increase the firm's effectiveness in meeting consumer demand.

Drivers of Supply Chain Management:

- Ongoing need to improve operations and increase efficiency
- Increased occurrence of outsourcing
- Freer trade and increasing globalization
- Increasing levels of e-commerce
- Increasing competition (using lean or JIT)
- Desire to effectively control inventories (Bullwhip effect)

5.1.3 Bullwhip Effect

Bullwhip Effect: Demand/order variability gets progressively larger the further back in a supply chain is the company.

- **Causes:** Isolation of manufacturing from the retail sector, errors in forecasting, promotional pricing, trade show effect.
- **Implications:** Strain on manufacturing capacity, rescheduling, increased inventory holdings resulting in increased costs and shelf-life issues.

- **Remedies:** Make product to order, increase inventories.

5.1.4 Strategic and Tactical/Operational Activities in SCM

Strategic: Agreement of goals between supply chain members, desired product characteristics, expected response times to consumer demand, information system requirements, target fill rate.
Tactical/Operational: Forecasting, purchasing/ordering, transportation of material, warehouse and inventory control, scheduling of production and distribution, customer service functions.

5.1.5 Efficient Replenishment Systems

- **Quick Response:** Just-in-time inventory replenishment (used in retailing).
- **Efficiency Consumer Response (ECR):** Expanded version of quick response initiative which includes some collaboration (used in the grocery industry).
- **Vendor Managed Inventory (VMI):** Agreement for supplier to access and maintain customer's inventory (used in convenience stores).

5.1.6 Information Technology Used in SCM

- **Distribution Requirements Planning (DRP):** A system for synchronizing replenishment schedules across the supply chain; is a push system (based on forecasts).
- **Management Information System (MIS):** Tools used to gather and access, analyze, and share information; two types are planning software and execution software.
- **Electronic Data Interchange (EDI):** Direct, computer-to-computer transmission of transactions between organizations.
- **RFID Technology:** Used to track goods in supply chain with RFID tags attached to them, transmits product information to receiver, eliminates need for manual counting.

5.1.7 Requirements and Key Steps in Creating Effective SCM

Requirements:

- Formation of close relationships based upon trust, co-operation, and agreement.
- Create effective communication channels to facilitate improved co-ordination.
- Supply chain visibility and information sharing, (unexpected) event management, performance measurement.

Key Steps:

- Develop strategic objectives and tactics
- Integrate and coordinate internal activities
- Coordinate with suppliers and customers
- Coordinate planning and execution across the supply chain
- Form strategic partnerships

5.1.8 Reasons for Outsourcing

- **Outsourcing:** Buying goods or services instead of producing or providing them in-house.
- **Reasons**: Lower cost, gain expertise and knowledge, gain flexibility, increase capacity.

5.1.9 CPFR and the Value of Strategic Planning

- **Collaborative Planning, Forecasting, and Replenishment (CPFR):** Practical test as to the sincerity and effectiveness of a co-operative and effective supply chain.
- Three step process: Planning, initial forecasting, and replenishment

5.1.10 SCOR Performance Metrics Model

Supply Chain Operations Reference (SCOR) Model:

Perspective	Metrics
Reliability	Perfect order fulfillment
Responsiveness	Lead time
Agility	Upside flexibility/adaptability
Costs	Supply chain management cost, COGS
Assets management	Cash-to-cash cycle time, return on fixed asset +/- inventory

5.2 SCM Part 2

5.2.1 Responsibilities and Activities of Purchasing

- **Purchasing:** Involves the procurement of raw materials, parts needed for manufacturer, machinery, repair parts for existing machinery, general office and plant supplies and the acquisition of required services; develop and implement purchasing plans.
- **Responsibilities:** Source goods and services, monitor quality of inputs, negotiate and determining prices, maintain database of suppliers and products, cost management, etc.

- **Purchasing Cycle:** Series of steps that begin with a request and ends with paying the supplier. Requisition received, supplier selected, decide how to purchase, monitor orders, receive orders, pay suppliers.

5.2.2 Benefits of E-Commerce

Companies can have a global presence, improve competitiveness and quality, analyze customer interests, collect detailed information, shorten supply chain response times and costs, etc.

5.2.3 Value Analysis and Spend Analysis

- **Value Analysis:** An assessment of the function of a particular manufacturing part to see if it can be modified or replaced with another part that will reduce costs without sacrificing its functionality; select item, identify function, ask questions, evaluate.
- **Price Determination:** Published prices, competitive bidding, and negotiated pricing.
- **Centralized vs. Decentralized Purchasing:** Purchasing handled by one special department vs. individual departments handling their own purchasing.
- **Spend Analysis:** The collection, organization, classification, and analysis of expenditures with the goal of reducing costs, increasing purchasing efficiency, and monitoring supplier performance.

5.2.4 Supplier Management and Partnership

- Choosing suppliers, supplier relationships, supplier partnerships.
- Factors in choosing a supplier: Quality and quality assurance, flexibility, location, price, reputation and stability, lead times and reliability, other customers, service after sale.

5.2.5 Logistics and Reverse Logistics

Logistics: The movement and storage (warehousing) of materials, finished products, and information that occur both within the facility and outside of the facility.

Example:

Total Delivery Costs = freight costs + in-transit holding costs
= freight costs + H(d)/365

Where: H is the annual holding costs of the goods shipped
d is the number of days in transit

Calculate total **ANNUAL** freight costs, in-transit costs and safety stock costs associated with the shipment of the following:

23,000 units of a good that sells for **$ 210** each

	Costs ($/unit)	Time Req'd (days)	Safety Stocks Req'd (weeks)
Air Freight	52	7	2
Ocean Freight	10	35	8

Annual **Holding Costs of 20%** per annum

Air Freight:

$$Freight = \$52 \times 23{,}000 = \$1{,}196{,}000$$

$$In - Transit = \$210 \times 23{,}000 \times 0.20 \times \frac{7}{365} = \$18{,}526.03$$

$$Safety\ Stock = (\$210 + \$52) \times 23{,}000 \times 0.20 \times \frac{2}{52} = \$46{,}353.85$$

$$Total = \$1{,}260{,}879.88$$

Ocean Freight:

$$Freight = \$10 \times 23{,}000 = \$230{,}000$$

$$In - Transit = \$210 \times 23{,}000 \times 0.20 \times \frac{35}{365} = \$92{,}630.14$$

$$Safety\ Stock = (\$210 + \$10) \times 23{,}000 \times 0.20 \times \frac{8}{52} = \$155{,}692.31$$

$$Total = \$478{,}322.45$$

Reverse Logistics: The backward flow of goods returned by consumers or retailers.

5.2.6 Process and Factors Considered When Selecting a Transportation Mode

- Modes of transportation: Ocean freights, trains, delivery trucks, air freights, etc.
- Speed vs. cost, balance transportation cost with inventory holding costs

Example: Selecting a Transportation Mode

Cost of item = $1,750.00
Holding cost = $700 per year
Alternative A cost $100 and takes 8 days
Alternative B cost $120 and takes 7 days

Total delivery cost = transportation (freight) cost + in-transit holding cost

In-transit $$\text{Holding cost} = \frac{H(d)}{365}$$

where H = annual holding cost of items being transported
d = duration of transport (in days)

$$For\ A: \$100 + \frac{\$700(8)}{365} = \$115.24$$

$$For\ B: \$120 + \frac{\$700(7)}{365} = \$133.42$$

Since it costs less to hold the product one day longer than it does for the faster shipping, choose Alternative A.

6 INVENTORY MANAGEMENT (I)

6.1 Basics

6.1.1 Definition of Inventory

- **Inventory:** Inventory is nothing more than a stock of goods being held in a warehouse or some other storage facility
- For example: inputs, packaging, finished or unfinished goods, spare machinery, supplies
- Inventory Management: Involves some system to plan for and manage these stocks

6.1.2 Why Inventories Demand Respect

Inventories are important because they are worth money:

- Outdated **finished goods** inventories increase waste
- Excessive **input inventories** risk the changes of some goods becoming unsuitable for use
- Inventories tie up funds and will therefore drive-up costs and drive down efficiency

$$ROI = \frac{Profit\ after\ taxes}{Total\ assets}$$

6.1.3 Turnover Rate

$$Turnover\ Rate = \frac{Annual\ cost\ of\ goods}{Average\ inventory\ value}$$

6.2 Functions and Characteristics of Effective Inventory Management

Functions: In-transit inventories, safety stocks, cycle stocks, seasonal stocks, buffer inventories, anticipation inventories

Characteristics:

- Safe Storage and Inventory Utilization: Warehouse management systems
- Tracking and Inventory Control: Periodic counting, perpetual tracking, two-bin system, bar code systems, radio frequency identification tags
- Forecasting and Lead Times: Purchase lead times
- Estimating Inventory Costs: Carrying costs, ordering costs, shortage costs
- A-B-C Product Classification

6.3 Requirements for Effective Inventory Management

6.3.1 Efficient Order Quantity (EOQ)

- Firms want to strike a balance between the costs associated with holding inventory and the costs incurred in ordering product
- For high volume/high value goods there is a double incentive to increase order frequency

Assumptions: Single product, annual demand needs are known, constant demand, constant lead time, single delivery per order, no quantity order discounts, no transportation discounts based upon load size

Annual Holding Costs:

Assumption of constant rate of use allows to define average inventory as half of the order:

$Average\ Inventory = \frac{Q}{2}$, where Q is the order quantity

$Average\ Holding\ Cost = \frac{Q}{2} \times H$, where H is the annual holding cost per unit

Annual Ordering Costs:

$Number\ of\ Orders = \frac{D}{Q}$, where D is annual demand and Q is order size

$Annual\ Ordering\ Costs = \frac{D}{Q} \times S$, where S is per order process cost

Since annual demand is known, the annual ordering cost will be inversely related to order size

Total Inventory Control Cost:

- When annual demand (D), holding costs (H), and per unit order processing costs (S) are known, then total inventory holding and ordering costs (TC) can be described as follows:

$$TC = \frac{Q}{2} \times H + \frac{D}{Q} \times S$$

- This suggests that optimal total costs can be plotted as the minimum point on a u-shaped total cost curve, where costs increase if order size is too small but also increase if inventory levels are too high:

$$\frac{dTC}{dQ} = \frac{H}{2} - \frac{DS}{Q^2}$$

$$\frac{H}{2} - \frac{DS}{Q^2} = 0$$

$$Q = \sqrt{\frac{2DS}{H}} = Q_0$$

- Therefore, if we substitute $EOQ = Q_0$, we can solve for minimum costs

$$Length\ of\ order\ cycle\ (in\ days) = \frac{Q_0}{D} \times 365$$

EOQ Example 1:

A tire store expects to sell approximately 100 all-season tires of a certain make, model, and size next year. Annual holding cost is $16 per tire and ordering cost is $20 per order. The store operates 360 days a year and has enough storage space in the back.

a. What is the EOQ?

b. How many times per year would the store reorder if EOQ units are ordered each time?

c. What is the length of an order cycle if EOQ units are ordered each time?

d. What is the total annual inventory control cost if EOQ units are ordered each time?

$$D = 100\ tires\ per\ year$$

$$H = \$16\ per\ unit\ per\ year$$

$$S = \$20\ per\ order$$

a. $Q_0 = \sqrt{\frac{2DS}{H}} = \sqrt{\frac{2(100)(20)}{16}} = 15.8$, round to $16\ units$

b. Number of orders per year: $\frac{D}{Q_0} = \frac{100\ tires/year}{16\ tires\ each\ time} = 6.25\ times\ per\ year$

c. Length of order cycle: $\frac{Q_0}{D} = \frac{16\ tires}{100\ tires/year} = 0.16\ year$, which is 0.16×360, or 57.6 workdays or 57.6

d. $TC = Annual\ holding\ cost + Annual\ ordering\ cost = \frac{Q_0}{2}H + \frac{D}{Q_0}S$

$TC = \frac{16}{2}16 + \frac{100}{16}20 = \$128 + 125 = \$253$

EOD Example 2:

A distributor of security monitors purchases 3,600 black-and-white monitors a year from the manufacturer at the cost of $65 each. Ordering cost is $30 per order and annual holding cost rate is 20 percent of the unit cost. Calculate the optimal order quantity and the total annual cost of ordering and holding the inventory.

$$D = 3{,}600\ monitors\ per\ year$$

$$S = \$30\ per\ order$$

$$i = holding\ cost\ rate\ per\ year = 20\%$$

$$R = unit\ cost = \$65$$

$$H = iR = 0.20(\$65) = \$13$$

$Q_0 = \sqrt{\frac{2DS}{H}} = \sqrt{\frac{2(3{,}600)(30)}{13}} = 128.9$, round to 129 monitors

$TC = \frac{Q_0}{2}H + \frac{D}{Q_0}S = \frac{129}{2}13 + \frac{3{,}600}{129}30 = \$838.50 + \$837.21 = \$1{,}675.71$

6.3.2 Efficient Production Quantity (EPQ)

- Similar to EOQ as we are still looking at annual inventory cost control
- Rate of production exceeds the rate of consumption
- Since the good is produced in-house the ordering cost associated with EOQ is replaced by a setup cost to change over production equipment

Analysis:

- Variables

I_{MAX}: maximum inventory level

Q: batch size or production lot size per run

S: setup cost per run (cleanouts, tooling changes, etc.)

D: annual demand

p: production rate per day

d: demand rate (consumption) per day

H: holding cost

- Equations

$$Optimal\ batch\ size = Q = Q_0 = \sqrt{\frac{2DS}{H}} \times \sqrt{\frac{p}{p-d}}$$

$$I_{MAX} = \left(\frac{Q}{p}\right)(p-d)$$

$$Average\ inventory\ level = \frac{I_{MAX}}{2}$$

$$Annual\ holding\ cost = \frac{I_{MAX}}{2} \times H$$

$$Annual\ setup\ costs = \frac{D}{Q} \times S$$

$$Total\ inventory\ control\ costs = \frac{I_{MAX}}{2} \times H + \frac{D}{Q} \times S$$

$$Production\ length = \frac{Q}{p}$$

$$Number\ of\ runs\ per\ year = \frac{D}{Q}$$

$$Cycle\ length\ between\ production\ runs = \frac{Q}{d}$$

Example:

A toy manufacturer uses 48,000 rubber wheels per year for its popular dump truck series. The company can make its own wheels at a rate of 800 per day. The toy trucks are assembled uniformly over the entire year. Holding cost is $1 per wheel per year. Setup cost for a production run of wheels is $45. The company operates 240 days per year. Determine the:

a. Optimal production run quantity.
b. Minimum total annual cost for holding and setup.
c. Cycle length for the optimal production run quantity.
d. Production run length for the optimal production run quantity.

$$D = 48{,}000\ wheels\ per\ year$$

$$S = \$45\ per\ production\ run$$

$$H = \$1\ per\ wheel\ per\ year$$

$$p = 800\ wheels\ per\ day$$

$$d = 48{,}000\ wheels\ per\ 240\ days, or\ 200\ wheels\ per\ day$$

a. $Q_0 = \sqrt{\frac{2DS}{H}} \times \sqrt{\frac{p}{p-d}} = \sqrt{\frac{2(48{,}000)(45)}{1}} \times \sqrt{\frac{800}{800-200}} = 2{,}400\ wheels$

b. $TC_{min} = \frac{I_{MAX}}{2} \times H + \frac{D}{Q_0} \times S$

$I_{MAX} = \left(\frac{Q}{p}\right)(p-d) = \left(\frac{2{,}400}{800}\right)(800-200) = 1{,}800\ wheels$

$TC_{min} = \frac{1{,}800}{2} \times \$1 + \frac{48{,}000}{2{,}400} \times \$45 = \$900 + \$900 = \$1{,}800$

c. $Cycle\ length = \frac{Q}{d} = \frac{2{,}400\ wheels}{200\ wheels\ per\ day} = 12\ days$

d. $Production\ run\ length = \frac{Q}{p} = \frac{2{,}400\ wheels}{800\ wheels\ per\ day} = 3\ days$

6.3.3 EOQ with Quantity Discounts

- **Quantity Discounts:** Price discounts used as an incentive for purchasers to order in large quantities
- Objective: To compare the benefits of purchase price savings for buying in quantity as opposed to the increase in annual holding costs of maintaining larger average inventories

Revised Total Cost Simplification:

- Without quantity discounts, the efficient order quantity was selected to minimize annual holding and orders cost, such that:

$$\frac{Q}{2} \times H \approx \frac{D}{Q} \times S$$

- With quantity discounts we want to select an order quantity that takes the purchase price into account such that total cost can now be defined as:

$$TC = \frac{Q}{2} \times H + \frac{D}{Q} \times S + RD, where\ R\ is\ the\ per\ unit\ price$$

Process of Calculating EOQ (Discounts):

1. **Finding an initial feasible EOQ:** Calculate the EOQ for each price level starting with the lowest price level, until you find a feasible EOQ
2. **Refining your choice:** If the EOQ for the lowest price unit is feasible, you are done. If it is not, then compare the **Total Costs** for each price break larger than the feasible EOQ with the **Total Cost** of the feasible EOQ

Example:

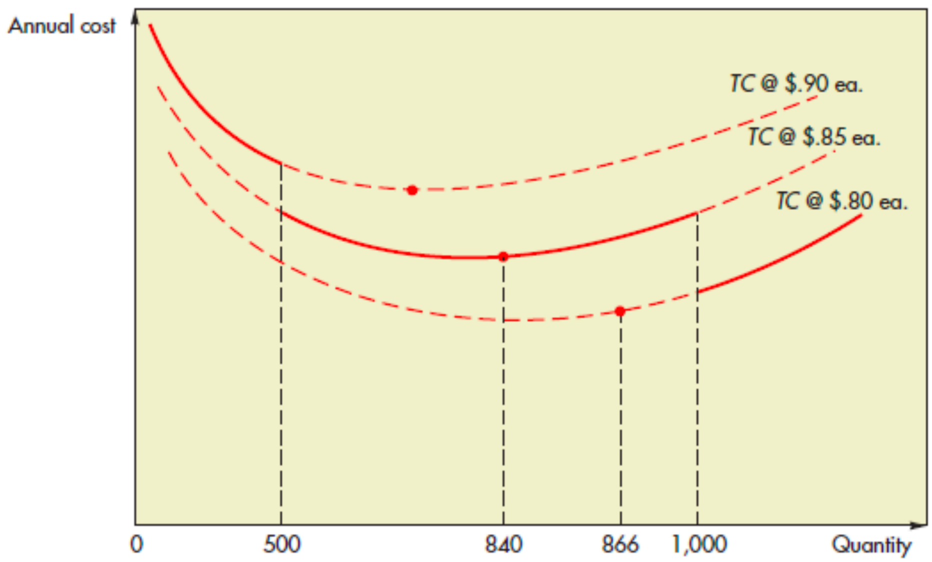
A factory uses 4,000 light bulbs per year. Light bulbs are priced as follows:

1 – 499	.90
500 – 999	.85
>1,000	.80

It costs $ 30 to prepare a purchase order, receive the goods and pay for them

The firm incurs a 40% interest rate charge to fund operations

a) Determine the optimal order size
b) Calculate the total annual costs



$$D = 4{,}000\ light\ bulbs\ per\ year, S = \$30, H = 0.40R, R = unit\ price$$

a) Find the EOQ for each price, starting with the lowest, until you locate a feasible EOQ:

$$EOQ_{0.80} = \sqrt{\frac{2DS}{H}} = \sqrt{\frac{2(4{,}000)(30)}{0.40(0.80)}} = 866\ light\ bulbs$$

Because an order size of 866 light bulbs is fewer than 1,000 units, 866 is not feasible for the unit price of $0.80 per light bulb. Next, try $0.85 per unit:

$$EOQ_{0.85} = \sqrt{\frac{2DS}{H}} = \sqrt{\frac{2(4{,}000)(30)}{0.40(0.85)}} = 840\ light\ bulbs$$

This EOQ is feasible; it falls in the $0.85 per light bulb quantity range (500 to 999).

b) Now calculate the total cost for 840 order size, and compare it to the total cost of the break quantity larger than 840, i.e., 1,000 units:

$$TC = \frac{Q}{2}H + \frac{D}{Q}S + RD$$

$$TC_{840} = \frac{840}{2}(0.34) + \frac{4{,}000}{840}(30) + 0.85(4{,}000) = \$3{,}686$$

$$TC_{1000} = \frac{1{,}000}{2}(0.32) + \frac{4{,}000}{1{,}000}(30) + 0.80(4{,}000) = \$3{,}480$$

Because $3,480 < $3,686, the minimum cost order quantity is 1,000 light bulbs.

6.3.4 EOQ with Planned Shortages

Assumptions:

- High costs of some goods may encourage suppliers to allow shortages (backorders) if the market is willing and demand can wait
- Backorders will incur shortage costs with these charges proportional to the amount of time that product is backordered

Variables:

Q: the quantity that you want to order (demand you want to fill)

Q_b: the quantity that you want to backorder (demand that you are willing to defer until the next order arrives)

Equations:

$$TC = annual\ ordering\ costs + annual\ holding\ costs + annual\ backorder\ costs$$

$$TC = \frac{D}{Q} \times S + \left[\frac{(Q - Q_b)^2}{2Q}\right] \times H + \frac{Q_b^2}{2Q} \times B$$

$$Q = \sqrt{\frac{2DS}{H} \times \frac{H + B}{B}}$$

$$Q_b = Q \times \frac{H}{H + B}$$

Example:

Annual demand for a particular model of a refrigerator at an appliance store is 50 units. The holding cost per unit per year is \$200. The back-order cost per unit per year is estimated to be \$500. Ordering cost from the manufacturer is \$10 per order. Determine the optimal order quantity and the back-order quantity per order cycle.

$$D = 50\ units\ per\ year$$

$$H = \$200\ per\ unit\ per\ year$$

$$B = \$500\ per\ unit\ per\ year$$

$$S = \$10\ per\ order$$

$$Q = \sqrt{\frac{2DS}{H} \times \frac{H + B}{B}} = \sqrt{\frac{2(50)(10)}{200} \times \frac{200 + 500}{500}} = 2.65, round\ to\ 3\ units$$

$$Q_b = Q \times \frac{H}{H + B} = 3 \times \frac{200}{200 + 500} = 0.86, round\ to\ 1$$

7 INVENTORY MANAGEMENT (II)

7.1 Fixed Order Quantity – Reorder Point Model

Reorder Point:

- Definition: The inventory level that triggers a replacement order.
- $ROP = d \times LT$ with demand d and lead time LT being expressed in similar units of time (day, week or month).
- If demand is not constant, then a case can be made for holding extra inventory to act as insurance against a shortage – **Safety Stock**.
    - ROP inventory is now equal to $(d \times LT) + Safety\ Stock$.

Safety Stocks and Service Levels:

- Lead Time Service Levels (probability that demand ≤ supply during the lead time):

$$Lead\ time\ service\ level = 1 - \frac{number\ short}{lead\ time\ demand}$$

- Annual Service Level (annual fill rate):

$$Annual\ service\ level = 1 - \frac{number\ short}{order\ cycle\ demand}$$

- Both of these service levels assume demand is normally distributed during a lead time:
    - $Safety\ stock = z \cdot \sigma_{dLT}$
    - If stockout risk $= 1 -$ lead time service level, → then lead time service level $=$ $1 -$ stockout risk
    - Then look up this probability on the Standard Normal Distribution Table to get z

7.1.1 ROP Using Lead Time Service Level

- When lead time demand data is known:

$$ROP = d \cdot LT + z \cdot \sigma_{dLT}$$

- When only demand is variable:

$$ROP = \overline{d} \cdot LT + z\sqrt{LT} \cdot \sigma_d$$

- When both demand and lead time are variable:

$$ROP = \overline{d} \cdot \overline{LT} + z\sqrt{\overline{LT}\sigma_d^2 + \overline{d}^2 \sigma_{LT}^2}$$

7.1.2 ROP Using Annual Service Level

- Step 1: Calculate the standardized expected number of units that you will be short during the order cycle $E(z)$ where:

$$E(z) = \frac{Q(1 - SL_{ANNUAL})}{\sigma_{dLT}}$$

$$SL_{ANNUAL} = \frac{\#\, orders\ filled}{\#\, orders\ taken} = fill\ rate$$

- Step 2: Convert $E(z)$ number to its "z" equivalent using Lead Time Service Table
- Step 3: Substitute this "z" value into the calculation of ROP where:

$$ROP = expected\ demand\ during\ order\ lead\ time + z \cdot \sigma_{dLT}$$

7.2 Fixed Order Interval – Order Up to Level Model

7.2.1 Definition

Definition: This model is used when orders are placed at fixed intervals with the amount of the order changed adjusted to bring inventory up to a pre-determined level.

Setting Up an Order: Determine how often you will order and then how much you will order.

7.2.2 Equations

Order Interval Notation:

- OI: order interval (fraction of a year)
- S: fixed order processing costs
- s: variable ordering costs (per SKU)
- n: number of SKUs purchased from the supplier
- R_j: unit cost per SKU_j
- i: annual holding cost rate
- D_j: annual demand of SKU_j

Step 1: Determining Order Interval

$$Optimal\ order\ interval = \sqrt{\frac{2(S + ns)}{i \sum D_j R_j}}$$

$$Total\ annual\ inventory\ costs = \frac{\sum (D_j \cdot OI) R_j}{2} \cdot i + (S + ns)\frac{1}{OI}$$

where $Q_j = D_j \cdot OI$

Step 2: Determining Order Up to Level

- Definition: An up to inventory level is the amount of good that should be sufficient to last until the next order arrives.
- The order quantity is the difference between the order up to level (I_{MAX}) and the quantity of the good still on hand at the time of order placement.

$$I_{MAX} = \overline{d}(OI + LT) + z \cdot \sigma_d \sqrt{OI + LT}$$
$$Q(order\ quantity) = I_{MAX} - inventory\ position$$

7.2.3 Examples

The manager of a hardware store has determined, from historical records, that demand for a given type and size of bagged cement during its lead time could be described by a Normal distribution that has a mean of 50 bags and a standard deviation of 5 bags. Answer these questions, assuming that the manager is willing to accept a stock-out risk of no more than 3 percent during a lead time:

a. What value of *z* is appropriate?
b. How many bags of safety stock should be held?
c. What reorder point should be used?

$Expected\ demand\ during\ a\ lead\ time = 50\ bags, \sigma_{dLT} = 5\ bags, Stockout\ risk = 3\%$

a. Service level of $1 - 0.03 = 0.97$, obtain value of $z = 1.88$ (Table 12-3 on Learn)
b. $Safety\ stock = z \cdot \sigma_{dLT} = 1.88(5) = 9.40\ bags$
c. $ROP = Expected\ demand + Safety\ stock = 50 + 9.40 = 59.40$ round to $59\ bags$

A restaurant uses an average of 50 jars of a special sauce each week. Weekly usage of sauce has a standard deviation of 3 jars. The manager is willing to accept no more than a 10 percent risk of stock-out during a lead time, which is 2 weeks. Assume the distribution of usage is Normal.

a. Which of the above formulas is appropriate for this situation? Why?
b. Determine the value of *z*.
c. Determine the ROP.

$$\overline{d} = 50\ jars\ per\ week, \sigma_d = 3\ jars\ per\ week, LT = 2\ weeks, stockout\ risk = 10\%$$
$$service\ level = 1 - stockout\ risk = 1 - 0.10 = 0.90$$

a. Because only demand is variable (has a standard deviation): $ROP = \overline{d} \cdot LT + z\sqrt{LT} \cdot \sigma_d$
b. Using a service level of 0.90, we obtain $z = 1.28$ from the Table 12-3.

c. $ROP = \bar{d} \cdot LT + z\sqrt{LT} \cdot \sigma_d = 50(2) + 1.28\sqrt{2}(3) = 105.43$ round to $105\ jars$

An inventory item has order quantity $Q = 250$ units, expected demand during a lead time = 50 units, and standard deviation of demand during a lead time $\sigma d_{LT} = 16$ units. Determine the ROP if the desired annual service level is (a) 0.997, and (*b*) 0.98.

a. $E(z) = \frac{Q(1-SL_{annual})}{\sigma_{dLT}} = \frac{250(1-0.997)}{16} = 0.047$

From Table 12-3, $E(z) = 0.047$ falls between $E(z) = 0.048$ with $z = 1.28$ and $E(z) = 0.044$ with $z = 1.32$. Therefore, using interpolation, $z = 1.29$. Finally:

$ROP = 50 + 1.29(16) = 70.64$ round to 71 units.

b. $E(z) = \frac{250(1-0.98)}{16} = 0.3125$

From Table 12-3, $E(z) = 0.3125$ falls between $E(z) = 0.324$ with $z = 0.16$ and $E(z) = 0.307$ with $z = 0.20$. Therefore, using interpolation, $z = 0.19$. Finally:

$ROP = 50 + 0.19(16) = 53.04$ round to 53 units.

Three parts are purchased from the same supplier. The basic cost of placing an order for one of the SKUs is \$1.50. The inclusion of each additional SKU costs \$.50 more. The annual holding cost rate is 24 percent of unit cost. The annual demand (in units) and unit prices are given below. Assume that the buying company works 250 days a year. Calculate the optimal order interval.

SKU	Demand/Year	Price/Unit
1	12,000	.50
2	8,000	.30
3	700	.10

$$S = \$1.50 - \$0.50 = \$1.00,\ s = \$0.50,\ i = 0.24$$

$$OI^* = \sqrt{\frac{2(1.00 + 3(0.50))}{0.24(12{,}000 \times 0.50 + 8{,}000 \times 0.30 + 700 \times 0.10)}} = 0.0496\ years = 12.4\ days$$

Round to 12 days.

Given the following information for a SKU, determine its order up to level and amount to order (i.e., order quantity).

$\bar{d} = 30$ units per day, Desired service level = 99 percent

$\sigma_d = 3$ units per day, Inventory position at reorder time = 71 units

LT = 2 days, OI = 7 days

$$z = 2.33 \text{ for 99 percent desired service level from Table 12-3}$$

$$I_{max} = \bar{d}(OI + LT) + z\sigma_d\sqrt{OI + LT} = 30(7 + 2) + 2.33(3)\sqrt{7 + 2} = 291 \; units$$

$$Amount \; to \; order = I_{max} - inventory \; position = 291 - 71 = 220 \; units$$

7.3 Single Period Model

7.3.1 Characteristics

- Goods typically cannot be held over to the next period, and when they can they incur significant price reductions
- Objective is to choose an order quantity that will minimize shortage and excess costs.
- Described by examining shortage costs and the costs of having excess goods.

7.3.2 Costs

Shortage Costs:

$$C_{SHORTAGE} = C_S = Revenue \; per \; unit - Cost \; per \; unit$$

Excess Costs:

$$C_{EXCESS} = C_E = Cost \; per \; unit - Salvage \; value$$

7.3.3 Continuous Stocking Levels

- The service level (SL) is the probability that demand will not be greater than the quantity of goods on hand:

$$SL = P(D \leq Q) = \frac{C_S}{C_E + C_S}$$

- **Uniform Demand** distributions will have an optimal order quantity that is equal to the sum of the minimum order quantity plus an amount that is equal to the product of the SL and the difference between minimum and maximum order quantity levels.

Normal Distribution of Demand:

- Optimal $Q = \mu + z\sigma$ where μ is the mean of demand and σ is the standard deviation of demand (both of which will be given).
- Solution process is to use C_S and C_E values to determine the service level and then use that service level to find the corresponding z-value and then apply the optimal equation.

7.3.4 Example: Continuous Stocking Levels

A cafeteria buys muffins daily. Demand is **approximately normal with a mean of 40 and standard deviation of 5 muffins per day**. The cafeteria pays \$0.20 per muffin and charges \$0.80 per muffin. Find the optimal stocking level.

$$\text{If service level is } 0.75\text{, then from Table 12-3, } z = 0.675$$

$$Optimal = 40 + 0.675(5) = 43\ muffins$$

A cafeteria buys muffins daily. Demand **varies uniformly between 30 and 50 muffins per day**. The cafeteria pays \$0.20 per muffin and charges \$0.80 per muffin. Unsold muffins are discarded at the end of the day. Find the service level.

$$C_E = Cost\ per\ unit - Salvage\ per\ unit = \$0.20 - \$0.00 = \$0.20\ per\ unit$$

$$C_s = Revenue\ per\ unit - Cost\ per\ unit = \$0.80 - \$0.20 = \$0.60\ per\ unit$$

$$SL = \frac{0.60}{0.20 + 0.60} = 0.75$$

$$Optimal = min + SL(max - min) = 30 + 0.75(50 - 30) = 45\ muffins$$

7.3.5 Discrete Stocking Levels

- In this case, the goal is to choose a **stocking level** that will **just** exceed demand.
- Service level is calculated as it was before with $SL = \frac{C_S}{C_E + C_S}$ where the results are compared to the cumulative probability levels.

7.3.6 Example: Discrete Stocking Levels

Historical records on the use of a spare part for an old press (shown in the following table) are used to estimate usage for the spare part in a similar but new press. Stock-out cost involves downtime expenses and special ordering costs. These average \$4,200 per unit short. The spare part costs \$1,200 each, and an unused part has \$400 salvage value. Determine the optimal stocking level for the spare part.

Number of Spares Used	Probability	Cumulative Probability
0	.20	.20
1	.40	.60
2	.30	.90
3	.10	1.00
4 or more	.00	
	1.00	

$C_S = \$4{,}200$, $C_E = \$1{,}200 - \$400 = \$800$, $SL = \frac{C_S}{C_E + C_S} = \frac{4{,}200}{4{,}200+800} = 0.84$

The cumulative probability column indicates the fraction of time that demand was equal to or less than some amount. For example, demand ≤ one spare occurred 60 percent of the time, or demand ≤ two spares occurred 90 percent of the time. Go down the table until cumulative probabilities just exceed service level of 84 percent. This is 0.90 which relates to two spares.

8 AGGREGATE OPERATIONS PLANNING (AOP)

8.1 Basic Concepts, Practical Options, Basic Strategies, AOP Techniques

8.1.1 Review of the Basic Concepts

Types of Decisions:

- Long Term: Deal with product matrix, location, size of facilities, product flow (layout).
- Medium Term: Employment levels, output capacity, inventory levels and capacities.
- Short Term: Scheduling of production shifts and labour needs, manufacturing schedules.

Theory and Goals Underlying AOP:

- Products are treated (aggregated) as a single grouping of "like" products.
- Aggregate planning links sales forecasts to production (capacity) planning.
- Goal: Satisfy anticipated consumer demand at lowest possible cost through increased efficiency (inventory appropriate, adequate labour, level of finished goods stocks).

Mechanics of AOP:

- Best described as the activity whereby sales and operations staff undertake monthly planning for the production of all products of the same family for the next 12 months.
- Goal is to develop a production plan that realistically assesses an organization's capacity to meet projected demand.
- Particularly useful in firms that experience seasonal demand spikes.

8.1.2 Practical Options to Deal with Demand and Capacity Fluctuations

Demand Influencing Options:

- Price (re-issuance of price lists, differential pricing to shift demand from peak periods).
- Promotion (temporary price discounts, advertising, bonus offerings, BOGO programs).
- Early orders.
- Backorders (advance orders placed in one period for delivery in the next period).
- Exporting.
- Development of complementary products (to fill out production schedules, fill in gaps).

Capacity Options:

- Determining permanent workforce level (hiring and firing of workers).
- Use of overtime (incentive for some workers) and idle time strategies (inefficient labour).

- Use of temporary workers (flexibility, suited to lower skilled jobs, costs less).
- Stockpiling inventories of finished goods (stock build-up preceding high demand).
- Subcontracting

8.1.3 Basic Strategies Available to Operations Planners

Option 1: Level Output – Workforce Strategy

- Maintain steady workforce and hopefully a constant flow of output.
- Uses inventory buildup (ensures employment during periods of slow demand, provides stocks of product to meet demand during periods of higher demand).

Option 2: Chase Demand Strategy

- Change output to match demand for period at hand.
- Planned output = forecast demand.
- Permanent workforce numbers dictated by low period demand.
- Reduced inventory levels.

Option 3: Mixed Strategy

8.1.4 AOP Techniques

Techniques for AOP:

1. Determine demand forecast for each period.
2. Determine capacities and production rates.
3. Identify pertinent policies.
4. Determine unit costs.
5. Develop alternative plans and costs.
6. Select the best plan that satisfies objectives.

General Assumptions About the Actual Model:

- There is only one aggregate group.
- Production is measured in the number of units.
- No allowance is made for the number of workdays in a month.
- No allowance for maintaining safety stock.
- No economies of scale.

Calculable AOP Relationships:

1. **Ending Inventory/Backorder** (in any period):

$$X = Begin\ Inv_i + (Production - Forcast)_{\boldsymbol{i}} - Backorder_{i-1}$$

If $X \geq 0$, then:

$$End\ Inv = X, Backorders = 0$$

If $X < 0$, then:

$$End\ Inv = 0, Backorders = X$$

2. **Average Inventory** (in any period):

$$Avg. Inv = \frac{Begin\ Inv + End\ Inv}{2}$$

3. **Beginning and Ending**:

$$Begin\ Inv_i = End\ Inv_{i-1}$$

8.2 AOP Relationships, Trial and Error Procedure, Trade-Off Analysis, ASP

8.2.1 AOP Relationships

Example 1:

Planners for a company that makes garden tractors are about to prepare an aggregate production plan that will cover the next six months. They have assembled the following information for an aggregate unit:

Month	1	2	3	4	5	6	Total
Forecast demand	2,000	2,000	3,000	4,000	5,000	2,000	18,000

Permanent workforce = 140

Production per month = 2,800 units or 20 per worker

Initial inventory = 1,000 units

Desired ending inventory at the end of 6th month = 1,000 units

Costs

- Output (labour)
  - Regular time permanent = $100 per tractor
  - Overtime = $150 per tractor
  - Temporary = $100 per tractor
- Hire cost = $500 per temporary worker or $25 (= $500/20 units) per unit (charged to the first month of employment); we have assumed that temp workers have the same productivity as permanent workers.
- Inventory = $10 per tractor per month (charged on the average inventory level)
- Backorder = $150 per tractor per month

They now want to evaluate a production plan that calls for level output/workforce (with the current level of permanent workforce, 140), using inventory to absorb the uneven forecast demand but allowing some backorder. They start with 1,000 units of inventory on hand in the first month and wish to end with the same amount. Prepare an aggregate production plan and determine its total cost.

SOLUTION

The total regular-time output of permanent workers per month is 2,800 units. The filled worksheet for this level output/workforce strategy is shown below. The computations are explained after the worksheet.

Month	1	2	3	4	5	6	Total
Forecast Demand	2,000	2,000	3,000	4,000	5,000	2,000	18,000
Output							
Regular permanent	2,800	2,800	2,800	2,800	2,800	2,800	16,800
Temporary	–	–	–	–	–	–	
Overtime	–	–	–	–	–	–	
Output – Forecast	800	800	−200	−1,200	−2,200	800	−1,200
Inventory							
Beginning	1,000	1,800	2,600	2,400	1,200	0	
Ending	1,800	2,600	2,400	1,200	0	0	
Average	1,400	2,200	2,500	1,800	600	0	8,500
Backorder	0	0	0	0	1,000	200	1,200
Costs							
Output (labour)							
Regular perm (at $100/unit)	$280,000	280,000	280,000	280,000	280,000	280,000	$1,680,000
Temporary (at $100/unit)	–	–	–	–	–	–	
Overtime (at $150/unit)	–	–	–	–	–	–	
Hire temporary (at $25/unit)	–	–	–	–	–	–	
Inventory (at $10/unit/month)	$14,000	22,000	25,000	18,000	6,000	0	$85,000
Backorder (at $150/unit/month)	$0	0	0	0	150,000	30,000	$180,000
Total cost	$294,000	302,000	305,000	298,000	436,000	310,000	$1,945,000

Starting with month 1, $(Output - Forecast)_1 = 2{,}800 - 2{,}000 = 800$

$$X = Begin\ Inv_1 + (Production - Forcast)_{\mathbf{1}} - Backorder_0 = 1{,}000 + 800 - 0 = 1{,}800$$

Therefore, $End\ Inv_1 = 1{,}800$ and $Backorder_1 = 0$. Also,

$$Avg.\ Inv_1 = \frac{Begin\ Inv_1 + End\ Inv_1}{2} = \frac{1{,}000 + 1{,}800}{2} = 1{,}400$$

Then, $Begin\ Inv_2 = End\ Inv_1 = 1{,}800$. Continue with the same formulas, but note that in month 5,

$$X = 1{,}200 + (-2{,}200) - 0 = -1{,}000$$

Therefore, $End\ Inv_5 = 0$ and $Backorder_5 = -(-1{,}000) = 1{,}000$. Also, in month 6,

$$X = 0 + 800 - 1{,}000 = -200$$

Therefore, $End\ Inv_6 = 0$ and $Backorder_6 = 200$.

The costs were computed as follows. Regular permanent cost in each month equals 2,800 units × $100 per unit, or $280,000. Inventory holding cost equals average inventory × $10 per unit. Backorder cost is $150 per unit times the number of backorders. The total cost for this plan (either sum the row totals of costs or sum the column totals of costs) is $1,945,000.

Example 2:

After reviewing the plan developed in the preceding example, planners noticed the large number of backorders in month 5 (1,000 units) and month 6 (200). Furthermore, the desired month-6 ending inventory of 1,000 units is not realized. Therefore, output has to increase by a total of 1,200 units during the planning horizon (the difference between total Forecast and total Regular permanent output, leaving the same amount of ending inventory as the initial inventory). The planners decided to investigate the use of overtime to make up for this shortage. It is the policy of the company that the maximum amount of overtime output per month be 400 units. Develop an aggregate production plan in this case and compare it to the previous plan.

SOLUTION

The 1,200 units to be produced during overtime must be scheduled on and before month 5 (when shortage or backorder starts to occur). Scheduling it earlier would increase inventory holding costs ($10/unit/month); scheduling it later would incur backorder cost ($150/unit/month), which is larger. That is why the maximum permitted overtime production should be used in months 3 to 5. The completed worksheet is given below.

Month	1	2	3	4	5	6	Total
Forecast	2,000	2,000	3,000	4,000	5,000	2,000	18,000
Output							
Regular permanent	2,800	2,800	2,800	2,800	2,800	2,800	16,800
Temporary	—	—	—	—	—	—	
Overtime	—	—	400	400	400	—	1,200
Output – Forecast	800	800	200	−800	−1,800	800	0
Inventory							
Beginning	1,000	1,800	2,600	2,800	2,000	200	
Ending	1,800	2,600	2,800	2,000	200	1,000	
Average	1,400	2,200	2,700	2,400	1,100	600	10,400
Backorder	0	0	0	0	0	0	0
Costs							
Output (labour)							
Regular perm (at $100/unit)	$280,000	280,000	280,000	280,000	280,000	280,000	$1,680,000
Temporary (at $100/unit)	0	0	0	0	0	0	0
Overtime (at $150/unit)	—	—	60,000	60,000	60,000	—	180,000
Hire temporary (at $25/unit)	—	—	—	—	—	—	
Inventory (at $10/unit/month)	14,000	22,000	27,000	24,000	11,000	6,000	$104,000
Backorder (at $150/unit/month)	$0	0	0	0	0	0	0
Total cost	$294,000	302,000	367,000	364,000	351,000	286,000	$1,964,000

Note that, even though plan 2 has a larger total cost than plan 1, it produces 1,200 more units and leaves 1,000 units at the end of month 6.

Alternatively, the company can use temporary workers to meet the 1,200 units short. The unit cost of temporary-worker production ($100) is lower than unit cost of overtime production ($150), but there is a per unit hire cost of $25 for units produced during the first month of employment. Overall, using temporary workers is less costly than using overtime.

Example 3:

A third option is to use temporary workers during months of high demand. Suppose that temporary workers will be working during a second shift and enough of them are available. Develop an aggregate production plan in this case.

SOLUTION

Dividing the number of units needed (1,200) by the output rate of 20 per temporary worker, you find that 60 temporary worker-months are needed (e.g., 60 temporary workers for 1 month each, or 30 temporary workers for two months each, or 20 temporary workers for three months each, etc.).

Therefore, the planners tried each of the alternatives, i.e., hiring 60 temporary workers in month 5 on a one-month contract, or hiring 30 temporary workers in month 4 on a two-month contract, or hiring 20 temporary workers in month 3 on a three-month contract, and so on. The plan with the lowest total cost, including inventory carrying cost, hires temporary workers in month 4 on a two-month contract. Later, we will describe a trade-off analysis which can assist us in determining the cheapest alternative without actually completing the worksheet for each alternative. The completed worksheet for hiring 30 temporary workers in month 4 on a two-month contract is given below. Note that the hiring cost applies to only the first month of employment.

Month	1	2	3	4	5	6	Total
Forecast	2,000	2,000	3,000	4,000	5,000	2,000	18,000
Output							
Regular permanent	2,800	2,800	2,800	2,800	2,800	2,800	16,800
Temporary				600	600		1,200
Overtime	—	—	—	—	—	—	
Output Forecast	800	800	−200	−600	−1,600	800	0
Inventory							
Beginning	1,000	1,800	2,600	2,400	1,800	200	
Ending	1,800	2,600	2,400	1,800	200	1,000	
Average	1,400	2,200	2,500	2,100	1,000	600	9,800
Backorder	0	0	0	0	0	0	0
Costs							
Output (labour)							
Regular perm (at $100/unit)	$280,000	280,000	280,000	280,000	280,000	280,000	$1,680,000
Temporary (at $100/unit)				60,000	60,000		$120,000
Overtime (at $150/unit)	—	—	—	—	—	—	
Hire temporary (at $25/unit)	$0	0	0	15,000	0	0	$15,000
Inventory (at $10/unit/month)	$14,000	22,000	25,000	21,000	10,000	6,000	$98,000
Backorder (at $150/unit/month)	$0	0	0	0	0	0	0
Total cost	$294,000	302,000	305,000	376,000	350,000	286,000	$1,913,000

Overall, the total cost for this plan ($1,913,000) seems to be the lowest possible, i.e., this plan seems to be optimal.

8.2.2 Trial and Error Procedure

Determine output for regular labour → determine total short units and periods → determine cheapest way to meet units short (use trade-off analysis to compare alternatives).

8.2.3 Trade-Off Analysis

- Compare unit costs of labour, inventory, and backorders.

- Without having to recalculate the total plan cost.

Example:

A food company makes puddings in a plant. It sells the puddings in cases (a case contains 48 pudding cups). The plant has 15 parallel production lines. The regular operating hours are 8 hours a day, 5 days a week, 13 weeks a quarter. Each line is automated but needs 6 workers to operate it and can produce 200 units of output (each unit = 1,000 cases) per quarter. Currently, only 11 production lines are used, for a total quarterly output of 2,200 units. The sales department has forecasted total demand for all flavours of puddings for the next five quarters as follows: 2,000, 2,200, 2,500, 2,700, and 2,200 units, respectively. Currently, there are no puddings, other than some safety stocks, in the warehouse. The company can increase production by hiring groups of six workers at a time, i.e., by opening one to four additional production lines. Hiring one worker costs approximately $2,000. Each worker is paid an average of $19.23 per hour. Overtime costs 1.5 times regular-time wage, and is limited to 20 percent of regular-time production in any quarter. Holding inventory of a unit for a quarter will cost $50 (charged on the average level of inventory in the quarter). Backorder per unit per quarter is estimated to cost $200.

a. Determine all the relevant unit costs.

b. If the current number of workers is kept for the next five quarters, how many units will the company be short of at the end of Quarter 5?

c. Meet the forecast demands at minimum cost by

   i. Adding another production line.

   ii. Adding any number of production lines and/or using overtime.

You may use trade-off analysis to limit the number of plans considered.

a. Labour cost per unit during regular time

$= \text{Labour cost of one line for one quarter} \div \text{production of the line in the quarter}$

$= \text{\# of workers for the line} \times \text{cost per worker per quarter} \div 200$

$= 6 \times \text{wage per hour} \times \text{hours per quarter} \div 200$

$= 6 \times \$19.23 \times \text{hours per day} \times \text{days per week} \times \text{weeks per quarter} \div 200$

$= 6 \times \$19.23 \times 8 \times 5 \times 13 \div 200 = 299.99$ round to $\$300$

Labour cost per unit during overtime

$= 1.5 \times \text{regular time cost}$

$= 1.5 \times \$300 = \$450$

Hiring cost per unit (charged to the first quarter employed)

$= \text{Hiring cost per worker} \times \text{\# workers per line} \div \text{production per line per quarter}$

$= \$2{,}000 \times 6 \div 200 = \$60$

b. Number short at the end of Quarter 5

$= \text{total demand forecasts} - 5 \times \text{regular production per quarter}$

$= 11{,}600 - 5(2{,}200) = 600$ units

c. i. Adding another production line.

The 12th production line should work three quarters because the number short is 600 units (from part *b*) and the capacity of a line is 200 units per quarter. Note that the quarters with higher-than-average demand are Q3 and Q4. Therefore, the 12th production line should work during Q3 and Q4. It is evident that the 12th line should also work Q2 because holding a unit in inventory for two quarters (from Q2 to Q4) costs only 2 × \$50 = \$100 < \$200 = cost of backordering a unit from Q5 back to Q4. The completed worksheet is displayed below. Note that the output of the 12th production line is shown in the "Temporary" row.

Aggregate plan using an additional production line (Q2–Q4)

Quarter	1	2	3	4	5	Total
Forecast	2,000	2,200	2,500	2,700	2,200	11,600
Output						
Permanent	2,200	2,200	2,200	2,200	2,200	11,000
Temporary		200	200	200		600
Overtime						
Output—Forecast	200	200	−100	−300	0	0
Inventory						
Beginning	0	200	400	300	0	
Ending	200	400	300	0	0	
Average	100	300	350	150	0	900
Backorder	0	0	0	0	0	0
Costs						
Permanent @ \$300	660,000	660,000	660,000	660,000	660,000	3,300,000
Temporary @ \$300	0	60,000	60,000	60,000	0	180,000
Overtime @ \$450	0	0	0	0	0	0
Hire temporary/unit @ \$60	0	12,000	0	0	0	12,000
Inventory @ \$50	5,000	15,000	17,500	7,500	0	45,000
Backorder @ \$200	0	0	0	0	0	0
Total	665,000	747,000	737,500	727,500	666,000	\$3,537,000

ii. Adding any number of production lines and/or using overtime.

First we will show that using temporary workers is cheaper than using overtime:

> Cost of a unit made by a temporary worker hired and laid off after one quarter = \$300 + \$60 = \$360 < \$450 = cost of a unit produced by a permanent worker during overtime.

Now, one way to reduce the total cost of the plan determined in part c_i above is to use two extra production lines during Q4. This will produce 400 units. To produce the remaining 200 units needed, it is clear that we need to start one of these two lines in Q3. As you can see in the worksheet below, the total cost in this case is lower than the plan in c_i.

Aggregate plan using two additional production lines (Q4 and Q3–Q4)

Quarter	1	2	3	4	5	Total
Forecast	2,000	2,200	2,500	2,700	2,200	11,600
Output						
Permanent	2,200	2,200	2,200	2,200	2,200	11,000
Temporary			200	400		600
Overtime						0
Output − Forecast	200	0	−100	−100	0	0
Inventory						
Beginning	0	200	200	100	0	
Ending	200	200	100	0	0	
Average	100	200	150	50	0	500
Backorder	0	0	0	0	0	0
Costs						
Permanent @ $300	660,000	660,000	660,000	660,000	660,000	3,300,000
Temporary @ $300	0	0	60,000	120,000	0	180,000
Overtime @ $450	0	0	0	0	0	0
Hire temporary/unit @ $60	0	0	12,000	12,000	0	24,000
Inventory @ $50	5,000	10,000	7,500	2,500	0	25000
Backorder @ $200	0	0	0	0	0	0
Total	665,000	670,000	739,500	794,500	672,000	$3,529,000

Note that producing 400 units in Q3 and 200 units in Q4 by extra lines will increase the total cost because 200 more units have to be carried in inventory from Q3 to Q4. Also, producing 600 units in Q3 and nothing in Q4 by the extra lines will increase the total cost because 400 more units have to be carried in inventory from Q3 to Q4, in addition to $60 extra hiring cost per unit. Finally, producing nothing in Q3 and 600 units in Q4 by the extra lines will increase the total cost because 100 units have to be backordered from Q4 to Q3, in addition to $60 extra hiring cost per unit. Therefore, the above plan (in the worksheet) is optimal.

8.2.4 Aggregate Services Planning (ASP)

ASP vs. AOP:

1. Services cannot be inventoried (**Chase Demand** strategy).
2. Service sector organizations must be measured in terms of either time or some standard measure of labour (i.e., fulltime equivalent) units.

Yield Management:

- A variable pricing strategy used to maximize revenue.
- Based on the premise that capacity cannot be inventoried.
- Prices are set according to availability.
- It's all about supply and demand.
- Commonly used by airlines and all-inclusive resorts.

Example:

The director of nursing of a hospital needs to plan the nursing levels for each quarter of next year. She has forecasted the average number of patients per day in each of the hospital wards throughout each quarter of next year. Then she multiplied these numbers by 90 days a quarter × 24 hours a day and divided the result by the number of patients to be assigned to each nurse in each ward (e.g., three patients per nurse in intensive care, etc.) to obtain the aggregate forecast for hours of nursing required in each quarter. Finally, these are converted into number of full-time equivalent (FTE) nurses needed each quarter by dividing them by 480 hours per quarter, and rounding them to the nearest integer. These numbers are displayed as Forecast (FTE) in the following table. There are currently 140 permanent nurses, each working 480 hours a quarter, and being paid an average of $14 an hour. Overtime is allowed up to 50 percent of regular permanent FTEs and is compensated at 1.5 times the regular wage rate. Temporary nurses are available but hospital policy dictates that the maximum number of temporary nurses be at most 20 percent of permanent nurses. Temporary nurses are paid an average of $17 per hour, but no overtime is permitted. The hiring cost is $480 per temporary nurse. Being a service, no inventory or shortage (backorder) is permitted.

a. Determine all the relevant costs per FTE and fill them in the table below.

b. Suppose one temporary nurse is hired for one quarter. Would this be cheaper than using a permanent nurse during overtime?

c. Determine the minimum total cost (feasible) aggregate service plan, and fill the whole table.

Given:

Aggregate forecast for FTE nursing:

$Q_1 = 167, Q_2 = 150, Q_3 = 158, Q_4 = 165.$

140 permanent nurses each working 480 $hours/Q$ @ $\$14/hour$.

Overtime cannot exceed 50% of regular permanent FTEs ($FTE = 480\ hours$) and is paid $\$21/hour$.

Temporary nursing staff must not exceed 20% of permanent staff @ $\$17/hour$ with no allowance for overtime.

$Hiring\ cost = \$480$.

SOLUTION

Note: The unit of product here is FTE of nursing service.

a. Regular permanent wages = $14/hour × 480 = $6,720 per quarter; temporary nurse wages = $17/hour × 480 = $8,160 per quarter; overtime wages = 1.5 × 6,720 = $10,080 per FTE per quarter. Hiring cost per temporary FTE (charged to the first quarter hired) is $480.

b. Cost per FTE of temporary nurse kept for a quarter = hire cost per nurse + wages = $480 + $8,160 = $8,640 < $10,080 = cost per FTE of overtime. Yes, using temporary nurses is cheaper than using permanent nurses during overtime.

c. Given the result in part *b*, use up to the maximum number of temporary nurses in each quarter so that total output (FTE) equals forecast (recall we cannot have inventory or shortage). Maximum number of temporary nurses = 0.20 × 140 = 28 FTE in any quarter. If there is any more need for nurses, we have to use permanent nurses during overtime. In this case, no overtime is necessary. The following aggregate service plan has minimum total cost and is feasible. Note that the hiring cost applies only when the number of temporary nurses in a quarter is larger than in the previous quarter, and it equals $480 × the difference.

Quarter	1	2	3	4	Total
Forecast (FTE)	167	150	158	165	
Output (FTE)					
Reg. perm.	140	140	140	140	
Temporary	27	10	18	25	
Overtime					
Costs per FTE					
Reg. perm. @ $6,720	940,800	940,800	940,800	940,800	3,763,200
Temporary @ $8,160	220,320	81,600	146,880	204,000	652,800
Overtime @ $10,080	0	0	0	0	0
Hire temporary @ $480	12,960	0	3,840	3,360	20,160
					$4,436,160

Because service capacity is perishable (e.g., an empty seat on an airplane can't be saved for use on another flight), aggregate planners need to take this fact into account when deciding how to match supply and demand. **Yield management** is an approach that seeks to maximize revenue by using a strategy of variable pricing; prices are set relative to capacity availability. Thus, during periods of low demand, price discounts are offered to attract a wider population. Conversely, during peak periods, higher prices are posted to take advantage of limited supply. Users of yield management include airlines, hotels, and resorts.

9 MATERIAL REQUIREMENTS PLANNING (MRP)

9.1 Concept of MRP, Key Requirements, Material Resource Plan

9.1.1 Concept of MRP

MRP:

- Simply a planning procedure for the purchase and production of demand-dependent components.
- Contrasts sharply with the fixed order quantity, fixed order interval and single period models described previously.
- Determine the plans for purchasing and production of dependent-demand components.

Process:

- Convert a production plan (MPS) for a finished product into the requirement needs for dependent-demand goods using a BOM.
- <u>Work backwards from the start-of-production date contained in the MPS</u>, taking into account the required lead times for components goods, to plan for the purchase and receipt of the goods needed.
- Objectives: Have inventory on hand when it is required in sufficient quantities as are needed and maintain and control low inventories of demand-dependent goods.

9.1.2 Key Requirements

1. **BOM** that identifies the dependent parts needs for one unit of finished good.
2. **Master Production Schedule** (MPS) to determine how much will be made and when it will be made.
3. A list of any **existing inventory** of each good on the BOM.
4. Estimated **lead time requirements** for individual components (from suppliers).
5. A list of any **existing open orders** for any of the components needed to avoid duplication.

9.1.3 Material Resource Plan

Cumulative Lead Times:

- This is nothing more than the sum of all of the lead times associated with the purchase (and acquisition) of goods and the process lead times required in an MPS.

- MPS ≥ Cumulative sum of lead times necessary to produce the finished good.

Planning Horizon of MPS:

- Separated into time buckets.
- Planning horizon > Cumulative (stacked) lead time (for all phases of process).

Order Planning:

- **Planned-Order Receipt:** Quantity of an order received at the beginning of a period.
- **Planned-Order Release:** Quantity planned to be released (purchased) at the beginning of a period. Planned-Order Release = Planned-Order Receipt adjusted for lead time.

Net Requirements Calculation:

Net Requirements = Gross Requirements – Projected Beginning Inventory – Scheduled Receipts

Lot-for-Lot vs. Lot-Size Ordering:

- **Lot-for-Lot Ordering:** Determine orders based on requirements.
- **Lot-Size Ordering:** Planned receipts may exceed net requirements.

Example:

A company that produces wood shutters has received two orders for a particular model of wood shutters: 100 units are due for delivery at the start of week 4 and 150 units are due for delivery at the start of week 8. Each shutter consists of two frames and four slatted wood sections. The wood sections are purchased, and the purchase lead time is one week. The frames are also purchased, and the purchase lead time is two weeks. Assembly of the shutters requires one week for lot sizes of 100 to 200 shutters. There will be a previously-arranged scheduled receipt of 70 wood sections from the vendor at the beginning of week 1. Currently, there is no on-hand inventory. Determine the size and timing of planned-order releases necessary to meet delivery requirements under each of these conditions:

Lot-for-lot ordering (i.e., order sizes are equal to net requirements).

Lot-size ordering with a minimum lot size of 320 units for frames and multiples of 70 units for wood sections.

Given:

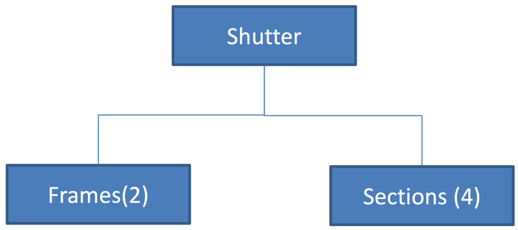
- Firm makes window shutters.
- Orders taken for 100 shutters in week 4 and 150 shutters in week 8.
- Each shutter has 2 frames and 4 wood sections.
- Wood section $LT = 1\ week$.
- Frame $LT = 2\ weeks$.
- Assembly time $= 1\ week$ for lots of $100 - 200$.
- Scheduled receipt of 70 wood sections at the beginning of week 1.
- No on-hand inventory.

a) Determine the size and timing of planned-order releases with lot-for-lot ordering.

b) Determine the size and timing of planned-order releases with lot-size ordering with minimum lot size of 320 units for frames and multiples of 70 units for wood sections.

a) Lot-for-lot ordering.

Product structure tree:



MRP table:

Production schedule for shutters:	Week number	Beg. Inv.	1	2	3	4	5	6	7	8
	Quantity					100				150
Shutters: Assembly LT = 1 week	Gross requirements					100				150
	Scheduled receipts									
	Projected on-hand									
	Net requirements					100				150
	Planned-order receipts					100				150
	Planned-order releases				100				150	
					times 2				times 2	
Frames: Purchase LT = 2 weeks	Gross requirements				200				300	
	Scheduled receipts									
	Projected on-hand									
	Net requirements				200				300	
	Planned-order receipts				200				300	
	Planned-order releases		200				300			
					times 4				times 4	
Wood sections: Purchase LT = 1 week	Gross requirements				400				600	
	Scheduled receipts		70							
	Projected on-hand		70	70	70				0	
	Net requirements				330				600	
	Planned-order receipts				330				600	
	Planned-order releases			330				600		

b) Lot-size ordering with lot size of 320 for frames and multiples of 70 for wood sections.

Production schedule for shutters:

Week number	Beg. Inv.	1	2	3	4	5	6	7	8
Quantity					100				150

Shutters assembly: LT = 1 week; Lot size = lot-for-lot	Gross requirements					100				150
	Scheduled receipts									
	Projected on-hand									
	Net requirements					100				150
	Planned-order receipts					100				150
	Planned-order releases				100				150	

times 2   times 2

Frames purchase: LT = 2 weeks; Lot size = minimum of 320	Gross requirements				200				300	
	Scheduled receipts									
	Projected on-hand					120	120	120	120	140
	Net requirements				200				180	
	Planned-order receipts				320				320	
	Planned-order releases		320				320			

times 4   times 4

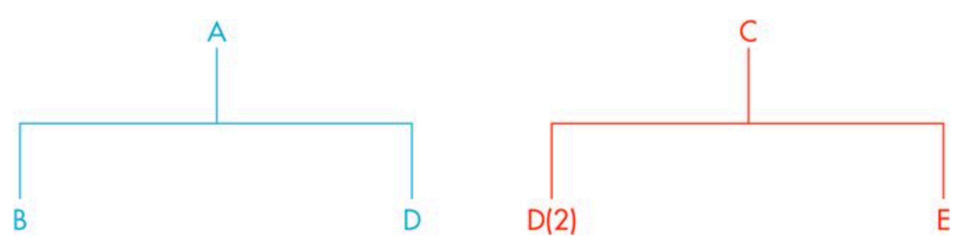
Wood sections purchase: LT = 1 week; Lot size = multiples of 70	Gross requirements				400				600	
	Scheduled receipts		70							
	Projected on-hand		70	70	70	20	20	20	20	50
	Net requirements				330				580	
	Planned-order receipts				350				630	
	Planned-order releases			350				630		

MRP Table for Component D:

Consider the two product structure trees shown below:

- Both A and C have D as a component.
- Demand for A is 80 units at the start of week 4.
- Demand for C is 50 units at the start of week 5.
- There is a beginning inventory of 110 units of D on hand.
- All lead times are 1 week.

Determine the size and timing of planned-order releases with lot-to-lot ordering:



MRP table:

Production schedule							
Week number		1	2	3	4	5	6
Quantity (A, C)					80	50	

A Assembly LT = 1	Beg. Inv.	1	2	3	4	5	6
Gross requirements					80		
Scheduled receipts							
Projected on-hand							
Net requirements					80		
Planned-order receipts					80		
Planned-order releases				80			

times 1

C Assembly LT = 1	Beg. Inv.	1	2	3	4	5	6
Gross requirements						50	
Scheduled receipts							
Projected on-hand							
Net requirements						50	
Planned-order receipts						50	
Planned-order releases					50		

times 2

D Purchase LT = 1	Beg. Inv.	1	2	3	4	5	6
Gross requirements				80	100		
Scheduled receipts							
Projected on-hand	110	110	110	110	30		
Net requirements					70		
Planned-order receipts					70		
Planned-order releases				70			

9.2 Review of MRP, Part Period Method, Capacity Requirements Planning

9.2.1 Review of MRP

Definitions:

- **Pegging:** Process of identifying the end product(s) manufactured from a specific part.
- **Non-Static Nature of MRP:** Based on the premise that MRPs are constantly changing to account for such things as short shipments in incoming parts, changes to finished goods orders, the need to rework defective output, etc.
- **Regenerative MRPs:** Synonymous with periodic revision where accumulated changes to materials requirements are updated in a batch-type format.
- **Net-Change MRPs:** Constantly being revised to address ongoing changes.
- **System Nervousness:** Even small changes to an item at the top of the BOM Tree can have large effects on the parts down the tree.

- **Backflushing:** This is nothing more than a method to check usage and to compare what has been estimated to have been used against what is left on hand.

Primary and Secondary MRP Reports:

- **Primary (Active) Reports:** Immediate order releases, planned order releases indicate the amount and timing of future orders, reports that detail changes to ongoing MRPs.
- **Secondary (Analysis) Reports:** Performance control reports that evaluate how well the MRP is working in terms of missed orders, demand history reports that are useful in forecasting future dependent demand requirements.

Safety Stocks, Appropriate Lot Sizing and Ordering Methods:

- **Safety Stocks:** Theoretically items with dependent demand should not require safety stock, but practically, bottleneck processes or ones with for example varying scrap rates can cause shortage.
- **Lot Sizing:** Minimize holding and ordering (or setup) costs, must take into account the nature of the underlying demand.

9.2.2 Part Period Method (PPM)

Definition:

- PPM attempts to balance holding and ordering costs.
- Refers to holding a part or parts over a number of periods.
- EPP (Economic Part Period) is calculated as:

$$EPP = \frac{Ordering\ (or\ setup)\ costs}{Holding\ cost\ per\ period}$$

- Solution method: various order sizes corresponding to various cumulative demands are examined and each one's number of part periods is determined. The one that comes closest to the EPP is the one chosen.

Example:

Given:

Period								
	1	2	3	4	5	6	7	8
Demand	60	40	20	2	30	-	70	50

Cumulative Demand	60	100	120	122	152	152	222	272

Setup Costs = $80

Holding Costs = $0.95 per unit per period

Question: Determine production run sizes.

Solution Process:

1) Calculate EPP.
2) Try cumulative demand quantities until part periods approximately match the EPP.
3) Repeat process for remaining periods.

SOLUTION

1. First calculate the EPP: EPP = $80/$0.95 = 84.21, which rounds to 84 part periods. This is the target.

2. Next, try the cumulative lot sizes, beginning with 60, until the part periods approximate the EPP. The calculations of part periods on the next page indicate that 122 units should be ordered in period 1 to cover the demand for the first 4 periods. Repeat this process starting at period 5, which results in 100 units to be ordered in period 5 to cover periods 5 to 7. The next lot will be ordered in period 8, but there is insufficient information now to determine its size.

Period When Order Is Placed	Lot Size	Extra Inventory Carried	×	Periods Carried	=	Part Periods	Cumulative Part Periods
1	60	0		0		0	0
	100	40		1		40	40
	120	20		2		40	80
	122	2		3		6	86*
5	30	0		0		0	0
	100	70		2		140	140**
8	50	0		0		0	0

*Closer to 84 (than 80)
**Closer to 84 (than 0).
d

The part-period method worked well for the first lot size because the cumulative number of part periods is close to the EPP, but the effect of lumpy demand is apparent for the second lot size of 100 (140 part periods is not very close to 84 part periods).

9.2.3 Capacity Requirements Planning (CRP)

Definition:

- Process of determining short-range capacity requirements.
- Can convert quantity requirements into time requirements:

$$quantity\ requirements \times standard\ time\ per\ unit + setup\ time\ per\ run$$

- Ex. scheduled production $= 10\ units$, standard time $= 2\ hrs/unit$, setup time $= 8\ hrs$:

$$10\ units \times 2\ hrs/unit + 8\ hrs = 28\ hrs\ (mftg\ lead\ time\ for\ 10\ units)$$

Example:

Problem 4

Capacity requirements planning. Given the following planned-order releases and the production standard times for a component produced at a work centre, determine the labour hour requirements of the component each week. Are the planned-order releases feasible if capacity is 120 labour hours per week at the work centre?

Planned-order Releases:

Week	1	2	3	4
Quantity	200	300	100	150

Standard Times:

Processing	0.5 hour/unit
Machine setup	10 hours (assume one production run per week)

Solution

Convert the quantity requirements into labour requirements by multiplying the quantity requirements by the respective standard times and adding the setup time:

Week	1	2	3	4
Quantity	200	300	100	150
Processing hours	100	150	50	75
Machine setup hours	10	10	10	10
Total labour hours	110	160	60	85

10 JUST-IN-TIME, LEAN PRODUCTION AND PROJECT MANAGEMENT

10.1 JIT and Lean Production

10.1.1 JIT and Lean Production

JIT Definitions:

- Logistical system where work-in-progress and the receipt of inputs to maintain product flow are timed such that input deliveries coincide with production line requirements.
- Suggests a batch type of production system where the inputs for one batch or unit of a good arrives just as the preceding batch is completed and is leaving the production line.
- Objectives include limiting idle items, co-ordinate material movements, waste reduction.

Pull vs. Push Production Strategies:

- **Marketing:** Push strategy involves selling through promotion through the distribution system, while pull strategy is more consumer focused with things such as advertising.
- **Manufacturing:** MPS and MRP schedule production and acquisitions, JIT systems.
- **Overall Objective:** Enhance profitability through increased efficiencies.

Characteristics of JIT/Lean Production Systems:

Example: Toyota car plant.

- Produces one high-cost unit at a time.
- Production of each unit is driven by specific consumer demand.
- Objectives: defective-free car, zero waste, high rate of output, safe work environment.

10.1.2 The Goals of Lean Production

- Balanced flow of product within a production system.
- Elimination of disruptions.
- System flexibility.
- Waste reduction.
- Continuous improvement.

10.1.3 Product Design

- **Product Design:** Involves engineering quality into product attributes, quality must be designed into goods and services, consumer driven.

- **Science of Product Design:** Balancing the production system (take time calculations), promoting productive flexibility, focusing on small lot sizes, setup time reductions, cellular plant layouts, promoting process quality, process standardization, maintaining minimal inventories.

10.1.4 Process Design

A Balanced System:

Balancing the System: Objective is to even out the work time amongst available workstations.

Takt Time Calculation:

- Maximum time per workstation is called **takt time**.
- Calculate net time available per shift.
- Multiply by the number of shifts on a typical day to get net available time.
- Divide net available time by daily demand to get the maximum time per workstation that will still allow you to satisfy the demand within the aggregate time constraint.

$$Takt\ time = \frac{net\ available\ time\ per\ day}{daily\ demand}$$

Sample Takt Time Calculation:

Given the following information, calculate the takt time: total time per shift is 480 minutes per day, and there are two shifts per day. There are two 20-minute rest breaks and a 30-minute lunch break per shift. Daily demand is 80 units.

$$net\ available\ time\ per\ day = available\ time \times \#\ of\ shifts$$

$$available\ time = 480 - 20 - 20 - 30 = 410\ minutes\ per\ day$$

$$net\ available\ time\ per\ day = 410 \times 2\ shifts = 820\ minutes\ per\ day$$

$$daily\ demand = 80\ units$$

$$Takt\ time = \frac{820}{80} = 10.25$$

A Flexible System:

Increase productive flexibility by decreasing setup times for changeovers, cross-train workers, design plants with multiple workstations, use safety stocks, keep some idle capacity.

Small Lot Sizes:

- Reduces inventory.
- Permits switching between different products to match production to customer demand.

- Less rework if defects occur, increased visibility of problems, increased flexibility.

Setup Time Reduction:

- **WILL** involve production worker involvement in setup changes.
- Should include as much “external” ahead-of-time setup procedures as is possible.
- Can involve the use of machine-specific jigs to eliminate exacting measurements.

Cellular Layout:

- Objective is to create a team approach to manufacturing by creating a specialized and efficient production cell.
- Involves: identifying product families, mapping out operations, addressing capacity requirements, balancing out workloads, determining an acceptable level of WIP.
- Advantages: increased throughput, reduced space requirements and material handling.

Process Quality:

- Jidoka: Quality at the source, if a detect is found then correct it before it is passed on.
- Objective here is to assist the operator in making quality products through the use of signals, alarms or the involuntary shutdown of equipment.

Standardized Processes:

- Complete work specification.
- Provides the basis for worker training.
- Creates a sense of simplicity and predictability.

Little Inventory:

Theory Behind Low Inventory Levels:

- Process control is less of an issue if inventories exist to maintain product flow.
- Lost opportunity to increase efficiency is hidden as it is less critical to make improvements or to repair recurring process problems when we know we have inventory.
- Just-in-Time is synonymous with one-unit lot sizes.

Little Inventory: For example, it is better to investigate the causes of some machine breakdown and focus on eliminating them rather than relying on excess inventory of machine’s output to feed into the next workstation.

10.1.5 Personnel/Organization

Level Loading:

Objective: Smooth out the production in a mixed-model schedule or sequence.

Process:

- Determine due times for each product based upon the daily demand for that good with the aim of smoothing out production throughout the day.
- Sequence their due times for all products by arranging them from the smallest to the longest due times.
- Time starts at "**0**" for the beginning of the day and ends at "**1**" for the end of the day.
- Due times for "n" units of a product $= \frac{1}{2n}, \frac{3}{2n}, \frac{5}{2n}, \ldots, \frac{2n-1}{2n}$.

Sample Question:

Firm produces three goods and therefore needs a mixed-output schedule to smooth out daily production.

$A = 7$										
$B = 16$										
$C = 5$										

Determine due times for each product and the daily production sequence.

The due times for each product are:

A: 1/14 = .071, 3/14 = .214, 5/14 = .357, 7/14 = .5, 9/14 = .643, 11/14 = .786, 13/14 = .929

B: 1/32 = .031, 3/32 = .094, 5/32 = .156, 7/32 = .219, 9/32 = .281, 11/32 = .344, 13/32 = .406, 15/32 = .469, 17/32 = .531, 19/32 = .594, 21/32 = .656, 23/32 = .719, 25/32 = .781, 27/32 = .844, 29/32 = .906, 31/32 = .969

C: 1/10 = .1, 3/10 = .3, 5/10 = .5, 7/10 = .7, 9/10 = .9

Now, sequence the due times from the smallest to the largest. The smallest due time is .031 for a B, so the first unit to produce is B. The next smallest due time is .071 for an A, so the second unit to produce is A, and so on. The level mixed model sequence is:

B-A-B-C-B-A-B-B-C-B-A-B-B-A-C-B-B-A-B-C-B-B-A-B-C-B-A-B

Pull System and Kanban:

Kanban System of Pulling Product through the Plant:

- Process works in reverse whereby consumer demand pulls finished product off the end of the line.
- As a result, each workstation pulls work from the work centre that immediately precedes it and so on down the line.
- Objective is to move batches or units of good through the system just as they are needed to minimize work in progress.

Kanban Calculation:

- Periodic adjustments to the number of Kanbans (replenishment order cards) can be made to either shrink or expand buffer inventory levels.
- Calculation of the actual number of Kanbans required in the first place is as follows:

$$N = \frac{DT(1+X)}{C}$$

- Where:
    - $N =$ total number of kanbans (1 kanban per container).
    - $D =$ average usage rate.
    - $T =$ lead time for replenishment of one container.
    - $X =$ safety stock demand as a proportion of average usage during lead time T for the replenishment of one container.
    - $C =$ capacity of a standard container.

Sample Kanban Calculation:

Usage at a work centre is 300 units of a specific part per day, and a standard container holds 25 units. It takes an average of 0.12 days from the time a *kanban* card is posted until the full container is received by the using work centre. Calculate the number of *kanban cards* needed for this part between these two work centres, if $X = 0.20$.

$N = ?$, $D = 300$ units per day, $T = 0.12$ days, $C = 25$ units per container, $X = 0.20$

$$N = \frac{300(0.12)(1+0.20)}{25} = 1.728 \text{ round to 2 containers.}$$

10.2 Project Management

10.2.1 Definition of a Project, Nature of a Project Manager's Job

- **Projects:** Unique one-time operations, specific set of objectives, limited time frame.
- **Examples:** Building construction, research project, product development, event.
- **Performance Goals:** Time/schedule, cost/budget, performance/quality guidelines.
- **Nature:** Project initiator/sponsor creates project scope, team of people with diverse knowledge and skills contribute as needed, influenced by strategy/culture, output.

10.2.2 Project Planning

- Project Planning: Analyzing the project into work packages and activities, estimating.

- Quality Planning: How project and product quality is to be assured and controlled.
- Communications Planning: Determining nature of information needed by stakeholders.
- Purchase Planning: What to purchase, specs, supplier evaluation and selection.

10.2.3 Project Scheduling

Project Management Tools: Work Breakdown Structure (WBS), Gantt chart, CPM/PERT, Software (e.g., Microsoft Project).

10.2.4 PERT/CPM Technique and Deterministic Activity Durations

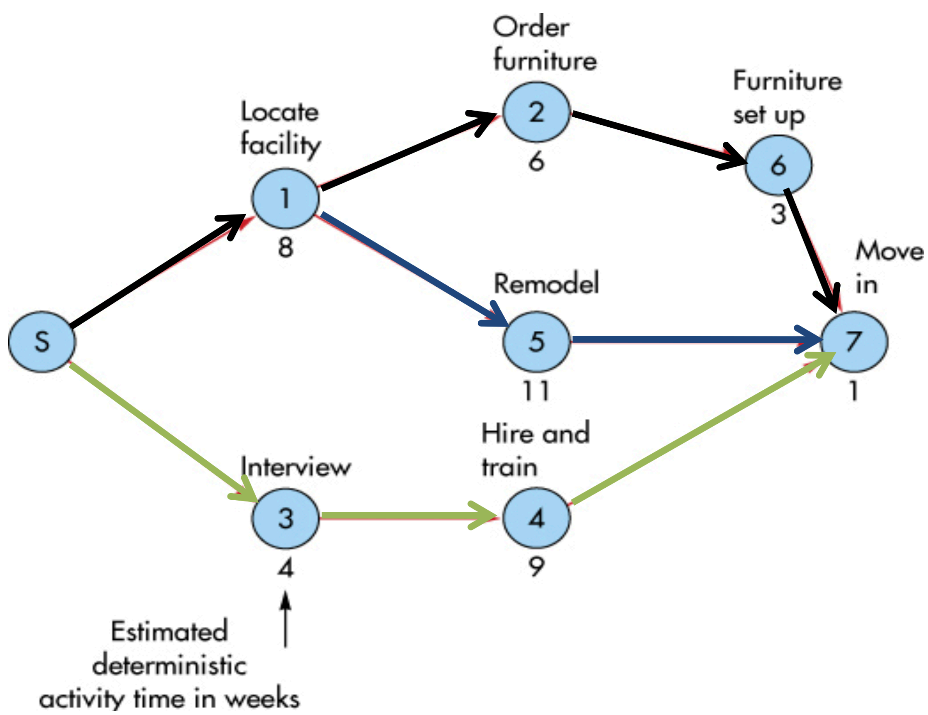
PERT and CPM:

- PERT (program evaluation and review technique) and CPM (critical path method).
- Techniques used to schedule and control large projects.

Precedence Network:

- Critical Path: Longest path from start to end, determines expected project durations.
- Critical Activities: Activities on the critical path.
- Path Slack Time:
    - Allowable slippage for a path.
    - $length\ of\ critical\ path - length\ of\ a\ path.$

Example: Precedence Network:



Path	Length (weeks)	Path Slack (weeks)
$S-1-2-6-7$	$8+6+3+1=18$	$20-18=2$
$S-1-5-7$	$8+11+1=20$	$20-20=0$
$S-3-4-7$	$4+9+1=14$	$20-14=6$

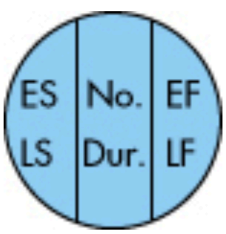
Deterministic Activity Durations:

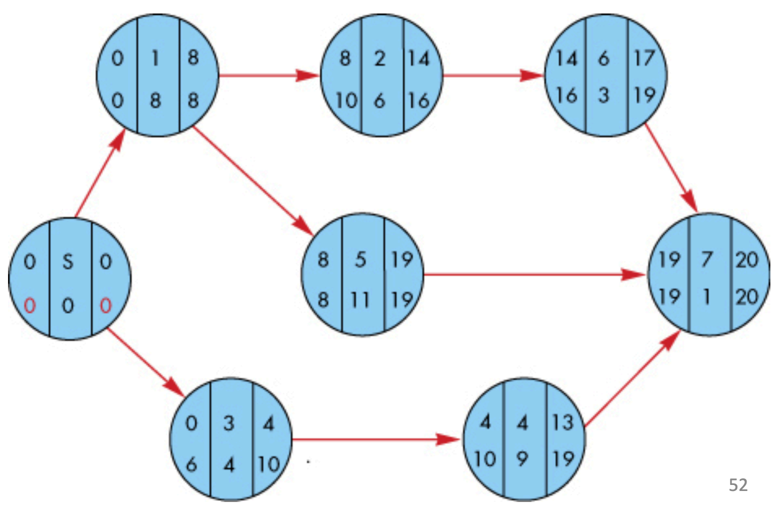
- Deterministic: Time estimates that are fairly certain.
- Probabilistic: Time estimates that allow for variation.

Solution Technique:

- Network activities:
    - ES: **earliest** time the activity can **start**
    - EF: **earliest** time the activity can **finish**
    - LS: **latest** time the activity can **start**
    - LF: **latest** time the activity can **finish**
- Used to determine expected project duration, activity slack times, critical path.

PERT/CPM Solution Technique:





Forward Pass: Earliest Start and Finish

- Start at the left side of the precedence network (start node) and work towards right side.
    - For the start activity: $ES=0$.
- If an activity has a *unique* immediately preceding activity:
    - $ES=EF$ of the immediately preceding activity.

- If an activity has *multiple* immediately preceding activities:
    - $ES =$ largest EF of immediate predecessors.
- For each activity:
    - $EF = ES +$ activity duration.

Backward Pass: Latest Start and Finish

- Start at the right side of the precedence network (end node) and work toward the left side.
    - For the end activity: $LF = EF$.
- If an activity has a *unique* immediate follower:
    - $LF = LS$ of the immediate follower.
- If an activity has *multiple* immediate followers:
    - $LF =$ smallest LS of immediate followers.
- For each activity:
    - $LS = LF -$ activity duration.

Slack and the Critical Path:

- Slack can be computed one of two ways:
    - Slack $= LS - ES$.
    - Slack $= LF - EF$.
- Critical path:
    - The critical path is indicated by the activities with zero slack.

Using Slack Times:

- Helps planning of allocation of scarce resources.
- Slack is **SHARED**.