Solutions Manual

for

Automation, Production Systems, and Computer Integrated Manufacturing

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Chapter 1
INTRODUCTION

REVIEW QUESTIONS

1.1 What are some of the realities mentioned at the beginning of the chapter that modern manufacturing enterprises must cope with? Name four.

Answer: The realities mentioned in the text are (1) globalization, (2) international outsourcing, (3) local outsourcing, (4) contract manufacturing, (5) trend toward the service sector, (6) quality expectations, and (7) the need for operational efficiency.

1.2 What is a production system?

Answer: As defined in the text, a production system is a collection of people, equipment, and procedures organized to perform the manufacturing operations of a company (or other organization).

1.3 Production systems can be divided into two categories or levels. Name and briefly define the two levels.

Answer: The two categories given in the text are (1) facilities, which consist of the factory, the equipment in the factory, and the way the equipment is organized; and (2) manufacturing support systems, which is the set of procedures used by the company to manage production and to solve the technical and logistics problems encountered in ordering materials, moving the work through the factory, and ensuring that products meet quality standards. Product design and certain business functions are included among the manufacturing support systems.

1.4 What are manufacturing systems, and how are they distinguished from production systems?

Answer: A manufacturing system is a logical grouping of equipment in the factory and the worker(s) who operate(s) it. Examples include worker-machine systems, production lines, and machine cells. A production system is a larger system that includes a collection of manufacturing systems and the support systems used to manage them. A manufacturing system is a subset of the production system.

1.5 Manufacturing systems are divided into three categories, according to worker participation. Name the three categories.

Answer: The three categories are (1) manual work systems, (2) worker-machine systems, and (3) automated systems.

1.6 What are the four functions included within the scope of manufacturing support systems?

Answer: As identified in the text, the four functions are (1) business functions, (2) product design, (3) manufacturing planning, and (4) manufacturing control.

1.7 Three basic types of automation are defined in the text. What is fixed automation and what are some of its features?

Answer: Fixed automation is a system in which the sequence of processing (or assembly) operations is fixed by the equipment configuration. Each operation in the sequence is usually simple, but the integration and coordination of many such operations into one piece of equipment makes the system complex. Typical features of fixed automation are (1) high initial investment for custom-engineered equipment, (2) high production rates, and (3) relatively inflexible in accommodating product variety.

1.8 What is programmable automation and what are some of its features?

Answer: In programmable automation, the production equipment is designed with the capability to change the sequence of operations to accommodate different product configurations. The operation sequence is controlled by a program, which is a set of instructions coded so that they can be read and interpreted by the system. Some of the features of programmable automation are (1) high investment in general purpose equipment, (2) lost production time due to changeovers of physical setup and reprogramming, (3) lower production rates than fixed automation, (4) flexibility to deal with variations and changes in product configuration, and (5) most suitable for batch production.

1.9 What is flexible automation and what are some of its features?
**Answer:** Flexible automation is an extension of programmable automation. A flexible automated system is capable of producing a variety of parts (or products) with virtually no time lost for changeovers from one part style to the next. There is no lost production time while reprogramming the system and altering the physical setup. Accordingly, the system can produce various mixes and schedules of parts or products instead of requiring that they be made in batches. The features of flexible automation are (1) high investment for a custom-engineered system, (2) continuous production of variable mixtures of products, (3) medium production rates, and (4) flexibility to deal with product design variations.

1.10 What is computer integrated manufacturing?

**Answer:** As defined in the text, computer-integrated manufacturing (CIM) denotes the pervasive use of computer systems to design the products, plan the production, control the operations, and perform the various information-processing functions needed in a manufacturing firm. True CIM involves integrating all of these functions in one system that operates throughout the enterprise.

1.11 What are some of the reasons why companies automate their operations? Nine reasons are given in the text. Name five.

**Answer:** The reasons give in the text are (1) to increase labor productivity, (2) to reduce labor cost, (3) to mitigate the effects of labor shortages, (4) to reduce or eliminate routine manual and clerical tasks, (5) to improve worker safety, (6) to improve product quality, (7) to reduce manufacturing lead time, (8) to accomplish processes that cannot be done manually, and (9) to avoid the high cost of not automating.

1.12 Identify three situations in which manual labor is preferred over automation.

**Answer:** The five situations listed in the text are the following: (1) The task is technologically too difficult to automate. (2) Short product life cycle. (3) Customized product. (4) To cope with ups and downs in demand. (5) To reduce risk of product failure.

1.13 Human workers will be needed in factory operations, even in the most highly automated operations. The text identifies at least four types of work for which humans will be needed. Name three.

**Answer:** The four types of work identified in the text are (1) equipment maintenance, (2) programming and computer operations, (3) engineering project work, and (4) plant management.

1.14 What is the USA Principle? What does each of the letters stand for?

**Answer:** The USA Principle is a common sense approach to automation and process improvement projects. U means “understand the existing process,” S stands for “simplify the process,” and A stands for “automated the process.”

1.15 The text lists ten strategies for automation and process improvement. Identify five of these strategies.

**Answer:** The ten strategies listed in the text are (1) specialization of operations, (2) combined operations, (3) simultaneous operations, (4) integration of operations, (5) increased flexibility, (6) improved material handling and storage, (7) on-line inspection, (8) process control and optimization, (9) plant operations control, and (10) computer-integrated manufacturing (CIM).

1.16 What is an automation migration strategy?

**Answer:** As defined in the text, an automation migration strategy is a formalized plan for evolving the manufacturing systems used to produce new products as demand grows.

1.17 What are the three phases of a typical automation migration strategy?

**Answer:** As defined in the text, the three typical phases are the following: Phase 1: Manual production using single-station manned cells operating independently. Phase 2: Automated production using single-station automated cells operating independently. Phase 3: Automated integrated production using a multi-station automated system with serial operations and automated transfer of work units between stations.
Chapter 2
MANUFACTURING OPERATIONS

REVIEW QUESTIONS

2.1 What is manufacturing?

Answer: Two definitions are given in the text, one technological and the other economic. The technological definition is the following: Manufacturing is the application of physical and chemical processes to alter the geometry, properties, and/or appearance of a given starting material to make parts or products; manufacturing also includes the joining of multiple parts to make assembled products. The economic definition is the following: Manufacturing is the transformation of materials into items of greater value by means of one or more processing and/or assembly operations.

2.2 What are the three basic industry categories?

Answer: The three basic industry categories are the following: (1) Primary industries, which are those that cultivate and exploit natural resources, such as agriculture and mining; (2) secondary industries, which convert the outputs of the primary industries into products; they include manufacturing, construction, and power generation; and (3) tertiary industries, which constitute the service sector of the economy, which includes banking, retail, transportation, education, government, and so on.

2.3 What is the difference between consumer goods and capital goods?

Answer: Consumer goods are products that are purchased directly by consumers, such as cars, personal computers, TVs, tires, toys, and tennis rackets. Capital goods are products purchased by other companies to produce goods and supply services. Examples include commercial aircraft, mainframe computers, machine tools, railroad equipment, and construction machinery.

2.4 What is the difference between a processing operation and an assembly operation?

Answer: A processing operation transforms a work material from one state of completion to a more advanced state that is closer to the final desired part or product. It adds value by changing the geometry, properties, or appearance of the starting material. An assembly operation joins two or more components to create a new entity, called an assembly, subassembly, or some other term that refers to the joining process.

2.5 Name the four categories of part-shaping operations, based on the state of the starting work material.

Answer: The four categories are (1) solidification processes, (2) particulate processing, (3) deformation processes, and (4) material removal processes.

2.6 Assembly operations can be classified as permanent joining methods and mechanical assembly. What are the four types of permanent joining methods?

Answer: The joining processes are (1) welding, (2) brazing, (3) soldering, and (4) adhesive bonding.

2.7 What is the difference between hard product variety and soft product variety?

Answer: Hard product variety is when the products differ substantially. In an assembled product, hard variety is characterized by a low proportion of common parts among the products; in many cases, there are no common parts. Soft product variety is when there are only small differences between products. There is a high proportion of common parts among assembled products whose variety is soft.

2.8 What type of production does a job shop perform?

Answer: Low production of specialized and customized products. The products are typically complex, such as space capsules, aircraft, and special machinery.

2.9 Flow line production is associated with which one of the following layout types: (a) cellular layout, (b) fixed-position layout, (c) process layout, or (d) product layout?

Answer: (d) Product layout.

2.10 What is the difference between a single-model production line and a mixed-model production line?
**Answer**: A single-model production line makes products that are all identical. A mixed-model production line makes products that have model variations characterized as soft product variety.

2.11 What is meant by the term *technological processing capability*?

**Answer**: Technological processing capability of a plant (or company) is its available set of manufacturing processes. It includes not only the physical processes, but also the expertise possessed by plant personnel in these processing technologies.

2.12 What is lean production?

**Answer**: The definition given in the text is the following: Lean production means operating the factory with the minimum possible resources and yet maximizing the amount of work that is accomplished with these resources. Lean production also implies completing the products in the minimum possible time and achieving a very high level of quality, so that the customer is completely satisfied. In short, lean production means doing more with less, and doing it better.

2.13 In lean production, what is just-in-time delivery of parts?

**Answer**: As defined in the text, just-in-time delivery of parts refers to the manner in which parts are moved through the production system when a sequence of manufacturing operations is required to make them. In the ideal just-in-time system, each part is delivered to the downstream workstation immediately before that part is needed at the station.

2.14 In lean production, what does worker involvement mean?

**Answer**: As explained in the text, worker involvement means that workers are assigned greater responsibilities and are provided with training that allows them to be flexible in the work they can do. Also, workers participate in problem-solving exercises to address issues faced by the company.

2.15 In lean production, what does continuous improvement mean, and how is it usually accomplished?

**Answer**: Continuous improvement involves an unending search for ways to make improvements in products and manufacturing operations. It is usually accomplished by worker teams who cooperate to develop solutions to production and quality problems.

**PROBLEMS**

2.1 A plant produces three product lines: A, B, and C. There are 6 models within product line A, 4 models within B, and 8 within C. Average annual production quantities of each A model is 500 units, 700 units for each B model, and 1100 units for each C model. Determine the values of (a) \( P \) and (b) \( Q_f \) for this plant.

**Solution**: (a) The parameter \( P \) is the total number of different product models produced.

\[ P = 6 + 4 + 8 = 18 \text{ different models.} \]

(b) \( Q_f \) is the total production quantity of all products made in the factory.

\[ Q_f = 6(500) + 4(700) + 8(1100) = 3000 + 2800 + 8800 = 14,600 \text{ units} \]

2.2 The ABC Company is planning a new product line and will build a new plant to manufacture the parts for a new product line. The product line will include 50 different models. Annual production of each model is expected to be 1000 units. Each product will be assembled of 400 components. All processing of parts will be accomplished in one factory. There are an average of 6 processing steps required to produce each component, and each processing step takes 1.0 minute (includes an allowance for setup time and part handling). All processing operations are performed at workstations, each of which includes a production machine and a human worker. If each workstation requires a floor space of 250 ft\(^2\), and the factory operates one shift (2000 hr/yr), determine (a) how many production operations, (b) how much floorspace, and (c) how many workers will be required in the plant.

**Solution**: This problem neglects the effect of assembly time.

(a) \( n_S = P Q_n n_p = 50(1000)(400)(6) = 120,000,000 \text{ operations} \) in the factory per year.

(c) Total operation time = \((120 \times 10^6 \text{ ops})(1 \text{ min.}/(60 \text{ min.}/\text{hr})) = 2,000,000 \text{ hr/yr}.\)

At 2000 hours/yr per worker,

\[ w = \frac{2,000,000 \text{ hr/yr}}{2000 \text{ hr/worker}} = 1000 \text{ workers}. \]
2.3 The XYZ Company is planning to introduce a new product line and will build a new factory to produce the parts and assemble the final products for the product line. The new product line will include 90 different models. Annual production of each model is expected to be 1200 units. Each product will be assembled of 600 components. All processing of parts and assembly of products will be accomplished in one factory. There are an average of 10 processing steps required to produce each component, and each processing step takes 30 sec. (includes an allowance for setup time and part handling). Each final unit of product takes 3.0 hours to assemble. All processing operations are performed at work cells that each includes a production machine and a human worker. Products are assembled on single workstations consisting of two workers each. If each work cell and each workstation require 200 ft$^2$, and the factory operates one shift (2000 hr/yr), determine: (a) how many production operations, (b) how much floorspace, and (c) how many workers will be required in the plant.

Solution: (a) $Q_f = PQ = 90(1200) = 108,000$ products/yr
Number of final assembly operations = 108,000 asby ops/yr
Number of processing operations $n_{op} = PQn_p = 90(1200)(600)(10) = 648,000,000$ proc ops/yr
(c) Total processing operation time = $(648 \times 10^6 \text{ ops})(0.5 \text{ min.}/(60 \text{ min./hr})) = 5,400,000 \text{ hr/yr}$.
Total assembly operation time = $(108 \times 10^3 \text{ asby ops})(3 \text{ hr/product}) = 324,000 \text{ hr/yr}$
With two workers at each assembly station, labor hours = $2(324,000) = 648,000 \text{ hr/yr}$
Total processing and assembly time = $6,048,000 \text{ hr/yr}$
At 2000 hours/yr per worker, $w = \frac{6,048,000 \text{ hr/yr}}{2000 \text{ hr/wor ker}} = 3024$ workers.

(b) With 1 worker per workstation for processing operations, $n = w = 5,400,000/2000 = 2700$ workstations.
With 2 workers per stations for assembly, $n = 0.5(648,000/2000) = 162$ workstations.
Total floor space $A = (2700 + 162) \text{ stations})(200 \text{ ft}/\text{station}) = 572,400 \text{ ft}^2$

2.4 If the company in Problem 2.3 were to operate three shifts (6000 hr/yr) instead of one shift, determine the answers to (a), (b), and (c).

Solution: (a) Same total number of processing and assembly operations but spread over three shifts.
Number of final assembly operations = 108,000 asby ops/yr
Number of processing operations $n_{op} = PQn_p = 90(1200)(600)(10) = 648,000,000$ operations/yr
(c) Same total number of workers required but spread over three shifts.
Total workers $w = 3024$ workers. Number of workers/shift = $w/3 = 1008$ workers/shift.

(b) Number of workers for processing operations = $2700/3 = 900$ worker per shift
Number of workers for assembly = $162/3 = 54$ workers per shift.
Number of workstations $n = 900 + 54/2 = 927$.
Using the higher number, Total floor space $A = (927 \text{ stations})(200 \text{ ft}/\text{station}) = 185,400 \text{ ft}^2$
Chapter 3
MANUFACTURING METRICS

REVIEW QUESTIONS

3.1 What is the cycle time in a manufacturing operation?

Answer: As defined in the text, the cycle time $T_c$ is the time that one work unit spends being processed or assembled. It is the time between when one work unit begins processing (or assembly) and when the next unit begins.

3.2 What is a bottleneck station?

Answer: The bottleneck station is the slowest workstation in a production line, and therefore it limits the pace of the entire line.

3.3 What is production capacity?

Answer: As defined in the text, production capacity is the maximum rate of output that a production facility (or production line, work center, or group of work centers) is able to produce under a given set of assumed operating conditions.

3.4 How can plant capacity be increased or decreased in the short term?

Answer: As listed in the text, the two ways that plant capacity can be increased or decreased in the short term are (1) change the number of work shifts per week $S_w$ or (2) change the number of hours worked per shift $H_{sh}$.

3.5 What is utilization in a manufacturing plant? Provide a definition.

Answer: Utilization is the amount of output of a production facility relative to its capacity. Expressing this as an equation, $U = Q/PC$, where $U$ = utilization, $Q$ = actual output quantity produced during the period of interest, and $PC$ is the production capacity during the same period.

3.6 What is availability and how is it defined?

Answer: Availability is a reliability metric that indicates the proportion of time that a piece of equipment is up and working properly. It is defined as follows: $A = (MTBF - MTTR)/MTBF$, where $A$ = availability, $MTBF =$ mean time between failures, and $MTTR =$ mean time to repair.

3.7 What is manufacturing lead time?

Answer: As defined in the text, manufacturing lead time is the total time required to process a given part or product through the plant, including any lost time due to delays, time spent in storage, reliability problems, and so on.

3.8 What is work-in-process?

Answer: As defined in the text, work-in-process (WIP) is the quantity of parts or products currently located in the factory that are either being processed or are between processing operations. WIP is inventory that is in the state of being transformed from raw material to finished product.

3.9 How are fixed costs distinguished from variable costs in manufacturing?

Answer: Fixed costs remain constant for any level of production output. Examples include the cost of the factory building and production equipment, insurance, and property taxes. Variable costs vary in proportion to the level of production output. As output increases, variable costs increase. Examples include direct labor, raw materials, and electric power to operate the production equipment.

3.10 Name five typical factory overhead expenses?

Answer: Table 3.1 in the text lists the following examples of factory overhead expenses: plant supervision, applicable taxes, factory depreciation, line foremen, insurance, equipment depreciation, maintenance, heat and air conditioning, fringe benefits, custodial services, light, material handling, security personnel, power for machinery, shipping and receiving, tool crib attendant, payroll services, and clerical support.

3.11 Name five typical corporate overhead expenses?
Answer: Table 3.2 in the text lists the following examples of corporate overhead expenses: corporate executives, engineering, applicable taxes, sales and marketing, research and development, cost of office space, accounting department, support personnel, security personnel, finance department, insurance, heat and air conditioning, legal counsel, fringe benefits, and lighting.

PROBLEMS

Production Concepts and Mathematical Models

3.1 A certain part is routed through six machines in a batch production plant. The setup and operation times for each machine are given in the table below. The batch size is 100 and the average nonoperation time per machine is 12 hours. Determine (a) manufacturing lead time and (b) production rate for operation 3.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Setup time (hr.)</th>
<th>Operation time (min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>5.0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>10.0</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>1.9</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>4.1</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Solution: Average $T_a = (4 + 2 + 8 + 3 + 3 + 4)/6 = 24/6 = 4.0$ hr
Average $T_c = (5 + 3.5 + 10 + 1.9 + 4.1 + 2.5)/6 = 27/6 = 4.5$ min
(a) $MLT = 6(4.0 + 100(4.5/60)) + 12) = 6(23.5) = 141$ hr
(b) $R_p$ for operation 3: $T_p = \frac{[8.0 + 100(10/60)]}{100} = 24.67/100 = 0.2467$ hr/pc $R_p = 4.05$ pc/hr

3.2 Suppose the part in the previous problem is made in very large quantities on a production line in which an automated work handling system is used to transfer parts between machines. Transfer time between stations = 15 s. The total time required to set up the entire line is 150 hours. Assume that the operation times at the individual machines remain the same. Determine (a) manufacturing lead time for a part coming off the line, (b) production rate for operation 3, (c) theoretical production rate for the entire production line?

Solution: (a) $MLT = 6(10.25) = 61.5$ min for an average part after production has achieved steady state operation.
$MLT = 61.5/60 + 150 = 151.025$ hr for first part including setup
(b) $T_p$ for operation 3 = 10.25 min, $R_p = 60/10.25 = 5.8536$ pc/hr
(c) Theoretical production rate for line = $5.8536$ pc/hr since station 3 is the bottleneck station on the line.

3.3 The average part produced in a certain batch manufacturing plant must be processed sequentially through six machines on average. Twenty (20) new batches of parts are launched each week. Average operation time = 6 min., average setup time = 5 hours, average batch size = 36 parts, and average nonoperation time per batch = 10 hr/machine. There are 18 machines in the plant working in parallel. Each of the machines can be set up for any type of job processed in the plant. The plant operates an average of 70 production hours per week. Scrap rate is negligible. Determine (a) manufacturing lead time for an average part, (b) plant capacity, (c) plant utilization. (d) How would you expect the nonoperation time to be affected by the plant utilization?

Solution: (a) $MLT = 6(5 + 36(0.1) + 10) = 111.6$ hr
(b) $T_p = (5 + 36 \times 0.1)/36 = 0.2389$ hr/pc, $R_p = 4.186$ pc/hr.
(c) Parts launched per week = 20 x 36 = 720 pc/week. Utilization $U = 720/879 = 0.819 = 81.9\%$
(d) As utilization increases towards 100%, we would expect the nonoperation time to increase. When the workload in the shop grows, the shop becomes busier, but it usually takes longer to get the jobs out. As utilization decreases, we would expect the nonoperation time to decrease.

3.4 Based on the data in the previous problem and your answers to that problem, determine the average level of work-in-process (number of parts-in-process) in the plant.
3.5 An average of 20 new orders are started through a certain factory each month. On average, an order consists of 50 parts that are processed sequentially through 10 machines in the factory. The operation time per machine for each part = 15 min. The nonoperation time per order at each machine averages 8 hours, and the required setup time per order = 4 hours. There are a total of 25 machines in the factory working in parallel. Each of the machines can be set up for any type of job processed in the plant. Only 80% of the machines are operational at any time (the other 20% are in repair or maintenance). The plant operates 160 hours per month. However, the plant manager complains that a total of 100 overtime machine-hours must be authorized each month in order to keep up with the production schedule. (a) What is the manufacturing lead time for an average order? (b) What is the plant capacity (on a monthly basis) and why must the overtime be authorized? (c) What is the utilization of the plant according to the definition given in the text? (d) Determine the average level of work-in-process (number of parts-in-process) in the plant.

**Solution:**

(a) \( MLT = 10(4 + 50 \times 0.25 + 8) = 245 \text{ hr/order} \)

(b) \( T_p = (4 + 50 \times 0.25)/50 = 16.5/50 = 0.33 \text{ hr/pc}, R_p = 3.0303 \text{ pc/hr} \)

\( PC = (25 \times 0.80)(160)(3.0303)/10 = 969.7 \text{ pc/month} \)

Parts launched per month = 20x25 = 1000 pc/month

Schedule exceeds plant capacity by 1000 - 969.7 = 30.3 pc.

This requires overtime in the amount = (30.303 pc x 10 machines)/(3.0303 pc/hr) = 100 hr.

(c) Utilization \( U = (1000 \text{ pc})/(969.7 \text{ pc}) = 1.03125 = 103.125\% \)

(d) \( WIP = (245 \text{ hr})(969.7 \text{ pc/mo})(1.03125)/(160 \text{ hr/mo}) = 1531.25 \text{ parts} \)

3.6 The mean time between failure for a certain production machine is 356 hours, and the mean time to repair is 6 hours. Determine the availability of the machine.

**Solution:** Availability \( A = (356 - 6)/356 = 0.983 = 98.3\% \)

3.7 One million units of a certain product are to be manufactured annually on dedicated production machines that run 24 hours per day, five days per week, 50 weeks per year. (a) If the cycle time of a machine to produce one part is 1.0 minute, how many of the dedicated machines will be required to keep up with demand? Assume that availability, utilization, worker efficiency = 100%, and that no setup time will be lost. (b) Solve part (a) except that availability = 0.90.

**Solution:**

(a) Total workload \( WL = 1,000,000(1 \text{ min/60}) = 16,666.7 \text{ hr/yr} \)

Hours available/machine = 24 x 5 x 50 = 6000 hr/yr per machine

Number of machines \( n = \frac{16,666.7 \text{ hr}}{6000 \text{ hr/machine}} = 2.78 \rightarrow 3 \text{ machines} \)

(b) At \( A = 90\% \), \( n = \frac{16,666.7 \text{ hr}}{6000 \text{ hr/machine}(0.90)} = 3.09 \rightarrow 4 \text{ machines} \)

3.8 The mean time between failures and mean time to repair in a certain department of the factory are 400 hours and 8 hours, respectively. The department operates 25 machines during one 8-hour shift per day, five days per week, 52 weeks per year. Each time a machine breaks down, it costs the company $200 per hour (per machine) in lost revenue. A proposal has been submitted to install a preventive maintenance program in this department. In this program, preventive maintenance would be performed on the machines during the evening so that there will be no interruptions to production during the regular shift. The effect of this program is expected to be that the average MTBF will double, and half of the emergency repair time normally accomplished during the day shift will be performed during the evening shift. The cost of the maintenance crew will be $1500 per week. However, a reduction of maintenance personnel on the day shift will result in a savings of $700 per week. (a) Compute the availability of machines in the department both before and after the preventive maintenance program is installed. (b) Determine how many total hours per year the 25 machines in the department are under repair both before and after the preventive maintenance program is installed. In this part and in part (c), ignore effects of queueing of the machines that might have to wait for a maintenance crew. (c) Will the preventive maintenance program pay for itself in terms of savings in the cost of lost revenues?
Solution: (a) Without preventive maintenance (PM), availability \( A = \frac{400 - 8}{400} = 0.98 = 98.0\% \).
With PM, availability \( A = \frac{800 - 8}{800} = 0.99 = 99.0\% \). This 99\% value ignores the fact that half the repair time is on the evening shift. If we use time of repair during the day to calculate availability, \( MTTR = 4 \) hr, and Availability \( A = \frac{800 - 4}{800} = 0.995 = 99.5\% \).

(b) Total operating hours per year = 5 x 8 x 52 = 2080 hr/year.
Without PM, \( MTBF = 400 \) hr. We expect 2080/400 = 5.2 breakdowns/year for each machine. With 25 machines, breakdowns/year = 5.2 x 25 = 130.
Total downtime hours = 130 x 8 = 1040 hr/year.
With PM, \( MTBF = 800 \) hr. This means 2080/800 = 2.6 breakdowns/yr for each machine. With 25 machines, breakdowns/year = 2.6 x 25 = 65. Total downtime hours = 65 x 4 = 260 hr/year.

(c) Without PM, cost of downtime = $200 x 1040 downtime hr/yr = $208,000/year
With PM, cost of downtime = $200 x 260 downtime hr/yr = $52,000/year
Additional labor cost of PM program = 1500 - 700 = $800/week
Additional labor cost of PM program/year = $800 x 52 = $41,600/yr
Total cost per year pf PM = $52,000 + 41,600 = $93,600/yr.
Since this is substantially lower than $208,000/yr, PM program is justified.

3.9 There are nine machines in the automatic lathe section of a certain machine shop. The setup time on an automatic lathe averages 6 hours. The average batch size for parts processed through the section is 80. The average operation time = 9.0 minutes. Under shop rules, an operator can be assigned to run up to three machines. Accordingly, there are three operators in the section for the nine lathes. In addition to the lathe operators, there are two setup workers who perform machine setups exclusively. These setup workers are kept busy the full shift. The section runs one 8-hour shift per day, 6 days per week. However, an average of 15\% of the production time is lost due to machine breakdowns. Scrap losses are negligible. The production control manager claims that the capacity of the section should be 1836 pieces per week. However, the actual output averages only 1440 units per week. What is the problem? Recommend a solution.

Solution: Hours/week = 6 days/wk x 8 hr/day x (1 - 0.15) = 40.8 hr/week.
\[ T_p = \frac{6 + 80 \times 9/60}{90} = 18 \text{ hr/90 pc} = 0.2 \text{ hr/pc}, \quad R_p = 5 \text{ pc/hr}. \]

Production capacity of automatic lathe section \( PC = \frac{40.8 \text{ hr/wk}}{5 \text{ pc/hr}}(9 \text{ machines}) = 1836 \text{ pc/wk}. \)
But the actual output = 1440 pc/wk. Why? Consider workload of the setup men.
Number of batches set up per week = (2 setup men)(48 hr/wk)/(6 hr/setup) = 16 batches/wk.
At 90 pc/batch, total pc/week = 16 x 90 = **1440 pc/week**.
The problem is that the setup workers represent a bottleneck. To solve the problem, hire one more setup worker.

3.10 A certain job shop specializes in one-of-a-kind orders dealing with parts of medium-to-high complexity. A typical part is processed sequentially through ten machines in batch sizes of one. The shop contains a total of eight conventional machine tools and operates 35 hours per week of production time. The machine tools are interchangeable in the sense that they can be set up for any operation required on any of the parts. Average time values on the part are: machining time per machine = 0.5 hour, work handling time per machine = 0.3 hour, tool change time per machine = 0.2 hour, setup time per machine = 6 hours, and nonoperation time per machine = 12 hours. A new programmable machine has been purchased by the shop that is capable of performing all ten operations in a single setup. The programming of the machine for this part will require 20 hours; however, the programming can be done off-line, without tying up the machine. The setup time will be 10 hours. The total machining time will be reduced to 80\% of its previous value due to advanced tool control algorithms; the work handling time will be the same as for one machine; and the total tool change time will be reduced by 50\% because it will be accomplished automatically under program control. For the one machine, nonoperation time is expected to be 12 hours. (a) Determine the manufacturing lead time for the traditional method and for the new method. (b) Compute the plant capacity for the following alternatives: (i) a job shop containing the eight traditional machines, and (ii) a job shop containing two of the new programmable machines. Assume the typical jobs are represented by the data given above. (c) Determine the average level of work-in-process for the two alternatives in part (b), if the alternative shops operate at full capacity. (d) Identify which of the ten automation strategies (Section 1.5.2) are represented (or probably represented) by the new machine.

Solution: (a) Present method: \( MLT = 10(6 + 1 + 12) = 190 \) hr.
New method: \( MLT = 1(10 + 5.3 + 12) = 27.3 \) hr.
(b) Present method: For 1 machine, \( T_c = (6 + 1)/1 = 7 \text{ hr}, \quad R_c = 1/7 = 0.1429 \text{ pc/hr} \)
For 8 machines, plant capacity \( PC = (8 \text{ machines})(35 \text{ hr})(0.1429 \text{ pc/hr})(10 \text{ ops/pc}) = 4 \text{ orders/week} \)

New method: For each machine, \( T_b = (10 + 5.3)/1 = 15.3 \text{ hr} \), \( R_b = 1/15.3 = 0.063536 \text{ pc/hr} \)

For 2 machines, plant capacity \( PC = (2 \text{ machines})(35 \text{ hr})(0.063536 \text{ pc/hr})(1 \text{ op/pc}) = 4.575 \text{ orders/week} \)

(c) Present method: \( WIP = (4 \text{ orders/week})(190 \text{ hr/order})/(35 \text{ hr/wk}) = 21.7 \text{ orders} \)

New method: \( WIP = (4.575 \text{ orders/week})(27.3 \text{ hr/order})/(35 \text{ hr/wk}) = 3.57 \text{ orders} \)

(d) Automation strategies represented: Strategy 2 - combined operations; Strategy 5 - increased flexibility; Strategy 6 - improved material handling; Strategy 8 - process control; Strategy 9 - plant operations control.

3.11 A factory produces cardboard boxes. The production sequence consists of three operations: (1) cutting, (2) indenting, and (3) printing. There are three machines in the factory, one for each operation. The machines are 100% reliable and operate as follows when operating at 100% utilization: (1) In cutting, large rolls of cardboard are fed into the cutting machine and cut into blanks. Each large roll contains enough material for 4,000 blanks. Production cycle time = 0.03 minute/blank during a production run, but it takes 35 minutes to change rolls between runs. (2) In indenting, indentation lines are pressed into the blanks to allow the blanks to later be bent into boxes. The blanks from the previous cutting operation are divided and consolidated into batches whose starting quantity = 2,000 blanks. Indenting is performed at 4.5 minutes per 100 blanks. Time to change dies on the indentation machine = 30 min. Between batches, changeover of the printing plates is required, which takes 20 minutes. In-process inventory is allowed to build up between machines 1 and 2, and between machines 2 and 3, so that the machines can operate independently as much as possible. Based on this data and information, determine the maximum possible output of this factory during a 40-hour week, in completed blanks/week (completed blanks have been cut, indented, and printed)? Assume steady state operation, not startup.

Solution: Determine maximum production rate \( R_p \) for each of the three operations:

Operation (1) - cutting: \( T_b = 35 \text{ min.} + 4000 \text{ pc}(0.03 \text{ min/pc}) = 35 + 120 = 155 \text{ min./batch} \)

\[ R_p = \frac{(4000 \text{ pc / batch})(60 \text{ min./hr})}{155 \text{ min./batch}} = 1548.4 \text{ pc/hr} \]

Operation (2) - indenting: \( T_b = 30 \text{ min.} + 2000 \text{ pc}(4.5/100 \text{ min./pc}) = 30 + 90 = 120 \text{ min./batch} \)

\[ R_p = \frac{(2000 \text{ pc / batch})(60 \text{ min./hr})}{120 \text{ min./batch}} = 1000 \text{ pc/hr} \]

Operation (3) - printing: \( T_b = 20 \text{ min.} + \frac{1000 \text{ pc}}{30 \text{ pc / min.}} = 20 + 33.33 = 53.33 \text{ min./batch} \)

\[ R_p = \frac{(1000 \text{ pc / batch})(60 \text{ min./hr})}{53.33 \text{ min./batch}} = 1125 \text{ pc/hr} \]

Bottleneck process is operation (2). Weekly output = \( (40 \text{ hr/wk})(1000 \text{ pc/hr}) = 40,000 \text{ blanks/wk} \).

Costs of Manufacturing Operations

3.12 Theoretically, any given production plant has an optimum output level. Suppose a certain production plant has annual fixed costs \( FC = \$2,000,000 \). Variable cost \( VC \) is functionally related to annual output \( Q \) in a manner that can be described by the function \( VC = 12 + 0.005Q \). Total annual cost is given by \( TC = FC + VC \times Q \). The unit sales price for one production unit \( P = \$275 \). (a) Determine the value of \( Q \) that minimizes unit cost \( UC \), where \( UC = \frac{TC}{Q} \); and compute the annual profit earned by the plant at this quantity. (b) Determine the value of \( Q \) that maximizes the annual profit earned by the plant; and compute the annual profit earned by the plant at this quantity.

Solution: (a) \( TC = 2,000,000 + (12 + 0.005Q)Q = 2,000,000 + 12Q + 0.005Q^2 \)

\[ UC = \frac{TC}{Q} = \frac{2,000,000}{Q} + 12 + 0.005Q \]

\[ \frac{d(UC)}{dQ} = \frac{-2,000,000}{Q^2} + 0.005 = 0 \]

\[ 0.005Q^2 = 2,000,000 \]

\[ Q^2 = 400 \times 10^6 \]

\[ Q = 20 \times 10^3 = 20,000 \text{ pc} \]
Profit = 275(20,000) - (2,000,000 + 12(20,000) + 0.005(20,000)^2) = \$1,260,000/yr

(b) Profit \( \Pi = 275Q - (2,000,000 + 12Q + 0.005Q^2) = 263Q - 2,000,000 - 0.005Q^2 \)

\[ \frac{d\Pi}{dQ} = 263 - 2(0.005Q) = 263 - 0.010Q = 0 \]

\[ Q = \frac{263}{0.010} = 26,300 \text{ pc} \]

Profit = 275(26,300) - (2,000,000 + 12(26,300) + 0.005(26,300)^2) = \$1,490,850/yr

3.13 Costs have been compiled for a certain manufacturing company for the most recent year. The summary is shown in the table below. The company operates two different manufacturing plants, plus a corporate headquarters. Determine (a) the factory overhead rate for each plant, and (b) the corporate overhead rate. The firm will use these rates in the following year.

<table>
<thead>
<tr>
<th>Expense category</th>
<th>Plant 1</th>
<th>Plant 2</th>
<th>Corporate headquarters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct labor</td>
<td>$1,000,000</td>
<td>$1,750,000</td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td>$3,500,000</td>
<td>$4,000,000</td>
<td></td>
</tr>
<tr>
<td>Factory expense</td>
<td>$1,300,000</td>
<td>$2,300,000</td>
<td></td>
</tr>
<tr>
<td>Corporate expense</td>
<td></td>
<td></td>
<td>$5,000,000</td>
</tr>
</tbody>
</table>

**Solution:** (a) Plant 1: Factory overhead rate \( FOHR_1 = \frac{1,300,000}{1,000,000} = 1.30 = 130\% \)

Plant 2: Factory overhead rate \( FOHR_2 = \frac{2,300,000}{1,750,000} = 1.3143 = 131.43\% \)

(b) Corporate overhead rate \( COHR = \frac{5,000,000}{1,000,000 + 1,750,000} = 1.8182 = 181.82\% \)

3.14 The hourly rate for a certain work center is to be determined based on the following data: direct labor rate = $15.00/hr; applicable factory overhead rate on labor = 35%; capital investment in machine = $200,000; service life of the machine = 5 years; rate of return = 15%; salvage value in five years = zero; and applicable factory overhead rate on machine = 40%. The work center will be operated two 8-hour shifts, 250 days per year. Determine the appropriate hourly rate for the work center.

**Solution:** \( (A/P,i,n) = (A/P,15\%,5) = \frac{0.15(1 + 0.15)^5}{(1 + 0.15)^5 - 1} = 0.2983 \)

\[ UAC = 200,000(0.2983) = 59,663/yr \]

Hours/yr = (16 hr/day)(250 days/yr) = 4000 hr/yr, so \( C_m = 59,663/4000 = $14.92/hr \)

Given \( C_e = 15.00/hr, C_o = 15.00(1 + 0.35) + 14.92(1 + 0.40) = $41.13/hr \)

3.15 In the previous problem if the workload for the cell can justify a three-shift operation, determine the appropriate hourly rate for the work center.

**Solution:** Same \( UAC \) as in previous solution: \( UAC = 59,663/yr, C_m = 59,663/6000 = 9.94/hr \)

\( C_o = 15.00(1 + 0.35) + 9.94(1 + 0.40) = $34.17/hr \)

3.16 In the operation of a certain production machine, one worker is required at a direct labor rate = $10/hr. Applicable labor factory overhead rate = 50%. Capital investment in the system = $250,000, expected service life = 10 years, no salvage value at the end of that period, and the applicable machine factory overhead rate = 30%. The work cell will operate 2000 hr/yr. Use a rate of return of 25% to determine the appropriate hourly rate for this work cell.

**Solution:** \( (A/P,25\%,10) = \frac{0.25(1 + 0.25)^10}{(1 + 0.25)^10 - 1} = 0.2801 \)

\[ UAC = 250,000(0.2801) = 70,025/yr \]

Machine rate \( C_m = 70,025/2000 = $35.01 \)

\( C_o = 10.00(1 + 0.50) + 35.01(1 + 0.30) = $60.52/hr \)
In the previous problem, suppose that the machine will be operated three shifts, or 6000 hr/yr, instead of 2000 hr/yr. Note the effect of increased machine utilization on the hourly rate compared to the rate determined in the previous problem.

**Solution:** \( (A/P, 25\%, 10) = 0.2801 \) as in previous problem.

\[
\begin{align*}
UAC &= 250,000(0.2801) = 70,025 \text{/year} \\
\text{Machine rate } C_m &= 70,025/6000 = $11.67 \\
C_o &= 10.00(1 + 0.50) + 11.67(1 + 0.30) = $30.17/\text{hr}
\end{align*}
\]

3.18 The break-even point is to be determined for two production methods, one a manual method and the other automated. The manual method requires two workers at $10.00/hr each. Together, they produce at a rate of 36 units/hr. The automated method has an initial cost of $125,000, a 4-year service life, no salvage value, and annual maintenance costs = $3000. No labor (except for maintenance) is required to operate the machine, but the power required to run the machine is 50 kW (when running). Cost of electric power is $0.05/kWh. If the production rate for the automated machine is 100 units/hr, determine the break-even point for the two methods, using a rate of return = 25%.

**Solution:** Manual method: variable cost = (2 workers)($10.00/hr)/(36 pc/hr) = $0.5556/pc

Total cost as a function of \( Q \) is \( TC = 0.5556Q \) assuming no fixed costs.

Automated method: \( (A/P, 25\%, 4) = \frac{0.25(1 + 0.25)^4}{(1 + 0.25)^4 - 1} = (0.4234) \)

\[
\begin{align*}
UAC &= 125,000(A/P, 25\%, 4) + 3000 = 125,000(0.4234) + 3000 = $55,930/\text{yr} \\
\text{Variable cost} &= \frac{(50 \text{ kwh} / \text{hr})(\$0.05 / \text{kwh})}{100 \text{ pc} / \text{hr}} = 0.025/\text{pc} \\
\text{Total cost as a function of } Q &= 55,930 + 0.025Q \\
\text{Break-even point: } 0.5556Q &= 55,930 + 0.025Q, \quad 0.5306Q = 55,930, Q = \text{105,417 pc/yr}
\end{align*}
\]

Hours of operation per year: Manual: \( H = \frac{105,417 \text{ pc/yr}}{36 \text{ pc/hr}} = 2928.27 \text{ hr/yr.} \)

**Comment:** This would require two shifts.

Automated: \( H = \frac{105,417 \text{ pc/yr}}{100 \text{ pc/hr}} = 1054.17 \text{ hr/yr.} \)

**Comment:** Plenty of additional capacity in one shift beyond the break-even point.
Chapter 4
INTRODUCTION TO AUTOMATION

REVIEW QUESTIONS

4.1 What is automation?

Answer: Several definitions of automation are given throughout the book. The definition given in this chapter is the following: Automation can be defined as the technology by which a process or procedure is accomplished without human assistance.

4.2 An automated system consists of what three basic elements.

Answer: The three basic elements of an automated system are (1) power to accomplish the process and operate the system, (2) a program of instructions to direct the process, and (3) a control system to actuate the instructions.

4.3 What is the difference between a process parameter and a process variable?

Answer: Process parameters are inputs to the process, such as temperature setting of a furnace, coordinate axis value in a positioning system, and motor on or off. Process variables are outputs from the process; for example, the actual temperature of the furnace, the actual position of the axis, and the rotational speed of the motor.

4.4 What are two reasons why decision-making is required in a programmed work cycle?

Answer: Reasons given in the text are (1) operator interaction is required, so the operator enters the decision, (2) different part or product styles are processed by the system, and the system must decide how to process the current work unit, and (3) there are variations in the starting work units, and decisions must be made about adjustments in the work cycle to compensate.

4.5 What is the difference between a closed-loop control system and an open-loop control system?

Answer: A closed loop control system is one in which the output variable is compared with an input parameter using a feedback loop, and any difference between the output and input is used to drive the output into agreement with the input. By contrast, an open loop control system operates without the feedback loop, and so there is no verification that the control action has been correctly carried out.

4.6 What is safety monitoring in an automated system?

Answer: Safety monitoring in an automated system involves the use of sensors to track the system’s operation and identify conditions and events that are unsafe or potentially unsafe. The system is programmed to respond to unsafe conditions in some appropriate way, such as stopping the system or sounding an alarm.

4.7 What is error detection and recovery in an automated system?

Answer: Error detection and recovery refers to the capability of an automated system to both diagnose a malfunction when it occurs and take some form of corrective action to restore the system to normal operation. In the ideal recovery mode, the system recovers from the malfunction on its own, without human assistance.

4.8 Name three of the four possible strategies in error recovery.

Answer: The four possible strategies identified in the text are (1) make adjustments at the end of the current work cycle to recover from the malfunction, (2) make adjustments during the current cycle, (3) stop the process to invoke corrective action, and (4) stop the process and call for help.

4.9 Identify the five levels of automation in a production plant.

Answer: The five levels of automation defined in the text are (1) device level, (2) machine level, (3) cell or system level, (4) plant level, and (5) enterprise level.
Chapter 5
INDUSTRIAL CONTROLS

REVIEW QUESTIONS

5.1 What is industrial control?

**Answer:** As defined in the text, industrial control is the automatic regulation of unit operations and their associated equipment as well as the integration and coordination of the unit operations into a larger production system.

5.2 What is the difference between a continuous variable and a discrete variable?

**Answer:** A continuous variable (or parameter) is one that is uninterrupted as time proceeds, and it is generally considered to be analog, which means it can take on any value within a certain range. A discrete variable (or parameter) is one that can take on only certain values within a given range, such as on or off.

5.3 Name and briefly define each of the three different types of discrete variables.

**Answer:** The three different types of discrete variables are (1) binary, (2) discrete other than binary, and (3) pulse data. Binary means the variable can take on either of two possible values, ON or OFF, open or closed, and so on. Discrete variables other than binary are variables that can take on more than two possible values but less than an infinite number. Pulse data consist of a train of pulses and each pulse can be counted.

5.4 What is the difference between a continuous control system and a discrete control system?

**Answer:** A continuous control system is one in which the variables and parameters are continuous and analog. A discrete control system is one in which the variables and parameters are discrete, mostly binary discrete.

5.5 What is feedforward control?

**Answer:** Feedforward control is a means of control that anticipates the effect of disturbances that will upset the process by sensing them and compensating for them before they can affect the process. The feedforward control elements sense the presence of a disturbance and take corrective action by adjusting a process parameter that compensates for any effect the disturbance will have on the process.

5.6 What is adaptive control?

**Answer:** Adaptive control combines feedback control and optimal control by measuring the relevant process variables during operation (as in feedback control) and using a control algorithm that attempts to optimize some index of performance (as in optimal control). Adaptive control is distinguished from feedback control and steady-state optimal control by its unique capability to cope with a time-varying environment.

5.7 What are the three functions of adaptive control?

**Answer:** The three functions of adaptive control are the following: (1) Identification function, in which the current value of the index of performance of the system is determined, based on measurements collected from the process. (2) Decision function, which consists of deciding what changes should be made to improve system performance. Possible decisions include changing one or more input parameters to the process, altering some of the internal parameters of the controller, or making other changes. (3) Modification function, which means implementing the decision. Whereas decision is a logic function, modification is concerned with physical changes in the system, such as changing the system parameters or process inputs to drive the system toward a more optimal state.

5.8 What is the difference between an event-driven change and a time-driven change in discrete control?

**Answer:** An event-driven change means that some event has occurred to cause the state of the system to be altered. A time-driven change refers to a change that occurs at a specific point in time or after a certain time lapse has occurred.

5.9 What are the two basic requirements that must be managed by the controller to achieve real-time control?

**Answer:** The two basic requirements are: (1) it must be able to respond to process-initiated interrupts and (2) it must be able to execute certain actions at specified points in time. These two requirements correspond
5.10 What is polling in computer process control?

**Answer:** In computer process control, polling refers to the periodic sampling of data that indicates the status of the process.

5.11 What is an interlock? What are the two types of interlocks in industrial control?

**Answer:** An interlock is a capability by which the controller is able to sequence the activities in a work cell, ensuring that the actions of one piece of equipment are completed before the next piece of equipment begins its activity. The two types of interlocks are (1) input interlocks, which are signals originating from external devices and (2) output interlocks, which are signals sent by the controller to external devices.

5.12 What is an interrupt system in computer process control?

**Answer:** According to the text, an interrupt system is a computer control feature that permits the execution of the current program to be suspended in order to execute another program or subroutine in response to an incoming signal indicating a higher priority event. Upon receipt of an interrupt signal, the computer system transfers to a predetermined subroutine designed to deal with the specific interrupt.

5.13 What is computer process monitoring?

**Answer:** Computer process monitoring involves the use of the computer to observe the process and associated equipment and to collect and record data from the operation, but the computer is not used to directly control the process.

5.14 What is direct digital control (DDC), and why is it no longer used in industrial process control applications?

**Answer:** DDC is a computer process control system in which certain components in a conventional analog control system are replaced by the digital computer, and the regulation of the process is accomplished by the digital computer on a time-shared, sampled-data basis rather than by the many individual analog components working in a dedicated continuous manner. The reason why DDC is no longer used in industrial process control applications is that today’s control computers are capable of much more than simply imitating the proportion-integral-derivative (PID) control mode of analog devices.

5.15 Are programmable logic controllers (PLCs) more closely associated with the process industries or the discrete manufacturing industries?

**Answer:** The discrete manufacturing industries. They replaced the electromechanical relays previously used to control on-off type control actions.

5.16 What is a distributed control system?

**Answer:** A distributed control system is one consisting of multiple microcomputers connected together to share and distribute the process control workload.

5.17 What is the open architecture philosophy in control systems design?

**Answer:** The open architecture philosophy in control systems design means that vendors of control hardware and software agree to comply with published standards that allow their products to be interoperable, thus permitting components from different vendors to be interconnected in the same system.
Chapter 6
HARDWARE COMPONENTS FOR AUTOMATION AND INDUSTRIAL CONTROL

REVIEW QUESTIONS

6.1 What is a sensor?

**Answer:** As defined in the text, a sensor is a device that converts a physical stimulus or variable of interest (such as temperature, force, pressure, or displacement) into a more convenient form (usually an electrical quantity such as voltage) for the purpose of measuring the stimulus.

6.2 What is the difference between an analog sensor and a discrete sensor?

**Answer:** An analog measuring device produces a continuous analog signal such as electrical voltage, whose value varies in an analogous manner with the variable being measured. A discrete measuring device produces an output that can have only certain values. Discrete sensor devices divide into two categories: (1) binary, in which the measuring device produces an on/off signal, and (2) digital, in which the measuring device produces either a set of parallel status bits or a series of pulses that can be counted.

6.3 What is the difference between an active sensor and a passive sensor?

**Answer:** An active sensor is one that responds to a stimulus without the need for any external power. A passive sensor is one that requires an external source of power in order to operate.

6.4 What is the transfer function of a sensor?

**Answer:** A transfer function is the relationship between the value of the physical stimulus and the value of the signal produced by the sensor in response to the stimulus. It is the input/output relationship of the sensor.

6.5 What is an actuator?

**Answer:** An actuator is a hardware device that converts a controller command signal into a change in a physical parameter. An actuator is a transducer, because it changes one type of physical quantity, such as electric current, into another type of physical quantity, such as rotational speed of an electric motor.

6.6 Nearly all actuators can be classified into one of three categories, according to type of drive power. Name the three categories.

**Answer:** The three categories are (1) electrical, (2) hydraulic, and (3) pneumatic.

6.7 Name the two main components of an electric motor.

**Answer:** The two components are the stator, which is the stationary component, and the rotor, which rotates inside the stator.

6.8 In a DC motor, what is a commutator?

**Answer:** A commutator is a rotary switching device that rotates with the rotor and picks up current from a set of carbon brushes that are components of the stator assembly. Its function is to continually change the relative polarity between the rotor and the stator, so that the magnetic field produces a torque to continuously turn the rotor.

6.9 What are the two important disadvantages of DC electric motors that make the AC motor relatively attractive?

**Answer:** According to the text, the two important disadvantages of DC motors are (1) the commutator and brushes used to conduct current between the stator assembly and the rotor result in maintenance problems, and (2) the most common electrical power source in industry is alternating current, not direct current. In order to use AC power to drive a DC motor, a rectifier must be added to convert the alternating current to direct current.

6.10 How is the operation of a stepper motor different from the operation of conventional DC or AC motors?

**Answer:** Conventional DC and AC motors rotate continuously based on a continuous DC or AC power source. A stepper motor rotates in discrete angular displacements, called step angles. Each angular step is
actuated by a discrete electrical pulse. The total rotation of the motor shaft is determined by the number of pulses received by the motor, and rotational speed is determined by the frequency of the pulses.

6.11 What is a solenoid?

**Answer:** A solenoid is an actuator that consists of a movable plunger inside a stationary wire coil. When a current is applied to the coil, it acts as a magnet, drawing the plunger into the coil. When current is switched off, a spring returns the plunger to its previous position.

6.12 What is the difference between a hydraulic actuator and a pneumatic actuator?

**Answer:** Oil is used in hydraulic actuators, while compressed air is used in pneumatic actuators.

6.13 Briefly describe the three phases of the analog-to-digital conversion process?

**Answer:** The three phases of the A/D conversion process are (1) sampling, which consists of converting the continuous signal into a series of discrete analog signals at periodic intervals; (2) quantization, in which each discrete analog signal is assigned to one of a finite number of previously defined amplitude levels, which are discrete values of voltage ranging over the full scale of the ADC; and (3) encoding, in which the discrete amplitude levels obtained during quantization are converted into digital code, representing the amplitude level as a sequence of binary digits.

6.14 What is the resolution of an analog-to-digital converter?

**Answer:** The resolution of an ADC is the precision with which the analog signal is evaluated. Since the signal is represented in binary form, precision is determined by the number of quantization levels, which in turn is determined by the bit capacity of the ADC and the computer. In equation form, resolution \( R_{\text{ADC}} = \frac{L}{2^n-1} \), where \( L \) = full scale range of the ADC and \( n \) = number of bits.

6.15 Briefly describe the two steps in the digital-to-analog conversion process?

**Answer:** The two steps in the D/A conversion process are (1) decoding, in which the digital output of the computer is converted into a series of analog values at discrete moments in time, and (2) data holding, in which each successive value is changed into a continuous signal (usually electrical voltage) used to drive the analog actuator during the sampling interval.

6.16 What is the difference between a contact input interface and a contact output interface?

**Answer:** A contact input interface is a device by which binary data are read into the computer from some external source (e.g., the process). It consists of a series of simple contacts that can be either closed or open (on or off) to indicate the status of binary devices connected to the process. A contact output interface is a device that communicates on/off signals from the computer to the process.

6.17 What is a pulse counter?

**Answer:** A pulse counter is a device used to convert a series of pulses into a digital value.

**PROBLEMS**

**Sensors**

6.1 During calibration, an Iron/Constantan thermocouple is zeroed (set to emit a zero voltage) at 0°C. At 750°C, it emits a voltage of 38.8 mV. A linear output/input relationship exists between 0°C and 750°C. Determine (a) the transfer function of the thermocouple and (b) the temperature corresponding to a voltage output of 29.6 mV.

**Solution:** (a) \( E = mT \quad 38.8 \text{ mV} = m(750°C) \quad m = \frac{38.8}{750} = 0.05173 \text{ mV/°C} \)

Transfer function: \( E = 0.05173 \ T \)

(b) At \( E = 29.6 \text{ mV}, \ T = \frac{V}{m} = \left(0.05173^{-1}\right) (29.6) = 572°C \)

6.2 A digital tachometer is used to determine the surface speed of a rotating workpiece in surface ft/min. Tachometers are designed to read rotational speed in rev/min, but in this case the shaft of the tachometer is directly coupled to a wheel whose outside rim is made of rubber. When the wheel rim is pressed against the surface of the rotating workpiece, the tachometer provides a reading of surface speed. The desired units for surface speed are ft/min. What is the diameter of the wheel rim that will provide a direct reading of surface speed?
speed in ft/min?

**Solution:** Circumference of wheel \( C = 1 \text{ ft} = 12 \text{ in} \)

\[ C = \pi D \quad D = C/\pi = 3.8197 \text{ in} \]

6.3 A digital flow meter operates by emitting a pulse for each unit volume of fluid flowing through it. The particular flow meter of interest here has a unit volume of 57.9 cm\(^3\) per pulse. In a certain process control application, the flow meter emitted 4089 pulses during a period of 3.6 min. Determine (a) the total volume of fluid that flowed through the meter and (b) the flow rate of fluid flow. (c) What is the pulse frequency (Hz) corresponding to a flow rate of 75,000 cm\(^3\)/min?

**Solution:**

(a) \( V = 4089 \times 57.9 = 236,753 \text{ cm}^3 \)

(b) \( Q = 236,753/3.6 = 65,765 \text{ cm}^3/\text{min} \)

(c) \( f_p = (1250 \text{ cm}^3/\text{sec})/(57.9 \text{ cm}^3/\text{pulse}) = 21.59 \text{ pulse/sec} = 21.59 \text{ Hz} \)

6.4 A tool-chip thermocouple is used to measure the cutting temperature in a turning operation. The two dissimilar metals in a tool-chip thermocouple are the tool material and the workpiece metal. During the turning operation, the chip from the work metal forms a junction with the rake face of the tool to create the thermocouple at exactly the location where it is desired to measure temperature: at the interface between the tool and the chip. A separate calibration procedure must be performed for each combination of tool material and work metal. In the combination of interest here, the calibration curve (inverse transfer function) for a particular grade of cemented carbide tool when used to turn C1040 steel is the following:

\[ T = 88.1E_{tc} - 127 \]

where \( T \) = temperature in °F, and \( E_{tc} \) = the emf output of the thermocouple in mV. (a) Revise the temperature equation so that it is in the form of a transfer function similar to that given in Eq. (6.3). What is the sensitivity of this tool-chip thermocouple? (b) During a straight turning operation, the emf output of the thermocouple was measured as 9.25 mV. What was the corresponding cutting temperature?

**Solution:**

(a) \( T = 88.1E_{tc} - 127 \)

\[ s = T \quad s = C + ms \]

Manipulating the temperature equation into the form of Eq. (6.3), \( T + 127 = 88.1E_{tc} \)

\[ E_{tc} = (T + 127) / 88.1 = 0.01135T + 1.4415 \]

In Eq. (6.3), \( C = 1.4415 \text{ and m} = 0.01135 \), where \( m \) = sensitivity

(b) \( T = 88.1(9.25) - 127 = 815 - 127 = 688 \text{ °F} \)

**Actuators**

6.5 A DC servomotor is used to actuate one of the axes of an x-y positioner. The motor has a torque constant of 8.75 in-lb/A and a voltage constant of 10 V/(1000 rev/min). The armature resistance is 2.0 ohms. At a given moment, the positioner table is not moving and a voltage of 20 V is applied to the motor terminals. Determine the torque (a) immediately after the voltage is applied and (b) at a rotational speed of 400 rev/min. (c) What is the maximum theoretical speed of the motor?

**Solution:**

(a) \( I_a = 20/2 = 10 \text{ A} \)

\[ T = 8.75 \text{ in-lb/A}(10 \text{ A}) = 87.5 \text{ in-lb} \]

(b) \( I_a = \frac{20 - 10(400/1000)}{2} = (20 - 4)/2 = 8 \text{ A} \)

\[ T = 8.75(8) = 70 \text{ in-lb} \]

(c) Max \( N \) occurs at \( V_{in} = K_cN \)

Set \( K_cN = 20 = (10/1000)N = 0.01N \)

\[ N = 2000 \text{ rev/min} \]

6.6 A DC servomotor has a torque constant = 0.088 N-m/A and a voltage constant = 0.14 V/(rad/sec). The armature resistance is 2.15 ohms. A terminal voltage of 30 V is used to operate the motor. Determine (a) the starting torque generated by the motor just as the voltage is applied, (b) the maximum speed at a torque of zero, and (c) the operating point of the motor when it is connected to a load whose torque characteristic is proportional to speed with a constant of proportionality = 0.011 N-m/(rad/sec).

**Solution:**

(a) \( I_a = 30/2.15 = 13.95 \text{ A} \)

\[ T = 0.088(13.95) = 1.228 \text{ N-m} \]

(b) Max \( \omega \) occurs at \( K_c\omega = V_{in} \)

\[ \omega = 30 \]

\[ \omega = 30/0.14 = 214.3 \text{ rad/sec} \]
(c) \( T_L = 0.011 \omega \)

\[
T = K_i \left( \frac{V_a - K_v \omega}{R_a} \right) = 0.088 \left( \frac{30 - 0.14\omega}{2.15} \right) = 0.088(13.953 - 0.0651\omega) = 1.228 - 0.00573\omega
\]

Set \( T = T_L \)

\[
1.228 - 0.00573\omega = 0.011\omega
\]

\[
1.228 = (0.011 + 0.00573)\omega = 0.01673\omega
\]

\( \omega = 73.4 \text{ rad/sec} \)

6.7 In the previous problem, what is the power delivered by the motor at the operating point in units of (a) Watts and (b) horsepower?

Solution: (a) \( P = T\omega \)

\( \omega = 73.6 \text{ rad/sec from previous problem} \)

\[
T = 1.148 - 0.0459\omega = 1.148 - 0.00459(73.6) = 0.81 \text{ N-m}
\]

\[
P = 0.81(73.6) = 59.5 \text{ W}
\]

(b) \( HP = \frac{59.6}{745.7} = 0.080 \text{ hp} \)

6.8 A voltage of 24 V is applied to a DC servomotor whose torque constant = 0.115 N-m/A and voltage constant = 0.097 V/(rad/sec). Armature resistance = 1.9 ohms. The motor is directly coupled to a blower shaft for an industrial process. (a) What is the stall torque of the motor? (b) Determine the operating point of the motor if the torque-speed characteristic of the blower is given by the following equation: \( T_L = K_{L1}\omega + K_{L2}\omega^2 \), where \( T_L \) = load torque, N-m; \( \omega \) = angular velocity, rad/sec; \( K_{L1} = 0.005 \text{ N-m/(rad/sec)} \); and \( K_{L2} = 0.00033 \text{ N-m/(rad/sec)^2} \). (c) What horsepower is being generated by the motor at the operating point?

Solution: (a) \( I_a = \frac{24}{1.9} = 12.63 \text{ A} \)

\[
T = 0.115(12.63) = 1.45 \text{ N-m}
\]

(b) Load torque (given): \( T_L = 0.005\omega + 0.00033\omega^2 \)

Motor torque: \( T = 0.115 \left( \frac{24 - 0.097\omega}{1.9} \right) = 0.115(12.63 - 0.051\omega) \)

\[
T = 1.452 - 0.00587\omega
\]

Set \( T = T_L \)

\[
1.452 - 0.00587\omega = 0.005\omega + 0.00033\omega^2
\]

\[
1.452 - 0.001087\omega - 0.00033\omega^2 = 0
\]

Rearranging, \( 0.00033\omega^2 + 0.01087\omega - 1.452 = 0 \)

Solving the quadratic equation, \( \omega = -16.47 \pm 68.35 = 51.88 \text{ rad/sec} \) (negative value not feasible)

(c) \( HP = \frac{1.148(51.88)}{745.7} = 0.08 \text{ hp} \)

6.9 The step angle of a certain stepper motor = 1.8°. The application of interest is to rotate the motor shaft through 15 complete revolutions at an angular velocity of 25 rad/sec. Determine (a) the required number of pulses and (b) the pulse frequency to achieve the specified rotation.

Solution: \( \alpha = 1.8^\circ \)

\( n_x = 360/1.8 = 200 \text{ step angles} \)

(a) To rotate 15 revolutions, \( A_m = 15(360) = 5400^\circ \)

\( n_p = 5400/1.8 = 3000 \text{ pulses} \)

(b) To rotate at 25 rad/sec, \( f_p = 25(200) / 2\pi = 795.8 \text{ Hz} \)

6.10 A stepper motor has a step angle = 7.5°. (a) How many pulses are required for the motor to rotate through five complete revolutions? (b) What pulse frequency is required for the motor to rotate at a speed of 200 rev/min?

Solution: \( \alpha = 7.5^\circ \)

\( n_x = 360/7.5 = 48 \text{ step angles} \)

(a) To rotate 5 revolutions, \( A_m = 5(360) = 1800^\circ \)

\( n_p = 1800/7.5 = 240 \text{ pulses} \)

(b) To rotate at 200 rev/min, \( f_p = 200(48) / 60 = 160 \text{ Hz} \)

6.11 The shaft of a stepper motor is directly connected to a lead screw that drives a worktable in an x-y positioning system. The motor has a step angle = 5°. The pitch of the lead screw is 6 mm, which means that the worktable moves in the direction of the lead screw axis by a distance of 6 mm for each complete
revolution of the screw. It is desired to move the worktable a distance of 300 mm at a top speed of 40 mm/sec. Determine (a) the number of pulses and (b) the pulse frequency required to achieve this movement.

**Solution:** $\alpha = 5^\circ/\text{step}$

Pitch $p = 6 \text{ mm/rev}$

$x = 300 \text{ mm at } v = 40 \text{ mm/sec}$

Number of revolutions $= 300/6 = 50$ revolutions of the motor shaft

$N = (40 \text{ mm/sec})(60 \text{ sec/min})(1 \text{ rev/6 mm}) = 400 \text{ rev/min} = 6.667 \text{ rev/sec}$

(a) $A_m = (50 \text{ rev})(360^\circ/\text{rev}) = 18,000^\circ$

$n_p = 18,000^\circ/5^\circ = 3600$ pulses

(b) $f_p = Nn_p/60 = 6.667(72) = 480 \text{ Hz}$

6.12 A single-acting hydraulic cylinder with spring return has an inside diameter of 80 mm. Its application is to push pallets off of a conveyor into a storage area. The hydraulic power source can generate up to 3.2 MPa of pressure at a flow rate of 175,000 mm$^3$/sec to drive the piston. Determine (a) the maximum possible velocity of the piston and (b) the maximum force that can be applied by the apparatus.

**Solution:** Area of cylinder $A = 0.25\pi(80)^2 = 5026.55 \text{ mm}^2$

(a) $V = Q/A = (175,000 \text{ mm}^3/\text{sec}) / 5026.55 \text{ mm}^2 = 34.815 \text{ mm/sec}$

(b) $F = pA = (3.2 \text{ N/mm}^2)(5026.55) = 16,085 \text{ N}$

6.13 A double-acting hydraulic cylinder has an inside diameter = 75 mm. The piston rod has a diameter = 14 mm. The hydraulic power source can generate up to 5.0 MPa of pressure at a flow rate of 200,000 mm$^3$/sec to drive the piston. (a) What are the maximum possible velocity of the piston and the maximum force that can be applied in the forward stroke? (b) What are the maximum possible velocity of the piston and the maximum force that can be applied in the reverse stroke?

**Solution:** Forward stroke area $A = 0.25\pi(75)^2 = 4418 \text{ mm}^2$

Reverse stroke area $A = 4418 - 0.25\pi(14)^2 = 4264 \text{ mm}^2$

(a) Forward stroke $v = 200,000 / 4418 = 45.3 \text{ mm/sec}$

$F = 5(4418) = 22,090 \text{ N}$

(b) Reverse stroke $v = 200,000 / 4264 = 46.9 \text{ mm/sec}$

$F = 5(4264) = 21,320 \text{ N}$

6.14 A double-acting hydraulic cylinder is used to actuate a linear joint of an industrial robot. The inside diameter of the cylinder is 3.5 in. The piston rod has a diameter of 0.5 in. The hydraulic power source can generate up to 500 lb/in$^2$ of pressure at a flow rate of 1200 in$^3$/min to drive the piston. (a) Determine the maximum velocity of the piston and the maximum force that can be applied in the forward stroke. (b) Determine the maximum velocity of the piston and the maximum force that can be applied in the reverse stroke.

**Solution:** Forward stroke area $A = 0.25\pi(3.5)^2 = 9.62 \text{ in}^2$

Reverse stroke area $A = 9.62 - 0.25\pi(0.5)^2 = 9.42 \text{ in}^2$

(a) Forward stroke $v = 1200 / 9.62 = 124 \text{ in/min}$

$F = 500(9.62) = 4810 \text{ lb}$

(b) Reverse stroke $v = 1200 / 9.42 = 127.4 \text{ in/min}$

$F = 500(9.42) = 4710 \text{ lb}$

**ADC and DAC**

6.15 A continuous voltage signal is to be converted into its digital counterpart using an analog-to-digital converter. The maximum voltage range is ±30 V. The ADC has a 15-bit capacity. Determine (a) number of quantization levels, (b) resolution, (c) the spacing of each quantization level, and the quantization error for this ADC.

**Solution:** Number of quantization levels $= 2^{15} = 32,768$

$R_{ADC} = \frac{60}{32768-1} = 0.00183 \text{ volts}$
6.16 A voltage signal with a range of zero to 115 V, is to be converted by means of an ADC. Determine the minimum number of bits required to obtain a quantization error of (a) ±5 V maximum, (b) ±1 V maximum, (c) ±0.1 V maximum.

Solution: (a) ±5 volts max = ±0.5 \( R_{ADC} \) = \( \frac{1}{2} \left( \frac{115}{2^n - 1} \right) \)

Since 115 = 0.5(115)/5 = 11.5, 2^n = 12.5

\( n \ln(2) = \ln(12.5) \)

\( n = \frac{\ln(12.5)}{\ln(2)} = 3.64 \)

→ Use \( n = 4 \)

(b) ±1 volt max = ±0.5 \( R_{ADC} \) = \( \frac{1}{2} \left( \frac{115}{2^n - 1} \right) \)

Since 115 = 0.5(115)/1 = 57.5, 2^n = 58.5

\( n \ln(2) = \ln(58.5) \)

\( n = \frac{\ln(58.5)}{\ln(2)} = 5.87 \)

→ Use \( n = 6 \)

(c) ±0.1 volt max = ±0.5 \( R_{ADC} \) = \( \frac{1}{2} \left( \frac{115}{2^n - 1} \right) \)

Since 115 = 0.5(115)/0.1 = 575.0, 2^n = 576.0

\( n \ln(2) = \ln(576) \)

\( n = \frac{\ln(576)}{\ln(2)} = 9.17 \)

→ Use \( n = 10 \)

6.17 A digital-to-analog converter uses a reference voltage of 120 V dc and has eight binary digit precision. In one of the sampling instants, the data contained in the binary register = 01010101. If a zero-order hold is used to generate the output signal, determine the voltage level of that signal.

Solution: \( V_o = 120 \{0.5(0) + 0.25(1) + 0.125(0) + 0.0625 (1) + 0.03125(0) + 0.015625(1) + 0.007812(0) + 0.003906(1)\} \)

\( V_o = 39.84 \) volts

6.18 A DAC uses a reference voltage of 60 V and has 6-bit precision. In four successive sampling periods, each 1 second long, the binary data contained in the output register were 100000, 011111, 011101, and 011010. Determine the equation for the voltage as a function of time between sampling instants 3 and 4 using (a) a zero-order hold, and (b) a first-order hold.

Solution: First sampling instant: 100000, \( V_o = 60(0.5) = 30.0 \) volts

Second sampling instant: 011111, \( V_o = 60(0.25 + 0.125 + 0.0625 + 0.03125 + 0.015625) = 29.025 \) volts

Third sampling instant: 011101, \( V_o = 60(0.25 + 0.125 + 0.0625 + 0.015625) = 27.1875 \) volts

Fourth sampling instant: 011010, \( V_o = 60(0.25 + 0.125 + 0.015625) = 23.4375 \) volts

(a) Zero order hold: \( V(t) = 27.1875 \) between instants 3 and 4

(b) First order hold: \( V(t) = 27.1875 + a \cdot t \) between instants 3 and 4

\( a = (27.1875 - 29.025)/1 = -1.875 \)

\( V(t) = 27.1875 - 1.875 \cdot t \)

6.19 In the previous problem, suppose that a second order hold were to be used to generate the output signal. The equation for the second-order hold is the following: \( E(t) = E_0 + \alpha \cdot t + \beta \cdot t^2 \), where \( E_0 = \) starting voltage at the beginning of the time interval. (a) For the binary data given in the previous problem, determine the values of \( \alpha \) and \( \beta \) that would be used in the equation for the time interval between sampling instants 3 and 4. (b) Compare the first-order and second-order holds in anticipating the voltage at the 4th instant.

Solution: \( t = 0: V(t) = 27.19 = 27.19 + a(0) + b(0) \)

\( t = -1: V(t) = 29.06 = 27.19 + a(-1) + b(1) \)

\( t = -2: V(t) = 30.0 = 27.19 + a(-2) + b(4) \)

Simultaneous solution yields \( a = -3.444 \) and \( b = -0.469 \)

\( V(t) = 27.19 - 3.444 \cdot t - 0.469 \cdot t^2 \)

At the fourth instant, the second order hold yields \( V(t) = 27.19 - 3.444(1) - 0.469(1) = 24.38 \) volts

At the fourth instant, the first order hold yields
\[ V(t) = 27.19 - 1.875(1) = 25.31 \text{ volts} \]

The actual voltage level at the fourth instant is 24.38 volts. Hence, the second-order hold more accurately projects the voltage.
Chapter 7
NUMERICAL CONTROL

REVIEW QUESTIONS

7.1 What is numerical control?
   Answer: As defined in the text, numerical control (NC) is a form of programmable automation in which the mechanical actions of a machine tool or other equipment are controlled by a program containing coded alphanumeric data.

7.2 What are the three basic components of an NC system?
   Answer: The three components are (1) the part program of instructions, (2) the machine control unit, and (3) the processing equipment (e.g., machine tool) that accomplishes the operation.

7.3 What is the right-hand rule in NC and where is it used?
   Answer: The right-hand rule is used to distinguish positive and negative directions for the rotational axes in NC. Using the right hand with the thumb pointing in the positive linear axis direction (+x, +y, or +z), the fingers of the hand are curled in the positive rotational direction for the a, b, and c axes.

7.4 What is the difference between point-to-point and continuous path control in a motion control system?
   Answer: Point-to-point systems move the worktable to a programmed location without regard for the path taken to get to that location. By contrast, continuous path systems are capable of continuous simultaneous control of two or more axes, thus providing control of the tool trajectory relative to the workpart.

7.5 What is linear interpolation, and why is it important in NC?
   Answer: Linear interpolation is the capability to machine along a straight-line trajectory that may not be parallel to one of the worktable axes. It is important in NC because many workpiece geometries require cuts to be made along straight lines to form straight edges and flat surfaces, and the angles of the lines are not be parallel to one of the axes in the coordinate system.

7.6 What is the difference between absolute positioning and incremental positioning?
   Answer: In absolute positioning, the workhead locations are always defined with respect to the origin of the NC axis system. In incremental positioning, the next workhead position is defined relative to the present location.

7.7 How is computer numerical control (CNC) distinguished from conventional NC?
   Answer: CNC is an NC system whose machine control unit is a dedicated microcomputer rather than a hard-wired controller, as in conventional NC.

7.8 Name five of the ten features and capabilities of a modern CNC machine control unit listed in the text.
   Answer: The ten features and capabilities identified in the text are (1) storage of more than one part program, (2) various forms of program input, such as punched tape, magnetic tape, floppy diskette, RS-232 communications with external computers, and manual data input, (3) program editing at the machine tool, (4) fixed cycles and programming subroutines (macros), (5) linear and circular interpolation, (6) workpiece positioning features for setup, (7) cutter length and size compensation, (8) acceleration and deceleration calculations when the cutter path changes abruptly, (9) communications interface, and (10) diagnostics to detect malfunctions and diagnose system breakdowns.

7.9 What is distributed numerical control (DNC)?
   Answer: Distributed numerical control is a distributed computer system in which a central computer communicates with multiple CNC machine control units. It evolved from direct numerical control in which the central computer played the role of the tape reader, downloading part programs one block at a time. In a modern distributed NC system, entire part programs are downloaded to the MCUs. Also shop floor data is collected by the central computer to measure shop performance.

7.10 What are some of the machine tool types to which numerical control has been applied?
**Answer:** NC has been applied to nearly all machine tools types, including lathes, boring mills, drill presses, milling machines, and cylindrical grinders.

7.11 What is a machining center?

**Answer:** As defined in the text, a machining center is a machine tool capable of performing multiple machining operations on a single workpiece in one setup. The operations involve rotating cutters, such as milling and drilling, and the feature that enables more than one operation to be performed in one setup is automatic tool-changing.

7.12 Name four of the six part characteristics that are most suited to the application of numerical control listed in the text.

**Answer:** The six part characteristics identified in the text are the following: (1) batch production, (2) repeat orders, (3) complex part geometry, (4) much metal needs to be removed, (5) many separate machining operations on the part, and (6) the part is expensive.

7.13 Although NC technology is most closely associated with machine tool applications, it has been applied to other processes also. Name three of the six examples listed in the text.

**Answer:** The six non-machine tool applications listed in the text are (1) electrical wire-wrap machines, (2) component insertion machines, (3) drafting machines (x-y plotters), (4) coordinate measuring machines, (5) tape laying machines for polymer composites, and (6) filament winding machines for polymer composites.

7.14 What are four advantages of numerical control when properly applied in machine tool operations?

**Answer:** The text lists the following 11 advantages: (1) nonproductive time is reduced, (2) greater accuracy and repeatability, (3) lower scrap rates, (4) inspection requirements are reduced, (5) more-complex part geometries are possible, (6) engineering changes can be accommodated more gracefully, (7) simpler fixtures are needed, (8) shorter manufacturing lead times, (9) reduced parts inventory, (10) less floor space required due to fewer machines, and (11) operator skill requirements are reduced.

7.15 What are three disadvantages of implementing NC technology?

**Answer:** Four disadvantages are identified in the text: (1) higher investment cost because NC machines are more expensive than conventional machine tools, (2) higher maintenance effort due to greater technological sophistication of NC, (3) part programming is required, and (4) equipment utilization must be high to justify the higher investment, and this might mean additional work shifts are required in the machine shop.

7.16 Briefly describe the differences between the two basic types of positioning control systems used in NC?

**Answer:** The two types of positioning control systems used in NC systems are open loop and closed loop. An open-loop system operates without verifying that the actual position achieved in the move is the same as the programmed position. A closed-loop system uses feedback measurements to confirm that the final position of the worktable is the location specified in the program.

7.17 What is an optical encoder, and how does it work?

**Answer:** An optical encoder is a device for measuring rotational speed that consists of a light source and a photodetector on either side of a disk. The disk contains slots uniformly spaced around the outside of its face. These slots allow the light source to shine through and energize the photodetector. The disk is connected to a rotating shaft whose angular position and velocity are to be measured. As the shaft rotates, the slots cause the light source to be seen by the photocell as a series of flashes. The flashes are converted into an equal number of electrical pulses.

7.18 With reference to precision in an NC positioning system, what is control resolution?

**Answer:** Control resolution is defined as the distance separating two adjacent addressable points in the axis movement. Addressable points are locations along the axis to which the worktable can be specifically directed to go. It is desirable for control resolution to be as small as possible.

7.19 What is the difference between manual part programming and computer-assisted part programming?
Answer: In manual part programming, the programmer prepares the NC code using a low-level machine language. In computer-assisted part programming, the part program is written using English-like statements that are subsequently converted into the low-level machine language.

7.20 What is postprocessing in computer-assisted part programming?

Answer: Postprocessing converts the cutter location data and machining commands in the CLDATA file into low-level code that can be interpreted by the NC controller for a specific machine tool. The output of postprocessing is a part program consisting of G-codes, x-, y-, and z-coordinates, S, F, M, and other functions in word address format. A unique postprocessor must be written for each machine tool system.

7.21 What are some of the advantages of CAD/CAM-based NC part programming compared to computer-assisted part programming?

Answer: The text lists the following advantages of CAD/CAM NC part programming: (1) the part program can be simulated off-line to verify its accuracy; (2) the time and cost of the machining operation can be determined; (3) the most appropriate tooling can be automatically selected for the operation; (4) the CAD/CAM system can automatically insert the optimum values for speeds and feeds; (5) in constructing the geometry or the tool path, the programmer receives immediate visual feedback on the CAD/CAM monitor; (6) the CAD database containing the part design can be used to construct the tool path rather than redefining the part geometry; and (7) some of the steps in the tool path construction can be automated.

7.22 What is manual data input of the NC part program?

Answer: Manual data input is when the machine operator manually enters the part program data and motion commands directly into the MCU prior to running the job.

PROBLEMS

NC Applications

7.1 A machinable grade of aluminum is to be milled on an NC machine with a 20 mm diameter four-tooth end milling cutter. Cutting speed = 120 m/min and feed = 0.008 mm/tooth. Convert these values to rev/min and mm/rev, respectively.

Solution: 

\[ N = \frac{120 \text{ m/min}}{20\pi(10^{-3}) \text{ m/rev}} = 1909.9 \text{ rev/min} \]

Feed in mm/rev = (4 teeth/rev)(0.08 mm/tooth) = 0.32 mm/rev

7.2 A cast iron workpiece is to be face milled on an NC machine using cemented carbide inserts. The cutter has 16 teeth and is 120 mm in diameter. Cutting speed = 200 m/min and feed = 0.005 mm/tooth. Convert these values to rev/min and mm/rev, respectively.

Solution: 

\[ N = \frac{200 \text{ m/min}}{120\pi(10^{-3}) \text{ m/rev}} = 530.5 \text{ rev/min} \]

Feed in mm/rev = (16 teeth/rev)(0.05 mm/tooth) = 0.80 mm/rev

7.3 An end milling operation is performed on an NC machining center. The total length of travel is 800 mm along a straight-line path to cut a particular workpiece. Cutting speed = 2.0 m/s and chip load (feed/tooth) = 0.075 mm. The end-milling cutter has two teeth and its diameter = 15.0 mm. Determine the feed rate and time to complete the cut.

Solution: 

\[ f = \frac{2.0(60) \text{ m/min}}{15\pi(10^{-3}) \text{ m/rev}} = 2546.5 \text{ rev/min} \]

\[ T_m = \frac{800 + 15*}{382.0} = 2.134 \text{ min} \]

* overtravel allowance = 1.0 tool diameter = 15 mm.

7.4 A turning operation is to be performed on an NC lathe. Cutting speed = 2.5 m/s, feed = 0.2 mm/rev, and depth = 4.0 mm. Workpiece diameter = 100 mm and its length = 400 mm. Determine (a) rotational speed of the workbar, (b) feed rate, (c) metal removal rate, and (d) time to travel from one end of the part to the other.
Solution: (a) \( N = \frac{2.5(60) \text{m/min}}{100\pi(10^{-3}) \text{m/rev}} = 477.5 \text{ rev/min} \)

(b) \( f_r = \frac{477.5 \text{ rev/min}(0.2 \text{ mm/rev})}{2.5 \text{ m/s}} = 95.5 \text{ mm/min} \)

(c) \( R_{MR} = \pi v_f d = 2.5 \text{ m/s}(10^3)(0.2 \text{ mm})(4.0 \text{ mm}) = 2000 \text{ mm}^3/\text{s} \)

(d) \( T_m = \frac{400}{95.5} = 4.188 \text{ min} \)

7.5 A numerical control drill press drills four 10.0 mm diameter holes at four locations on a flat aluminum plate in a production work cycle. Although the plate is only 12 mm thick, the drill must travel a full 20 mm vertically at each hole location to allow for clearance above the plate and breakthrough of the drill on the underside of the plate. Cutting conditions: speed = 0.4 m/s and feed = 0.10 mm/rev. Hole locations are indicated in the following table:

<table>
<thead>
<tr>
<th>Hole number</th>
<th>x-coordinate (mm)</th>
<th>y-coordinate (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.0</td>
<td>25.0</td>
</tr>
<tr>
<td>2</td>
<td>25.0</td>
<td>100.0</td>
</tr>
<tr>
<td>3</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>4</td>
<td>100.0</td>
<td>25.0</td>
</tr>
</tbody>
</table>

The drill starts out at point (0,0) and returns to the same position after the work cycle is completed. Travel rate of the table in moving from one coordinate position to another is 500 mm/min. Owing to effects of acceleration and deceleration, and time required for the control system to achieve final positioning, a time loss of 3 s is experienced at each stopping position of the table. Assume that all moves are made so as to minimize the total cycle time. If loading and unloading the plate take 20 s (total handling time), determine the time required for the work cycle.

Solution: Drilling operations: \( N = \frac{0.4(60)}{10\pi(10^{-3})} = 763.9 \text{ rev/min} \)

\( f_r = \frac{Nf_r}{2.5} = 76.39 \text{ mm/min} \)

For each hole, \( T_m = \frac{20}{76.39} = 0.262 \text{ min} \)

Assume retraction of drill at each hole takes an equal time. Total time/hole = 0.524 min

For four holes, \( T_m = 4(0.524) = 2.096 \text{ min} \)

Workpart and axis system with assumed tool path shown in accompanying drawing:

Total distance traveled between positions = \( \sqrt{25^2 + 25^2} + 75 + 75 + 75 + \sqrt{25^2 + 100^2} = 363.43 \text{ mm} \)

Time to move between positions = \( \frac{363.43}{500} + \frac{5(3)}{60} = 0.977 \text{ min} \)

Cycle time = \( T_m + T_m + \text{move time} = 20/60 + 2.096 + 0.977 = 3.406 \text{ min} \)

Analysis of Open Loop Positioning Systems

7.6 Two stepping motors are used in an open loop system to drive the lead screws for x-y positioning. The range of each axis is 500 mm. The shafts of the motors are connected directly to the lead screws. The pitch of each lead screw is 4.0 mm, and the number of step angles on the stepping motor is 125. (a) How closely can the position of the table be controlled, assuming there are no mechanical errors in the positioning system? (b) What are the
required pulse train frequencies and corresponding rotational speeds of each stepping motor in order to drive the table at 275 mm/min in a straight line from point \((x = 0, y = 0)\) to point \((x = 130 \text{ mm}, y = 220 \text{ mm})\)?

**Solution:** (a) Table position can be controlled to \(\frac{4}{125} = 0.032 \text{ mm}\). (b) Travel rate of the table \(v_t = 275 \text{ mm/min}\) from \((x = 0, y = 0)\) to \((x = 130 \text{ mm}, y = 220 \text{ mm})\).

\[
\text{Angle} = \tan^{-1}(220/130) = 59.42^\circ
\]

Travel rate for \(x\)-axis = \(275 \cos 59.42 = 139.9 \text{ mm/min}\)

\(x\)-axis motor speed \(N = \frac{139.9}{4} = 34.975 \text{ rev/min}\)

Pulse rate \(f_p = \frac{125(34.975)}{60} = 72.865 \text{ Hz}\)

Travel rate for \(y\)-axis = \(275 \sin 59.42 = 236.7 \text{ mm/min}\)

\(y\)-axis motor speed \(N = \frac{236.7}{4} = 59.175 \text{ rev/min}\)

Pulse rate \(f_p = \frac{125(59.175)}{60} = 123.281 \text{ Hz}\)

7.7 One axis of an NC positioning system is driven by a stepping motor. The motor is connected to a lead screw whose pitch is 4.0 mm, and the lead screw drives the table. Control resolution for the table is specified as 0.015 mm. Determine (a) the number of step angles required to achieve the specified control resolution, (b) size of each step angle in the motor, and (c) linear travel rate of the motor at a pulse frequency of 200 pulses per second.

**Solution:** (a) Number of step angles \(n_s = \frac{4.0 \text{ mm/rev}}{0.015 \text{ mm/pulse}} = 266.67 \rightarrow 267 \text{ pulses/rev}\)

(b) Step angle \(\alpha = \frac{360^\circ}{267} = 1.348^\circ\)

(c) Motor speed \(N = \frac{60 \text{ s/min}(200 \text{ pulses/s})}{267 \text{ pulses/rev}} = 44.94 \text{ rev/min}\)

Linear travel rate of machine table = 44.94 rev/min(4.0 mm/rev) = 179.8 mm/min

7.8 The worktable in an NC positioning system is driven by a lead screw with a 4 mm pitch. The lead screw is powered by a stepping motor which has 250 step angles. The worktable is programmed to move a distance of 100 mm from its present position at a travel speed of 300 mm/min. (a) How many pulses are required to move the table the specified distance? (b) What is the required motor speed and (c) pulse rate to achieve the desired table speed?

**Solution:** (a) Eq. (6.14): \(x = \frac{pA}{360}\). Rearranging, \(A = 360x/p = 360(100 \text{ mm})/(4.0 \text{ mm/rev.}) = 9000^\circ\)

\(\alpha = \frac{360^\circ}{250} = 1.44^\circ\)

Since \(r_g = 1.0, A = A_m = n_p\alpha\). Rearranging, \(n_p = A_m/\alpha = 9000^\circ/1.44^\circ = 6250 \text{ pulses.}\)

(b) \(N_m = \frac{300 \text{ mm/min}}{4.0 \text{ mm/rev.}} = 75 \text{ rev/min}\)

(c) Since \(r_g = 1.0, N = N_m\). Eq. (6.16): \(N = \frac{60f_p}{nr_g} = 75 \text{ rev/min}\)

Rearranging, \(f_p = \frac{312.5 \text{ Hz}}{75} = 4.167 \text{ Hz}\)
7.9 A stepping motor with 100 step angles is coupled to a lead screw through a gear reduction of 5:1 (5 rotations of the motor for each rotation of the lead screw). The lead screw has 2.4 threads/cm. The worktable driven by the lead screw must move a distance = 25.0 cm at a feed rate = 75 cm/min. Determine (a) the number of pulses required to move the table, (b) required motor speed, and (c) pulse rate to achieve the desired table speed.

**Solution:**
(a) Pitch \( p = \frac{1}{2.4 \text{ th/s/cm}} = 4.1667 \text{ mm/rev} \) and \( \alpha = \frac{360}{100} = 3.6^\circ \)

\[
n_p = \frac{360 \times 250 \times (5.0)}{4.1667 \times (3.6^\circ)} = 30,000 \text{ pulses}
\]

(b) Leadscrew \( N = \frac{750 \text{ mm/ min.}}{4.1667 \text{ mm/ rev.}} = 180 \text{ rev/min} \)

Motor speed \( N_m = 5 \times 180 = 900 \text{ rev/min} \)

(c) \( f_p = \frac{n_s \cdot N_m}{60} = \frac{100 \times 900}{60} = 1500 \text{ pulses/s} \)

7.10 A component insertion machine takes 2.0 sec to put a component into a printed circuit (PC) board, once the board has been positioned under the insertion head. The \( x-y \) table that positions the PC board uses a stepper motor directly linked to a lead screw for each axis. The lead screw has a pitch = 5.0 mm. The motor step angle = 7.2 degrees and the pulse train frequency = 400 Hz. Two components are placed on the PC board, one each at positions (25, 25) and (50, 150), where coordinates = mm. The sequence of positions is (0,0), (25, 25), (50, 150), (0,0). Time required to unload the completed board and load the next blank onto the machine table = 5.0 sec. Assume that 0.25 sec. is lost due to acceleration and deceleration on each move. What is the hourly production rate for this PC board?

**Solution:**
\( n_s = \frac{360}{7.2} = 50 \text{ steps/rev} \)

\[
f_p = \frac{v_r \cdot r_s}{60p} \text{ given } r_s = 1.0 \text{ and rearranging the equation, } v_r = \frac{f_p p}{n_s} = \frac{(400 \text{ puls/s})(5.0 \text{ mm/rev})}{50 \text{ puls/rev}} = 40 \text{ mm/s}
\]

Time for move from (0, 0) to (25, 25) = \[
\frac{25 \text{ mm}}{40 \text{ mm/s}} = 0.625 \text{ s}
\]

Time for move from (25, 25) to (50, 150) = \[
\frac{150 - 25}{40} = 3.125 \text{ s}
\]

Time for move from (50, 150) to (0, 0) = \[
\frac{150}{40} = 3.75 \text{ s}
\]

Cycle time \( T_c = 5.0 + (0.625 + 0.25 + 2.0) + (3.125 + 0.25 + 2.0) + (3.75 + 0.25) = 17.25 \text{ s}
\]

Cycle rate (assumed equal to production rate) \( R_c = \frac{60 \times 60}{17.25} = 208.7 \text{ units/hr} \).

7.11 The two axes of an \( x-y \) positioning table are each driven by a stepping motor connected to a lead screw with a 4:1 gear reduction. The number of step angles on each stepping motor is 200. Each lead screw has a pitch = 5.0 mm and provides an axis range = 400.0 mm. There are 16 bits in each binary register used by the controller to store position data for the two axes. (a) What is the control resolution of each axis? (b) What are the required rotational speeds and corresponding pulse train frequencies of each stepping motor in order to drive the table at 600 mm/min in a straight line from point (25,25) to point (300,150)? Ignore acceleration.

**Solution:**
(a) \( CR_1 = \frac{p}{r_s \cdot n_s} = 5.0/4 \times 200 = 0.00625 \text{ mm} \)

\( CR_2 = L/(2^{16} - 1) = 400/(2^{16} - 1) = 400/65,535 = 0.00610 \text{ mm} \)

\( CR = \text{Max} \{0.00625, 0.00610\} = 0.00625 \text{ mm} \)

(b) \( v_r = 600 \text{ mm/min from (25, 25) to (300, 150)} \)

\( \Delta x = 300 - 25 = 275 \text{ mm, } \Delta y = 150 - 25 = 125 \text{ mm} \)

\( \text{Angle } A = \tan^{-1}(125/275) = 24.44^\circ \)

\( v_n = 600 \cos 24.44 = 546.22 \text{ mm/min} \)

\( N_s = r_s v_r / p = 4(546.22)/5.0 = 436.98 \text{ rev/min} \)

\( f_{ps} = N_s n_s / 60 = 436.98(200)/60 = 1456.68 \text{ Hz} \)
$v_y = 600 \sin 24.44 = 248.28 \text{ mm/min}$

$N_p = r_g v_y / p = 4(248.28)/5.0 = 198.63 \text{ rev/min}$

$f_p = N_p / 60 = 198.63(200)/60 = 662.1 \text{ Hz}$

**Analysis of Closed Loop Positioning Systems**

**7.12** A dc servomotor is used to drive one of the table axes of an NC milling machine. The motor is coupled directly to the lead screw for the axis, and the lead screw pitch = 5 mm. The optical encoder attached to the lead screw emits 360 pulses per revolution of the lead screw. The motor rotates at a normal speed of 300 rev/min. Determine (a) control resolution of the system, expressed in linear travel distance of the table axis, (b) frequency of the pulse train emitted by the optical encoder when the servomotor operates at full speed, and (c) travel rate of the table at normal rpm of the motor.

**Solution:**

(a) $CR = \frac{5 \text{ mm}}{360 \text{ pulse}} = 0.013889 \text{ mm}$

(b) $f_p = n_s N_m \frac{360 \text{ pulse}}{60 \text{ s/min}} = 1800 \text{ pulse/s} = 1800 \text{ Hz}$

(c) $v = 60 f_p / n_s = \frac{5 \text{ mm}}{(1800 \text{ pulse/s})(60 \text{ s/min})} = 1500 \text{ mm/min}$

**7.13** In Problem 7.3, the axis corresponding to the feed rate uses a dc servomotor as the drive unit and an optical encoder as the feedback sensing device. The motor is geared to the lead screw with a 10:1 reduction (10 turns of the motor for each turn of the lead screw). If the lead screw pitch = 5 mm, and the optical encoder emits 400 pulses per revolution, determine the rotational speed of the motor and the pulse rate of the encoder in order to achieve the feed rate indicated.

**Solution:** From Problem 7.3, $f = 382 \text{ mm/min}$

$N_m = r_g f / p = \frac{10(382 \text{ mm/min})}{5 \text{ mm/rev}} = 764 \text{ rev/min}$

$f_p = f_n / 60p = \frac{382 \text{ mm/min}(400 \text{ pulse/rev})}{5 \text{ mm/rev}} = 509.33 \text{ Hz}$

**7.14** The worktable of an NC machine is driven by a closed-loop positioning system which consists of a servomotor, lead screw, and optical encoder. The lead screw pitch = 4 mm and is coupled directly to the motor shaft (gear ratio = 1:1). The optical encoder generates 225 pulses per lead screw revolution. The table has been programmed to move a distance of 200 mm at a feed rate = 450 mm/min. (a) How many pulses are received by the control system to verify that the table has moved the programmed distance? What are (b) the pulse rate and (c) motor speed that correspond to the specified feed rate?

**Solution:**

(a) $x = \frac{p n_p}{n_r n_p}$. Rearranging, $n_p = x n_p = \frac{200 \text{ mm}(225 \text{ pulse/rev})}{4 \text{ mm/rev}} = 11250 \text{ pulses}$

(b) $f = \frac{(450 \text{ mm/min})(225 \text{ pulse/rev})}{(60 \text{ s/min})(4 \text{ mm/rev})} = 421.875 \text{ pulse/s} = 421.875 \text{ Hz}$

(c) $N = f/p = \frac{450 \text{ mm/min}}{4 \text{ mm/rev}} = 112.5 \text{ rev/min}$

**7.15** A NC machine tool table is powered by a servomotor, lead screw, and optical encoder. The lead screw has a pitch = 5.0 mm and is connected to the motor shaft with a gear ratio of 8:1 (8 turns of the motor for each turn of the lead screw). The optical encoder is connected directly to the lead screw and generates 200 pulses/rev of the lead screw. The table must move a distance = 100 mm at a feed rate = 500 mm/min. Determine (a) the pulse count received by the control system to verify that the table has moved exactly 100 mm; and (b) the pulse rate and (c) motor speed that correspond to the feed rate of 500 mm/min.

**Solution:**

(a) $x = p n_p / n_r$. Rearranging, $n_p = x n_p = \frac{100 \text{ mm}}{100(200)/5} = 4000 \text{ pulses}$

(b) $f_p = f n / 60p = \frac{500(200)(60)(5)}{333.3 \text{ Hz}}$
7.16 Solve the previous problem assuming the optical encoder is directly coupled to the motor shaft rather than to the lead screw.

Solution: (a) \( x = p n_p r_s \) Rearranging, \( n_p = r_s x n_s / p = 8(100)(200) / 5 = 32,000 \) pulses.
(b) \( f_p = r_s f_r n_s / 60p = 8(500)(200) / 60(5) = 2666.67 \) Hz
(c) \( N = r_s f_r / p = 8 \times 500 / 5 = 800 \) rev/min

7.17 A lead screw coupled directly to a dc servomotor is used to drive one of the table axes of an NC milling machine. The lead screw has 2.5 threads/cm. The optical encoder attached to the lead screw emits 100 pulses/rev of the lead screw. The motor rotates at a maximum speed of 800 rev/min. Determine (a) the control resolution of the system, expressed in linear travel distance of the table axis, (b) frequency of the pulse train emitted by the optical encoder when the servomotor operates at maximum speed; and (c) travel speed of the table at maximum motor speed.

Solution: (a) \( p = \frac{1}{2.5 \text{ threads/cm}} = 0.4 \text{ cm} = 4.0 \text{ mm} \), \( CR = p / n_s = 4.0 / 100 = 0.04 \) mm
(b) \( f_p = N n_s / 60 = 800 \text{ rev/min}(100 \text{ pulse/rev}) / (60 \text{ s/min}) = 1333.3 \) Hz
(c) \( v_t = N p / r_s = 800 \text{ rev/min}(4.0 \text{ mm/rev.}) / 5 = 640 \text{ mm/min} \)

7.18 Solve the previous problem only the servomotor is connected to the lead screw through a gear box whose reduction ratio = 5:1 (five revolutions of the motor for each revolution of the lead screw).

Solution: (a) \( p = \frac{1}{2.5 \text{ threads/cm}} = 0.4 \text{ cm} = 4.0 \text{ mm} \), \( CR = p / n_s = 4.0 / 100 = 0.04 \) mm
(b) \( f_p = N n_s / 60 = 800 \text{ rev/min}(100 \text{ pulse/rev}) / (5(60 \text{ s/min})) = 266.67 \) Hz
(c) \( v_t = N p / r_s = 800 \text{ rev/min}(4.0 \text{ mm/rev.}) / 5 = 640 \text{ mm/min} \)

7.19 A milling operation is performed on a NC machining center. Total travel distance = 300 mm in a direction parallel to one of the axes of the worktable. Cutting speed = 1.25 m/s and chip load = 0.05 mm. The end milling cutter has four teeth and its diameter = 20.0 mm. The axis uses a dc servomotor whose output shaft is coupled to a lead screw with pitch = 6.0 mm. The feedback sensing device is an optical encoder which emits 250 pulses per revolution. Determine (a) feed rate and time to complete the cut, (b) rotational speed of the motor and (c) pulse rate of the encoder at the feed rate indicated.

Solution: (a) \( N = (1.25 \times 10^3 \text{ mm/s}) / (20\pi \text{ mm/rev}) = 19.89 \) rev/s.
\( f_r = N f_n = 19.89(0.05)(4) = 3.978 \) mm/s. \( T_m = 300 / 3.978 = 75.4 \) s = 1.26 min
(b) \( N = f_r / p = (3.978 \text{ mm/s}) / (6 \text{ mm/rev}) = 0.663 \) rev/s. \( v_t = n_s N = 250(0.663) = 165.75 \) Hz

7.20 A dc servomotor drives the x-axis of a NC milling machine table. The motor is coupled directly to the table lead screw, whose pitch = 6.25 mm. An optical encoder is connected to the lead screw. The optical encoder emits 125 pulses per revolution. To execute a certain programmed instruction, the table must move from point (x = 87.5 mm, y = 35.0) to point (x = 25.0 mm, y = 180.0 mm) in a straight-line trajectory at a feed rate = 200 mm/min. Determine (a) control resolution of the system for the x-axis, (b) rotational speed of the motor, and (c) frequency of the pulse train emitted by the optical encoder at the desired feed rate.

Solution: (a) \( CR = p / n_s = (6.25 \text{ mm/rev}) / (125 \text{ pulse/rev}) = 0.05 \) mm
(b) Move from (87.5, 35.0) to (25.0, 180.0) at \( f_r = 200 \) mm/min
\( \Delta x = 25.0 - 87.5 = -62.5 \), \( \Delta y = 180.0 - 35.0 = 145.0 \), Angle \( A = \tan^{-1}(145/(-62.5)) = 113.32^\circ \)
\( f_r = 200 \cos 113.32 = 200(-0.9395) = -179.19 \) mm/min
\( N = f_r / p = (-179.19 \text{ mm/min}) / (6.25 \text{ mm/rev}) = 26.4 \) rev/min
(c) \( f_p = n_s N / 60 = (26.4)(125) / 60 = 42.67 \) Hz
Resolution and Accuracy of Positioning Systems

7.21 A two-axis NC system used to control a machine tool table uses a bit storage capacity of 16 bits in its control memory for each axis. The range of the x-axis is 500 mm and the range of the y-axis is 400 mm. The mechanical accuracy of the machine table can be represented by a Normal distribution with standard deviation = 0.002 mm for both axes. For each axis of the NC system, determine (a) the control resolution, (b) accuracy, and (c) repeatability.

Solution: (a) x-axis: \( CR_x = \frac{500}{2^{16} - 1} = \frac{500}{65,536 - 1} = 0.00763 \ mm \)

y-axis: \( CR_y = \frac{400}{65,535} = 0.00610 \ mm \)

(b) x-axis: Accuracy = \( \frac{CR_x}{2} + 3\sigma = \frac{0.00763}{2} + 3(0.002) = 0.00982 \ mm \)

y-axis: Accuracy = \( \frac{0.0076}{2} + 3(0.002) = 0.00905 \ mm \)

(c) Repeatability = \( \pm 3\sigma = \pm 3(0.002) = \pm 0.006 \ mm \)

7.22 Stepping motors are used to drive the two axes of an insertion machine used for electronic assembly. A printed circuit board is mounted on the table which must be positioned accurately for reliable insertion of components into the board. Range of each axis = 700 mm. The lead screw used to drive each of the two axes has a pitch of 3.0 mm. The inherent mechanical errors in the table positioning can be characterized by a Normal distribution with standard deviation = 0.005 mm. If the required accuracy for the table is 0.04 mm, determine (a) the number of step angles that the stepping motor must have, and (b) how many bits are required in the control memory for each axis to uniquely identify each control position.

Solution: (a) Accuracy = \( \frac{CR}{2} + 3\sigma = \frac{0.5CR}{2} + 3(0.005) = 0.04 \) (as specified)

Assume \( CR = CR_1 \). \( 0.5CR_1 = 0.04 - 0.015 = 0.025 \ mm, \quad CR_1 = 0.05 \ mm \)

\( CR_1 = \frac{P}{n_1r_1} \). Rearranging, \( n_1 = \frac{P}{CR_1}, \) since \( r_1 = 1 \).

\( n_1 = \frac{60 \text{ steps/rev}}{\frac{P}{CR_1}} \)

(b) Let \( CR_2 \leq CR_1 \). \( CR_2 = \frac{L}{2^n - 1} \). Rearranging, \( 2^n - 1 = \frac{L}{CR_2} = \frac{700 \text{ mm}}{0.05 \text{ mm/step}} = 14,000 \) positions

\( 2^n = 14,001 \)

\( b = \frac{\ln 14001}{\ln 2} = 9.5469, \quad b = 13.77 \rightarrow 14 \) bits

7.23 Referring back to Problem 7.8, the mechanical inaccuracies in the open loop positioning system can be described by a normal distribution whose standard deviation = 0.005 mm. The range of the worktable axis is 500 mm, and there are 12 bits in the binary register used by the digital controller to store the programmed position. For the positioning system, determine (a) control resolution, (b) accuracy, and (c) repeatability. (d) What is the minimum number of bits that the binary register should have so that the mechanical drive system becomes the limiting component on control resolution?

Solution: (a) \( CR_1 = \frac{P}{n_1} = 4 \text{ mm}/250 = 0.016 \ mm \).

\( CR_2 = \frac{L}{2^n - 1} = \frac{500}{2^{12} - 1} = \frac{500}{4095} = 0.122 \ mm \).

\( CR = \max\{CR_1, CR_2\} = \max\{0.016, 0.122\} = 0.122 \ mm \).

(b) Accuracy = \( 0.5 CR + 3\sigma = 0.5(0.122) + 3(0.005) = 0.076 \ mm \).

(c) Repeatability = \( \pm 3\sigma = \pm 3(0.005) = \pm 0.015 \ mm \).
(d) For mechanical errors to be the limiting factor in control resolution in this problem, $CR_1$ must = $CR_2$.

Thus, $0.016 = \frac{500}{2^a - 1}$. Rearranging, $2^b - 1 = 500/0.016 = 31,250$

$b \ln 2 = \ln 31,251$

$b = 14.93$ Use $b = 15$ bits

7.24 The positioning table for a component insertion machine uses a stepping motor and lead screw mechanism. The design specifications require a table speed of 0.5 m/s and an accuracy = 0.02 mm. The pitch of the lead screw = 6.0 mm, and the gear ratio = 2:1 (2 turns of the motor for each turn of the lead screw). The mechanical errors in the motor, gear box, lead screw, and table connection are characterized by a normal distribution with standard deviation = 0.0025 mm. Determine (a) the minimum number of step angles in the stepping motor and (b) frequency of the pulse train required to drive the table at the desired maximum speed.

Solution: (a) Accuracy = 0.5 $CR_1 + 3\sigma$: $0.02 = 0.5 CR + 3(0.0025) = 0.5 CR + 0.0075$

$0.02 - 0.0075 = 0.0125 = 0.5 CR$, $CR_1 = 0.025 mm$

Assume $CR_1 = CR_2$

$r = \frac{p}{(r_x n_x)} = 6.0/2 = 3.0$, Rearranging, $n_x = 6/(2 \times 0.025) = 120$ step angles

(b) $f_p = \frac{\Delta x \Delta y}{p} = \frac{2(0.5m/s)(120 pulse/rev)}{6(10^{-3}) m/rev} = 20,000 Hz$

7.25 The two axes of an x-y positioning table are each driven by a stepping motor connected to a lead screw with a 10:1 gear reduction. The number of step angles on each stepping motor is 20. Each lead screw has a pitch = 4.5 mm and provides an axis range = 300 mm. There are 16 bits in each binary register used by the controller to store position data for the two axes. (a) What is the control resolution of each axis? (b) What are the required rotational speeds and corresponding pulse train frequencies of each stepping motor in order to drive the table at 500 mm/min in a straight line from point (30,30) to point (100,200)? Ignore acceleration and deceleration.

Solution: (a) $CR_1 = \frac{L}{2^a - 1} = \frac{300}{2^{16} - 1} = 0.00458 mm$

$CR = Max\{0.0225, 0.00458\} = 0.0225 mm$

(b) $v_x = 500 \text{ mm/min from (30,30) to (100,200)}$

$\Delta x = 100 - 30 = 70 \text{ mm}, \Delta y = 200 - 30 = 170 \text{ mm}$, Angle $A = \tan^{-1}(170/70) = 67.62^\circ$

$v_x = 500 \cos 67.62 = 190.38 \text{ mm/min}, N_x = \frac{r_x v_x}{p} = 10(190.38)/4.5 = 423.06 \text{ rev/min}$

$f_{pu} = N_x n_x/60 = 423.06(20)/60 = 141.02 \text{ Hz}$

$v_y = 500 \sin 67.62 = 462.34 \text{ mm/min}, N_y = \frac{r_y v_y}{p} = 10(462.34)/4.5 = 1027.42 \text{ rev/min}$

$f_{pu} = N_y n_y/60 = 1027.42(20)/60 = 342.47 \text{ Hz}$

NC Manual Part Programming

Note: Appendix A7 will be required to solve the problems in this group.

7.26 Write the part program to drill the holes in the part shown in Figure P7.26. The part is 12.0 mm thick. Cutting speed = 100 m/min and feed = 0.06 mm/rev. Use the lower left corner of the part as the origin in the x-y axis system. Write the part program in the word address format using absolute positioning. The program style should be similar to Example A7.1.

Solution: At the beginning of the job, the drill point will be positioned at a target point located at $x = 0, y = 0,$ and $z = +10$. The program begins with the tool positioned at this target point. Feed is given as 0.06 mm/rev. Rotational speed of drill is calculated as follows:

$N = \frac{100}{10n(10^{-3})} = 3183 \text{ rev/min}$

**NC part program code**

<table>
<thead>
<tr>
<th>NC part program code</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>N001 G21 G90 G92 X0 Y0 Z010.0;</td>
<td>Define origin of axes.</td>
</tr>
<tr>
<td>N002 G00 X040.0 Y025.0;</td>
<td>Rapid move to first hole location.</td>
</tr>
<tr>
<td>N003 G01 G95 Z-20.0 F0.06 S3183 M03;</td>
<td>Drill first hole.</td>
</tr>
</tbody>
</table>
The part in Figure P7.27 is to be drilled on a turret-type drill press. The part is 15.0 mm thick. There are three drill sizes to be used: 8 mm, 10 mm, and 12 mm. These drills are to be specified in the part program by tool turret positions T01, T02, and T03. All tooling is high speed steel. Cutting speed = 75 mm/min and feed = 0.08 mm/rev. Use the lower left corner of the part as the origin in the x-y axis system. Write the part program in the word address format using absolute positioning. The program style should be similar to Example A7.1.

**Solution:** At the beginning of the job, the drill point will be positioned at a target point located at \(x = 0, y = 0,\) and \(z = +10.\) The program begins with the tool positioned at this target point. Feed is given as 0.08 mm/rev. Rotational speeds for the three drill diameters are calculated as follows:

For the 8 mm drill, \(N = \frac{75}{(8 \pi \times 10^{-3})} = 2984\) rev/min

For the 10 mm drill, \(N = \frac{75}{(10 \pi \times 10^{-3})} = 2387\) rev/min

For the 12 mm drill, \(N = \frac{75}{(12 \pi \times 10^{-3})} = 1989\) rev/min

**NC part program code**

<table>
<thead>
<tr>
<th>NC part program code</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>N001 G21 G90 G92 X0 Y0 Z10.0;</td>
<td>Define origin of axes.</td>
</tr>
<tr>
<td>N002 G00 X025.0 Y025.0 T01;</td>
<td>Rapid move to first hole location, select 8 mm drill.</td>
</tr>
<tr>
<td>N003 G01 G95 Z-20.0 F0.08 S2984 M03;</td>
<td>Drill first hole.</td>
</tr>
<tr>
<td>N004 G01 Z10.0;</td>
<td>Retract drill from hole.</td>
</tr>
<tr>
<td>N005 G00 X150.0;</td>
<td>Rapid move to second hole location.</td>
</tr>
<tr>
<td>N006 G01 G95 Z-20.0 F0.08;</td>
<td>Drill second hole.</td>
</tr>
<tr>
<td>N007 G01 Z10.0;</td>
<td>Retract drill from hole.</td>
</tr>
<tr>
<td>N008 G00 X175.0;</td>
<td>Rapid move to third hole location.</td>
</tr>
<tr>
<td>N009 G01 G95 Z-20.0 F0.08;</td>
<td>Drill third hole.</td>
</tr>
<tr>
<td>N010 G01 Z10.0;</td>
<td>Retract drill from hole.</td>
</tr>
<tr>
<td>N011 G00 X100.0 Y075.0 T02;</td>
<td>Rapid move to fourth hole location, select 10 mm drill.</td>
</tr>
<tr>
<td>N012 G01 G95 Z-20.0 F0.08;</td>
<td>Drill fourth hole.</td>
</tr>
<tr>
<td>N013 G01 Z10.0;</td>
<td>Retract drill from hole.</td>
</tr>
<tr>
<td>N014 G00 X050.0;</td>
<td>Rapid move to fifth hole location.</td>
</tr>
<tr>
<td>N015 G01 G95 Z-20.0 F0.08;</td>
<td>Drill fifth hole.</td>
</tr>
<tr>
<td>N016 G01 Z10.0;</td>
<td>Retract drill from hole.</td>
</tr>
<tr>
<td>N017 G00 X050.0 Y075.0 T03;</td>
<td>Rapid move to sixth hole location, select 12 mm drill.</td>
</tr>
<tr>
<td>N018 G01 G95 Z-22.0 F0.08;</td>
<td>Drill sixth hole.</td>
</tr>
<tr>
<td>N019 G01 Z10.0;</td>
<td>Retract drill from hole.</td>
</tr>
<tr>
<td>N020 G00 X0 Y0 M05;</td>
<td>Rapid move to target point, stop spindle rotation.</td>
</tr>
<tr>
<td>N021 M30;</td>
<td>End of program, stop machine.</td>
</tr>
</tbody>
</table>

7.28 The outline of the part in the previous problem is to be profile milled using a 30 mm diameter end mill with four teeth. The part is 15 mm thick. Cutting speed = 150 mm/min and feed = 0.085 mm/tooth. Use the lower left
corner of the part as the origin in the x-y axis system. Two of the holes in the part have already been drilled and will be used for clamping the part during profile milling. Write the part program in the word address format with TAB separation and variable word order. Use absolute positioning. The program style should be similar to Example A7.2.

**Solution:** As stated, two of the holes drilled in Problem 7.27 will be used to clamp the workpart for milling the outside edges. The part will be fixtured so that its top surface is 40 mm above the surface of the machine tool table, and the x-y plane of the axis system will be defined 40 mm above the table surface. As given, a 30 mm diameter end mill with four teeth will be used. The cutter is assumed to have a side tooth engagement length of 40 mm. Throughout the machining sequence the bottom tip of the cutter will be positioned 25 mm below the part top surface, which corresponds to \( z = -25 \) mm. Since the part is 15 mm thick, this \( z \) position will allow the side cutting edges of the milling cutter to cut the full thickness of the part during profile milling. Cutting speed is specified as 150 m/min. Rotational speed of the cutter is calculated as \( N = \frac{150 \times (30 \pi \times 10^{-3})}{30 \pi \times 10^{-3}} = 1592 \) rev/min. Given a feed = 0.085 mm/tooth, feed rate is calculated as \( 1592(4)(0.085) = 541 \) mm/min. Cutter diameter data has been manually entered into offset register 05. At the beginning of the job, the cutter will be positioned so that its center tip is at a target point located at \( x = -50 \), \( y = -50 \), and \( z = +10 \). The program begins with the tool positioned at this location.

**NC part program code**

```
N001 G21 G90 G92 X-050.0 Y-050.0 Z010.0;
N002 G00 Z-025.0 S1592 M03;
N003 G01 G94 G42 Y0 D05 F541;
N004 G01 X200.0;
N005 G01 Y050.0;
N006 G01 X150.0;
N007 G17 G02 X125.0 Y075.0 R025.0;
N008 G01 X125.0 Y100.0;
N009 G01 Y025.0;
N100 G01 X0 Y050.0;
N111 G01 Y0;
N122 G40 G00 X-050.0 Y-050.0 Z010.0 M05;
N13 M30;
```

**Comments**

- Define origin of axes.
- Rapid to cutter depth, turn spindle on.
- Bring tool to starting y-value, start cutter offset.
- Mill lower part edge.
- Mill right straight edge.
- Mill horizontal step above two 8 mm holes
- Circular interpolation around arc.
- Mill vertical step above arc.
- Mill top part edge.
- Mill angled edge at left of part.
- Mill vertical edge at left of part.
- Rapid move to target point, cancel offset, spindle stop.
- End of program, stop machine.

7.29 The outline of the part in Figure P7.29 is to be profile milled, using a 20 mm diameter end mill with two teeth. The part is 10 mm thick. Cutting speed = 125 mm/min and feed = 0.10 mm/tooth. Use the lower left corner of the part as the origin in the x-y axis system. The two holes in the part have already been drilled and will be used for clamping the part during milling. Write the part program in the word address format with TAB separation and variable word order. Use absolute positioning. The program style should be similar to Example A7.2.

**Solution:** As stated, the two holes will be used to clamp the workpart during milling. The part will be fixtured so that its top surface is 40 mm above the surface of the machine tool table, and the x-y plane of the axis system will be defined 40 mm above the table surface. As given, a 20 mm diameter end mill with two teeth will be used. The cutter is assumed to have a side tooth engagement length of 30 mm. Throughout the machining sequence the bottom tip of the cutter will be positioned 20 mm below the part top surface, which corresponds to \( z = -20 \) mm. Since the part is 10 mm thick, this \( z \) position will allow the side cutting edges of the milling cutter to cut the full thickness of the part during profile milling. Cutting speed is specified as 125 m/min. Rotational speed of the cutter is calculated as \( N = \frac{125 \times (20 \pi \times 10^{-3})}{(20 \pi \times 10^{-3})} = 1989 \) rev/min. Given a feed = 0.10 mm/tooth, feed rate is calculated as \( 1989(2)(0.10) = 398 \) mm/min. Cutter diameter data has been manually entered into offset register 05. At the beginning of the job, the cutter will be positioned so that its center tip is at a target point located at \( x = -50 \), \( y = -50 \), and \( z = +10 \). The program begins with the tool positioned at this location.

**NC part program code**

```
N001 G21 G90 G92 X-050.0 Y-050.0 Z010.0;
N002 G00 Z-020.0 S1989 M03;
N003 G01 G94 G42 Y0 D05 F398;
N004 G01 X075.0;
N005 G01 Y050.0;
N101 G01 X0;
N102 G40 G00 X-050.0 Y-050.0 Z010.0 M05;
N103 M30;
```

**Comments**

- Define origin of axes.
- Rapid to cutter depth, turn spindle on.
- Bring tool to starting y-value, start cutter offset.
- Mill lower horizontal edge of part.
- Mill angled edge at 35 degrees.
NC Part Programming in APT

Note: Appendix B7 will be required to solve the problems in this group.

7.30 Write the APT geometry statements to define the hole positions of the part in Figure P7.26. Use the lower left corner of the part as the origin in the x-y axis system.

Solution: Points are defined 10 mm above part surface for convenience in subsequent drilling.

P0 = POINT/0, 0, 10.0
P1 = POINT/40.0, 25.0, 10.0
P2 = POINT/40.0, 100.0, 10.0
P3 = POINT/100.0, 100.0, 10.0
P4 = POINT/160.0, 100.0, 10.0
P5 = POINT/200.0, 40.0, 10.0
P6 = POINT/125.0, 60.0, 10.0

7.31 Write the complete APT part program to perform the drilling operations for the part drawing in Figure P7.26. Cutting speed = 0.4 m/s, feed = 0.10 mm/rev., and table travel speed between holes = 500 mm/min. Postprocessor call statement is MACHIN/DRILL, 04.

Solution: Spindle speed $N = 0.4(60)/(10\pi \times 10^{-3}) = 764$ rev/min. See drawing in previous solution.

PARTNO PART P6.6 DRILLING
MACHIN/ MACHIN/DRILL, 04
CLPRNT
UNITS/MM
REMARK Part geometry. Points are defined 10 mm above part surface.
P0 = POINT/0, 0, 10.0
P1 = POINT/40.0, 25.0, 10.0
P2 = POINT/40.0, 100.0, 10.0
P3 = POINT/100.0, 100.0, 10.0
P4 = POINT/160.0, 100.0, 10.0
P5 = POINT/200.0, 40.0, 10.0
P6 = POINT/125.0, 60.0, 10.0
REMARK Drill bit motion statements. Rapid traverse speed (RAPID) set at 500 mm/min
FROM/P0
RAPID
GOTO/P1
SPINDL/764, CLW
FEDRAT/0.10, IPR
GODLTA/0, 0, -30
GODLTA/0, 0, 30
RAPID
GOTO/P2
SPINDL/764, CLW
FEDRAT/0.10, IPR
GODLTA/0, 0, -30
GODLTA/0, 0, 30
RAPID
GOTO/P3
SPINDL/764, CLW
FEDRAT/0.10, IPR
GODLTA/0, 0, -30
GODLTA/0, 0, 30
RAPID
GOTO/P4
SPINDL/764, CLW
FEDRAT/0.10, IPR
GODLTA/0, 0, -30
GODLTA/0, 0, 30
RAPID
GOTO/P5
SPINDL/764, CLW
FEDRAT/0.10, IPR
GODLTA/0, 0, -30
GODLTA/0, 0, 30
RAPID
GOTO/P6
SPINDL/764, CLW
FEDRAT/0.10, IPR
GODLTA/0, 0, -30
GODLTA/0, 0, 30
RAPID
GOTO/P0
SPINDL/OFF
FINI

7.32 Write the APT geometry statements to define the hole positions of the part in Figure P7.27. Use the lower left corner of the part as the origin in the x-y axis system.

Solution: Points are defined 10 mm above part surface for convenience in subsequent drilling. See drawing below.

P0 = POINT/0, 0, 10.0
P1 = POINT/25.0, 25.0, 10.0
P2 = POINT/150.0, 25.0, 10.0
P3 = POINT/175.0, 25.0, 10.0
P4 = POINT/100.0, 75.0, 10.0
P5 = POINT/50.0, 75.0, 10.0
P6 = POINT/50.0, 50.0, 10.0

36
Write the APT part program to perform the drilling operations for the part drawing in Figure P7.27. Use the TURRET command to call the different drills required. Cutting speed = 0.4 m/s, feed = 0.10 mm/rev., and table travel speed between holes = 500 mm/min. Postprocessor call statement is MACHIN/TURDRL,02.

Solution: Spindle speed $N = 0.4(60)/(10\pi \times 10^{-3}) = 764$ rev/min. See drawing in previous solution.

PARTNO PART P6.6 DRILLING
MACHIN/ MACHIN/TURDRL, 02
CLPRNT
UNITS/MM
REMARK Part geometry. Points are defined 10 mm above part surface.
P0 = POINT/0, 0, 10.0
P1 = POINT/25.0, 25.0, 10.0
P2 = POINT/150.0, 25.0, 10.0
P3 = POINT/175.0, 25.0, 10.0
P4 = POINT/100.0, 75.0, 10.0
P5 = POINT/50.0, 75.0, 10.0
P6 = POINT/50.0, 50.0, 10.0
REMARK Drill bit motion statements. Rapid traverse speed (RAPID) set at 500 mm/min
FROM/P0
RAPID
TURRET/T01
GOTO/P1
SPINDL/764, CLW
FEDRAT/0.10, IPR
GODLTA/0, 0, -30
GODLTA/0, 0, 30
RAPID
GOTO/P2
SPINDL/764, CLW
FEDRAT/0.10, IPR
GODLTA/0, 0, -30
GODLTA/0, 0, 30
RAPID
GOTO/P3
SPINDL/764, CLW
FEDRAT/0.10, IPR
GODLTA/0, 0, -30
GODLTA/0, 0, 30
RAPID
TURRET/T02
GOTO/P4
SPINDL/764, CLW
Write the APT geometry statements to define the outline of the part in Figure P7.27. Use the lower left corner of the part as the origin in the x-y axis system.

Solution: Points are defined 25 mm below part upper surface to provide full engagement of cutter.

P0 = POINT/0, 0, -25.0
P1 = POINT/200.0, 0, -25.0
P2 = POINT/200.0, 50.0, -25.0
P3 = POINT/125.0, 100.0, -25.0
P4 = POINT/25.0, 100.0, -25.0
P5 = POINT/0, 50.0, -25.0
L1 = LINE/P0, P1
L2 = LINE/P1, P2
L3 = LINE/P2, PARLEL, L1
L4 = LINE/P3, PERPTO, L3
L5 = LINE/P3, P4
L6 = LINE/P4, P5
L7 = LINE/P0, P5
C1 = CIRCLE/XLARGE, L4, YLARGE, L3, RADIUS, 25.0
PL1 = PLANE/P0, P1, P3

7.35 Write the complete APT part program to profile mill the outside edges of the part in Figure P7.27. The part is 15 mm thick. Tooling = 30 mm diameter end mill with four teeth, cutting speed = 150 mm/min, and feed = 0.085 mm/tooth. Use the lower left corner of the part as the origin in the x-y axis system. Two of the holes in the part have already been drilled and will be used for clamping the part during profile milling. Postprocessor call statement is MACHIN/MILL, 06.

Solution: Spindle speed \( N = \frac{150}{(30 \pi \times 10^{-3})} = 1592 \text{ rev/min.} \) Feed rate \( f_r = 1592(4)(0.085) = 541 \text{ mm/min.} \) See drawing in previous solution.

PARTNO PART P6.7 PROFILE MILLING
MACHIN/ MACHIN/MILL, 06
CLPRNT
UNITS/MM
INTOL/0.01
CUTTER/30.0

REMARK Points are defined 25 mm below part upper surface to provide full engagement of cutter.
PTARG = POINT/-20.0, -30.0, -25.0
P0 = POINT/0, 0, -25.0
P1 = POINT/200.0, 0, -25.0
P2 = POINT/200.0, 50.0, -25.0
P3 = POINT/125.0, 100.0, -25.0
P4 = POINT/25.0, 100.0, -25.0
P5 = POINT/0, 50.0, -25.0
L1 = LINE/P0, P1
L2 = LINE/P1, P2
L3 = LINE/P2, PARLEL, L1
L4 = LINE/P3, PERPTO, L3
L5 = LINE/P3, P4
L6 = LINE/P4, P5
L7 = LINE/P0, P5
C1 = CIRCLE/XLARGE, L4, YLARGE, L3, RADIUS, 25.0
PL1 = PLANE/P0, P1, P3
FROM/PTARG
SPINDL/1592, CLW
FEDRAT/541, IPM
GO/TO, L1, TO, PL1, TO, L7
GORGT/L1, PAST, L2
GOLFT/L2, PAST, L3
GOLFT/L3, TANTO, C1
GOFWD/C1, TO, L4
GOFWD/L4, PAST, L5
GOLFT/L5, PAST, L6
GOLFT/L6, PAST, L7
GOFWD, L7, PAST, L1
GOTO/PTARG
SPINDL/OFF
FINI

7.36 Write the APT geometry statements to define the part geometry shown in Figure P7.29. Use the lower left corner of the part as the origin in the x-y axis system.

Solution: Points are defined 20 mm below part upper surface to provide full engagement of cutter.
Write the complete APT part program to perform the profile milling operation for the part drawing in Figure P7.29. Tooling = 20 mm diameter end mill with two teeth, cutting speed = 125 mm/min, and feed = 0.10 mm/tooth. The part is 10 mm thick. Use the lower left corner of the part as the origin in the x-y axis system. The two holes in the part have already been drilled and will be used for clamping the part during milling. Postprocessor call statement is MACHIN/MILL, 01.

Solution: Spindle speed \( N = \frac{125/(20\pi \times 10^{-3})}{1000} = 1989 \text{ rev/min.} \) Feed rate \( f_r = 1989 \times (2)(0.10) = 398 \text{ mm/min.} \)

See drawing in previous solution.

PARTNO PART P6.9 PROFILE MILLING
MACHIN/ MACHIN/MILL, 01
CLPRNT
UNITS/MM
INTOL/0.01
CUTTER/20.0
REMARK Points are defined 20 mm below part upper surface to provide full engagement of cutter.
PTARG = POINT/-20.0, -30.0, -20.0
P0 = POINT/0, 0, -20.0
P1 = POINT/75.0, 0, -20.0
P2 = POINT/150.0, 70.0, -20.0
P3 = POINT/50.0, 125.0, -20.0
P4 = POINT/0, 125.0, -20.0
L1 = LINE/P0, P1
L2 = LINE/P1, ATANGL, 35
L3 = LINE/P2, PERPTO, L1
L4 = LINE/P2, PARLEL, L1
L5 = LINE/P3, PERPTO, L1
L6 = LINE/P4, P3
L7 = LINE/P0, P4
C1 = CIRCLE/XLARGE, L5, YLARGE, L4, RADIUS, 30.0
PL1 = PLANE/P0, P2, P4

7.37 Write the complete APT part program to perform the profile milling operation for the part drawing in Figure P7.29. Tooling = 20 mm diameter end mill with two teeth, cutting speed = 125 mm/min, and feed = 0.10 mm/tooth. The part is 10 mm thick. Use the lower left corner of the part as the origin in the x-y axis system. The two holes in the part have already been drilled and will be used for clamping the part during milling. Postprocessor call statement is MACHIN/MILL, 01.

PARTNO PART P6.9 PROFILE MILLING
MACHIN/ MACHIN/MILL, 01
CLPRNT
UNITS/MM
INTOL/0.01
CUTTER/20.0
REMARK Points are defined 20 mm below part upper surface to provide full engagement of cutter.
PTARG = POINT/-20.0, -30.0, -20.0
P0 = POINT/0, 0, -20.0
P1 = POINT/75.0, 0, -20.0
P2 = POINT/150.0, 70.0, -20.0
P3 = POINT/50.0, 125.0, -20.0
P4 = POINT/0, 125.0, -20.0
L1 = LINE/P0, P1
L2 = LINE/P1, ATANGL, 35
L3 = LINE/P2, PERPTO, L1
L4 = LINE/P2, PARLEL, L1

C1 = CIRCLE/XLARGE, L5, YLARGE, L4, RADIUS, 30.0
PL1 = PLANE/P0, P2, P4
L5 = LINE/P3, PERPTO, L1
L6 = LINE/P4, P3
L7 = LINE/P0, P4
C1 = CIRCLE/XLARGE, L5, YLARGE, L4, RADIUS, 30.0
PL1 = PLANE/P0, P2, P4
FROM/PTARG
SPINDL/1989, CLW
FEDRAT/398, IPM
GO/TO, L1, TO, PL1, TO, L7
GORGT/L1, PAST, L2
GOFWD/L2, PAST, L3
GOLFT/L3, PAST, L4
GOLFT/L4, TANTO, C1
GOFWD/C1, TO, L5
GOFWD/L5, PAST, L6
GOLFT/L6, PAST, L7
GOLFT, L7, PAST, L1
GOTO/PTARG
SPINDL/OFF
FINI

7.38 Write the APT geometry statements to define the outline of the cam shown in Figure P7.38.

Solution: Points are defined 15 mm below part upper surface to provide full engagement of cutter. Define the origin of the axis system at the bottom left (sharp) corner of the part.

P0 = POINT/0, 0, -15.0
P1 = POINT/75.0, 0, -15.0
P2 = POINT/0.0, 150.0, -15.0
P3 = POINT/80.0, 150.0, -15.0
P4 = POINT/-57.2, 37.8, -15.0
P5 = POINT/-10.0, 10.0, -15.0
L1 = LINE/P0, P1
C1 = CIRCLE/CENTER, P2, RADIUS, 100.0
C2 = CIRCLE/CENTER, P3, RADIUS, 20.0
C3 = CIRCLE/CENTER, P4, RADIUS, 17.8
C4 = CIRCLE/CENTER, P5, RADIUS, 10.0
L2 = LINE/P1, RIGHT, TANTO, C1
L3 = LINE/RIGHT, TANTO, C2, RIGHT, TANTO, C3
L4 = LINE/RIGHT, TANTO, C3, LEFT, TANTO, C4
L5 = LINE/P0, RIGHT, TANTO, C4
PL1 = PLANE/P1, P4, P3
7.39 The outline of the cam in Figure P7.38 is to be machined in an end milling operation, using a 12.5 mm diameter end mill with two teeth. The part is 7.5 mm thick. Write the complete APT program for this job, using a feed rate = 80 mm/min and a spindle speed = 500 rev/min. Postprocessor call statement is MACHIN/MILL, 03. Assume the rough outline for the part has been obtained in a band saw operation. Ignore clamping issues in the problem.

**Solution:** See drawing in previous solution.

```
PARTNO PART P6.18 PROFILE MILLING
MACHIN/ MACHIN/MILL, 03
CLPRNT
UNITS/MM
INTO/0.01
CUTTER/12.5

REMARK Points are defined 15 mm below part upper surface to provide full engagement of cutter.
PTARG = POINT/-20.0, -30.0, -20.0
P0 = POINT/0, 0, -15.0
P1 = POINT/75.0, 0, -15.0
P2 = POINT/0.0, 150.0, -15.0
P3 = POINT/80.0, 150.0, -15.0
P4 = POINT/-57.2, 37.8, -15.0
P5 = POINT/-10.0, 10.0, -15.0
L1 = LINE/P0, P1
C1 = CIRCLE/CENTER, P2, RADIUS, 100.0
C2 = CIRCLE/CENTER, P3, RADIUS, 20.0
C3 = CIRCLE/CENTER, P4, RADIUS, 17.8
C4 = CIRCLE/CENTER, P5, RADIUS, 10.0
L2 = LINE/P1, RIGHT, TANTO, C1
L3 = LINE/RIGHT, TANTO, C2, RIGHT, TANTO, C3
L4 = LINE/RIGHT, TANTO, C3, LEFT, TANTO, C4
L5 = LINE/P0, RIGHT, TANTO, C4
PL1 = PLANE/P1, P4, P3
FROM/PTARG
SPINDL/500, CLW
FEDRAT/80, IPM
GO/TO, L1, TO, PL1, TO, L5
GORGT/L1, PAST, L2
GOFWD/L2, TANTO, C1
GOFWD/C1, TANTO, C2
GOFWD/L3, TANTO, C3
GOFWD/C3, PAST, L4
GOFWD/L4, TANTO, C4
GOFWD/C4, TO, L5
GOFWD, L5, PAST, L1
GOTO/PTARG
SPINDL/OFF
FINI
```

7.40 The part outline in Figure P7.40 is to be profile milled in several passes from a rectangular slab (outline of slab shown in dashed lines), using a 25 mm diameter end mill with four teeth. The initial passes are to remove no more than 5 mm of material from the periphery of the part, and the final pass should remove no more than 2 mm to cut the outline to final shape. Write the APT geometry and motion statements for this job. The final part thickness is to be the same as the starting slab thickness, which is 10 mm, so no machining is required on the top and bottom of the part.

**Solution:** Only the geometry and motion statements are required. Part geometry will be defined with P0 as origin at point of teardrop shaped part, circle C1 at right end of part, and two lines L1 and L2 leading to each side of the circle, respectively. L2 will be on the upper side of the part. The starting passes will use lines parallel to L2 that are spaced at 5 mm intervals above L2 and larger circles than C1 with radii at 5 mm intervals. These

42
additional lines and circles will be designated with an X to indicate that they are not elements of the actual part surface. Considerations related to part fixturing are ignored.

APT geometry statements:

UNITS/MM
REMARK Points are defined 20 mm below part upper surface to provide full engagement of cutter.
PTARG = POINT/-20.0, -30.0, -20.0
REMARK Following geometry elements define the part outline.
P0 = POINT/0, 0, -20.0
P1 = POINT/100.0, 25.0, -20.0
C1 = CIRCLE/CENTER, P1, RADIUS, 25.0
L1 = LINE/P0, RIGHT, TANTO, C1
L2 = LINE/P0, LEFT, TANTO, C1
REMARK Following geometry elements are used to define tool path immediately prior to final pass.
P1X = POINT/0, -2.0, -20.0
L1X = LINE/P1X, PARLEL, L1
C1X = CIRCLE/CENTER, P1, RADIUS, 27
P2X = POINT/0, 2.0, -20.0
L2X = LINE/P2X, PARLEL, L2
REMARK Following elements are used to define preliminary passes in upper left of slab and around circle.
P3X = POINT/0, 7.0, -20.0
P4X = POINT/0, 12.0, -20.0
P5X = POINT/0, 17.0, -20.0
P6X = POINT/0, 22.0, -20.0
P7X = POINT/0, 27.0, -20.0
P8X = POINT/0, 32.0, -20.0
P9X = POINT/0, 37.0, -20.0
P10X = POINT/0, 42.0, -20.0
P11X = POINT/0, 47.0, -20.0
P12X = POINT/0, 52.0, -20.0
P13X = POINT/0, 55.0, -20.0
L3X = LINE/P0, PERPTO, L1
L4X = LINE/P2X, PARLEL, L2
L5X = LINE/P3X, PARLEL, L2
L6X = LINE/P4X, PARLEL, L2
L7X = LINE/P5X, PARLEL, L2
L8X = LINE/P6X, PARLEL, L2
L9X = LINE/P7X, PARLEL, L2
L10X = LINE/P8X, PARLEL, L2
L11X = LINE/P9X, PARLEL, L2
L12X = LINE/P10X, PARLEL, L2
L13X = LINE/P11X, PARLEL, L2
L14X = LINE/P12X, PARLEL, L2
L15X = LINE/P13X, LEFT, TANTO, C1X
C2X = CIRCLE/CENTER, P1, RADIUS, 32
C3X = CIRCLE/CENTER, P1, RADIUS, 37
C4X = CIRCLE/CENTER, P1, RADIUS, 40
PL1 = PLANE/P0, P1, P13X

APT motion statements:

FROM/PTARG
REMARK Preliminary pass around part.
GO/TO, L1X, TO, PL1, TO, L3X
GORGT/L1X, TANTO, C4X
GOFWD/C4X, PAST, L15X
GOFWD/L15X, PAST, L3X
REMARK Back and forth passes parallel to L2 to remove upper left portion of slab.
The top surface of a large cast iron plate is to be face-milled. The area to be machined is 400 mm wide and 700 mm long. The insert-type face-milling cutter has eight teeth and is 100 mm in diameter. Define the origin of the axis system at the lower left corner of the part with the long side parallel to the x-axis. Write the APT geometry and motion statements for this job.

**Solution:** Only the geometry and motion statements are required. Since the origin is defined at the lower left corner of the rectangular slab, at $x = 0$ and $y = 0$, we define the surface to be cut as the plane at $z = 0$ parallel to the $x$-$y$ plane. The target point will be established at $x = -60$, $y = -60$, and $z = 0$. Units are mm. Cuts will be taken parallel to the $x$-axis at 85 mm intervals. With a 100 mm diameter cutter, this will provide an overlap of 15 mm for successive passes back and forth across the part surface.

**APT geometry statements:**

```
UNITS/MM
PTARG = POINT/-60.0, -60.0, 0
P0 = POINT/0, 0, 0
P00 = POINT/760.0, -60.0, 0
P1L = POINT/0, 85.0, 0
P2L = POINT/0, 170.0, 0
P3L = POINT/0, 255.0, 0
P4L = POINT/0, 340.0, 0
P5L = POINT/0, 425.0, 0
```

P1R = POINT/700.0, 85.0, 0
P2R = POINT/700.0, 170.0, 0
P3R = POINT/700.0, 255.0, 0
P4R = POINT/700.0, 340.0, 0
P5R = POINT/700.0, 425.0, 0
PL1 = PLANE/P0, P5L, P5R
LL = LINE/P1L, P5L
LR = LINE/P1R, P5R
L1 = LINE/P1L, P1R
L2 = LINE/P2L, P2R
L3 = LINE/P3L, P3R
L4 = LINE/P4L, P4R
L5 = LINE/P5L, P5R

APT motion statements:
FROM/PTARG
GO/TO, L1, TO PL1, TO, LL
GORGT/L1, PAST, LR
GOLFT/LR, TO, L2
GORGT/L2, PAST, LL
GORGT/LL, TO, L3
GORGT/L3, PAST, LR
GOLFT/LR, TO, L4
GOLFT/L4, PAST, LL
GORGT/LL, TO, L5
GORGT/L5, PAST, LR
REMARK Move tool to PTARG without moving across newly cut surface.
RAPID
GOTO/P00
GOTO/PTARG

7.42 Write the APT geometry statements to define the part geometry shown in Figure P7.42.

Solution: Define origin of axis system (0, 0, 0) as indicated in Figure P7.42. See drawing below.

UNITS/MM
P0 = POINT/0, 0, 0
P010 = POINT/0, 0, -10.0
P015 = POINT/0, 0, -15.0
P1 = POINT/37.5, -25.0, 0
P2 = POINT/-50.0, -25.0, 0
PL0 = PLANE/P00, P1, P2
PL010 = PLANE/P010, PARLEL, PL0
PL015 = PLANE/P015, PARLEL, PL0
C1 = CIRCLE/P015, RADIUS, 12.5
C2 = CIRCLE/P015, RADIUS, 50.0
C3 = CIRCLE/P015, RADIUS, 37.5
P3 = POINT/-25.0, 0, 0
C4 = CIRCLE/P3, RADIUS, 37.5
C5 = CIRCLE/P3, RADIUS, 25.0
C6 = CIRCLE/P2, RADIUS, 12.5
C7 = CIRCLE/P1, RADIUS, 12.5
P4 = POINT/-25.0, -25.0, 0
C8 = CIRCLE/P4, RADIUS, 12.5
P5 = POINT/12.5, -25.0, 0
C9 = CIRCLE/P5, RADIUS, 12.5
P6 = POINT/-25.0, -12.5, 0
P7 = POINT/12.5, -12.5, 0
The part in Figure P7.42 is to be milled, using a 20 mm diameter end mill with four teeth. Write the APT geometry and motion statements for this job. Assume that preliminary passes have been completed so that only the final pass (“to size”) is to be completed in this program. Cutting speed = 500 rev./min, and feed rate = 250 mm/min. The starting slab thickness is 15 mm, so no machining is required on the top or bottom surfaces of the part. The three holes have been predrilled for fixturing in this milling sequence.

Solution: The APT geometry statements are the same as in previous Problem 7.42. We add a starting target point PTARG for locating the cutting tool at the beginning of machining. We assume the cutting tool is a flat-end mill (no corner radius), and that the workpart is fixtured so that its bottom surface is 20 mm above the machine tool table. That means that the $x$-$y$ plane of the axis system is 35 mm above the table surface. To accomplish the profile milling operation around the outside periphery of the part, we define a plane PL020 below the actual bottom surface of the part. See drawing in previous solution.

APT geometry statements:

REMARK See previous Problem 6.22 for most geometry statements.
REMARK The following geometry statements are added to facilitate tool path motions.

PTARG = POINT/0, -50.0, 0
P020 = POINT/0, 0, -20.0
PL020 = PLANE/P020, PARLEL, PL0
LX0 = LINE/P00, PERPTO, L1

APT motion statements:

REMARK The profile milling operation around the outside periphery will be accomplished first.
FROM/PTARG
GO/TO, L1, TO, PL020, ON, LX0
GORGT/L1, PAST, C9
GOFWD/C9, TANTO, C7
GO/TO, L1, TO, PL010, ON, LX0
GORGT/C1, L1, C9
GOFWD/L1, C9, TANTO, C7
GOBACK/C7, L1, C10
GOFWD/L3, C3, L5
GOFWD/C3, TO, L5
GOFWD/L5, C5, L2
GOFWD/L2, C11, TANTO, C6
GOFWD/C6, ON, C8
GOLFT/C8, ON, L1
GOFWD/L1, TANTO, C1
GOTO/PTARG
Chapter 8
INDUSTRIAL ROBOTICS

REVIEW QUESTIONS

8.1 What is an industrial robot?

**Answer:** As defined in the chapter introduction, an industrial robot is a general-purpose, programmable machine possessing certain anthropomorphic characteristics, the most obvious of which is a mechanical arm that is used to perform various industrial tasks.

8.2 What was the first application of an industrial robot?

**Answer:** According to Historical Note 8.1, the first application of an industrial robot was in a die casting operation at a General Motors plant in 1961.

8.3 What are the five joint types used in robotic arms and wrists?

**Answer:** The five joint types are the following: (1) Linear joint (type L joint), in which the relative movement between the input link and the output link is a translational sliding motion, with the axes of the two links being parallel; (2) orthogonal joint (type O joint), which is also a translational sliding motion, but the input and output links are perpendicular to each other during the move; (3) rotational joint (type R joint), which provides rotational relative motion, with the axis of rotation perpendicular to the axes of the input and output links; (4) twisting joint (type T joint), which also involves rotary motion, but the axis of rotation is parallel to the axes of the two links; and (5) revolving joint (type V joint), in which the axis of the input link is parallel to the axis of rotation of the joint, and the axis of the output link is perpendicular to the axis of rotation.

8.4 Name the five common body-and-arm configurations identified in the text.

**Answer:** The five common body-and-arm configurations are (1) polar, (2) cylindrical, (3) Cartesian coordinate, (4) joint-arm, and (5) SCARA, which stands for Selective Compliance Assembly Robot Arm.

8.5 What is the work volume of a robot manipulator?

**Answer:** The work volume of a robot manipulator is the envelope or three-dimensional space within which the robot can manipulate the end of its wrist.

8.6 What is a playback robot with point-to-point control?

**Answer:** Playback control means that the robot controller has a memory to record the sequence of motions in a given work cycle as well as the locations and other parameters (such as speed) associated with each motion and then to subsequently play back the work cycle during execution of the program.

8.7 What is an end effector?

**Answer:** An end effector is the special tool that is attached to the robot’s wrist that enables the robot to perform a given task. End effectors are either grippers (to grasp parts) or tools (e.g., spot welding gun).

8.8 In a machine loading and unloading application, what is the advantage of a dual gripper over a single gripper?

**Answer:** With a single gripper, the robot must reach into the production machine twice, once to unload the finished part and place it outside the machine, and then to pick up the next part and load it into the machine. With a dual gripper, the robot picks up the next part while the machine is still processing the current part; when the machine cycle is finished, the robot reaches into the machine only once: to remove the finished part and then load the next part. This reduces the cycle time per part.

8.9 Robotic sensors are classified as internal and external. What is the distinction?

**Answer:** Internal sensors are components of the robot and are used to control the positions and velocities of the various joints of the robot. These sensors form a feedback control loop with the robot controller. External sensors are additional components in the cell (external to the robot). They are used to coordinate the operation of the robot with the other equipment in the cell.

8.10 What are four of the six general characteristics of industrial work situations that tend to promote the substitution of robots for human workers?
Answer: The general characteristics of industrial work situations that tend to promote the substitution of robots for human workers are (1) hazardous work for humans, (2) repetitive work cycle, (3) difficult handling for humans, (4) multi-shift operation, (5) infrequent changeovers, and (6) part position and orientation are established in the work cell.

8.11 What are the three categories of robot industrial applications, as identified in the text?
Answer: The three categories are (1) material handling, (2) processing, and (3) assembly and inspection.

8.12 What is a palletizing operation?
Answer: Palletizing is a material handling application in which the robot must retrieve parts, cartons, or other objects from one location and deposit them onto a pallet or other container at multiple positions on the pallet.

8.13 What is a robot program?
Answer: A robot program can be defined as a path in space to be followed by the manipulator, combined with peripheral actions that support the work cycle.

8.14 What is the difference between powered leadthrough and manual leadthrough in robot programming?
Answer: The difference between powered leadthrough and manual leadthrough is the manner in which the manipulator is moved through the motion cycle during programming. Powered leadthrough involves the use of a teach pendant with toggle switches and/or contact buttons for controlling the movement of the manipulator joints. Using the toggle switches or buttons, the programmer power drives the robot arm to the desired positions, in sequence, and records the positions into memory. Manual leadthrough requires the operator to physically grasp the end-of-arm or the tool that is attached to the arm and move it through the motion sequence, recording the path into memory.

8.15 What is control resolution in a robot positioning system?
Answer: As defined in the text, control resolution refers to the capability of the robot’s positioning system to divide the range of the joint into closely spaced points to which the joint can be moved by the controller.

8.16 What is the difference between repeatability and accuracy in a robotic manipulator?
Answer: Repeatability is the robot’s ability to position its end-of-wrist at a previously taught point in the work volume. It is concerned with the errors associated with the robot’s attempts to return to the same addressable point and is usually defined as ± 3 standard deviations of the mechanical errors of the manipulator. Accuracy is the robot’s ability to position the end of its wrist at a desired location in the work volume. It is concerned with the errors associated with the robot’s attempts to move to a specified location that may not be located at an addressable point.

PROBLEMS

Robot Anatomy

8.1 Using the notation scheme for defining manipulator configurations (Section 8.1.2), draw diagrams (similar to Figure 8.1) of the following robots: (a) TRT, (b) VVR, (c) VROT.

Solution:

![Diagram of TRT, VVR, and VROT configurations]

(a) TRT  (b) VVR  (c) VROT

8.2 Using the notation scheme for defining manipulator configurations (Section 8.1.2), draw diagrams (similar to Figure 8.1) of the following robots: (a) TRL, (b) OLO, (c) LVL.
8.3 Using the notation scheme for defining manipulator configurations (Section 8.1.2), draw diagrams (similar to Figure 8.1) of the following robots: (a) TRT:R, (b) TVR:TR, (c) RR:T.

Solution:

8.4 Using the robot configuration notation scheme discussed in Section 8.1, write the configuration notations for some of the robots in your laboratory or shop.

Solution: Answer depends on robots in the laboratory or shop of interest.

8.5 Describe the differences in orientation capabilities and work volumes for a :TR and a :RT wrist assembly. Use sketches as needed.

Solution:

The work volume of the :TR wrist is the intersection of a sphere and a cone. The work volume of the :RT wrist is a circular arc, provided by the R joint, with the capability to rotate around the line established by the angle of the R joint.

Robot Applications

8.6 A robot performs a loading and unloading operation for a machine tool. The work cycle consists of the following sequence of activities:

<table>
<thead>
<tr>
<th>Seq.</th>
<th>Activity</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Robot reaches and picks part from incoming conveyor and loads into fixture on machine tool.</td>
<td>5.5 sec.</td>
</tr>
<tr>
<td>2</td>
<td>Machining cycle (automatic)</td>
<td>38.0 sec.</td>
</tr>
<tr>
<td>3</td>
<td>Robot reaches in, retrieves part from machine tool, and deposits it onto outgoing conveyor.</td>
<td>4.8 sec.</td>
</tr>
</tbody>
</table>

51
Move back to pickup position 1.7 sec.

The activities are performed sequentially as listed. Every 30 workparts, the cutting tools in the machine must be changed. This irregular cycle takes 3.0 minutes to accomplish. The uptime efficiency of the robot is 97%; and the uptime efficiency of the machine tool is 98%, not including interruptions for tool changes. These two efficiencies are assumed not to overlap (i.e., if the robot breaks down, the cell will cease to operate, so the machine tool will not have the opportunity to break down; and vice versa). Downtime results from electrical and mechanical malfunctions of the robot, machine tool, and fixture. Determine the hourly production rate, taking into account the lost time due to tool changes and the uptime efficiency.

Solution: \( T_c = 5.5 + 38.0 + 4.8 + 1.7 = 50 \text{ sec/cycle} \)

Tool change time \( T_{tc} = 180 \text{ sec/30 pc} = 6 \text{ sec/pc} \)

Robot uptime \( E = 0.97, \) lost time = 0.03. Machine tool uptime \( E = 0.98, \) lost time = 0.02. These two inefficiencies are assumed not to overlap in the following solution.

\[
T_c + T_{tc}/30 = 50 + 6 = 56 \text{ sec} = 0.9333 \text{ min/pc}
\]

\[
R_c = 60/0.9333 = 64.286 \text{ pc/hr}
\]

Accounting for uptime efficiencies, \( R_p = 64.286(1.0 - 0.03 - 0.02) = 61.1 \text{ pc/hr} \)

In the previous problem, suppose that a double gripper is used instead of a single gripper as indicated in that problem. The activities in the cycle would be changed as follows:

<table>
<thead>
<tr>
<th>Seq.</th>
<th>Activity</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Robot reaches and picks raw part from incoming conveyor in one gripper and awaits completion of machining cycle. This activity is performed simultaneously with machining cycle.</td>
<td>3.3 sec.</td>
</tr>
<tr>
<td>2</td>
<td>At completion of previous machining cycle, robot reaches in, retrieves finished part from machine, loads raw part into fixture, and moves a safe distance from machine.</td>
<td>5.0 sec.</td>
</tr>
<tr>
<td>3</td>
<td>Machining cycle (automatic).</td>
<td>38.0 sec.</td>
</tr>
<tr>
<td>4</td>
<td>Robot moves to outgoing conveyor and deposits part. This activity is performed simultaneously with machining cycle.</td>
<td>3.0 sec.</td>
</tr>
<tr>
<td>5</td>
<td>Robot moves back to pickup position. This activity is performed simultaneously with machining cycle.</td>
<td>1.7 sec.</td>
</tr>
</tbody>
</table>

Steps 1, 4, and 5 are performed simultaneously with the automatic machining cycle. Steps 2 and 3 must be performed sequentially. The same tool change statistics and uptime efficiencies are applicable. Determine the hourly production rate when the double gripper is used, taking into account the lost time due to tool changes and the uptime efficiency.

Solution: \( T_c = 5.0 + 38.0 = 43 \text{ sec/cycle} \)

\[
T_{tc} = 180/30 = 6 \text{ sec/pc} \text{ as in previous problem.}
\]

\[
T_c + T_{tc} = 43 + 6 = 49 \text{ sec} = 0.8167 \text{ min/pc}
\]

\[
R_c = (60/0.8167) = 73.47 \text{ pc/hr}.
\]

Accounting for uptime efficiencies, \( R_p = 73.47(1.0 - 0.03 - 0.02) = 69.8 \text{ pc/hr} \)

Since the robot's portion of the work cycle requires much less time than the machine tool in Problem 8.6, the possibility of installing a cell with two machines is being considered. The robot would load and unload both machines from the same incoming and outgoing conveyors. The machines would be arranged so that distances between the fixture and the conveyors are the same for both machines. Thus, the activity times given in Problem 8.6 are valid for the two machine cell. The machining cycles would be staggered so that the robot would be servicing only one machine at a time. The tool change statistics and uptime efficiencies in Problem 8.6 are applicable. Determine the hourly production rate for the two-machine cell. The lost time due to tool changes and the uptime efficiency should be accounted for. Assume that if one of the two machine tools is down, the other machine can continue to operate, but if the robot is down, the cell operation is stopped.

Solution: Robot cycle time \( T_c = 5.5 + 4.8 + 1.7 = 12 \text{ sec} \)

Machine tool cycle = 33 (machining) + 6 (tool change) + 12 (robot unload/load) = 51 sec. = 0.85 min.

Since robot cycle is significantly smaller than machine tool cycle, assume there is little or no risk of machine interference when robot services two machines. (The machine interference issue is considered in Chapter 14,
Section 14.4.2). The production rate for each machine tool, disregarding for the moment consideration of the uptime efficiency of the robot:

\[ R_p = \frac{60}{0.85}(1.0 - 0.02) = 69.176 \text{ pc/hr} \]

Since there are two machines, the production rate will be double this value. However, the uptime efficiency of the robot will reduce the production rate to:

\[ R_p = 2(69.176)(1 - 0.03) = 134.2 \text{ pc/hr} \]

8.9 Determine the hourly production rate for a two-machine cell as in Problem 8.8, only the robot is equipped with a double gripper as in Problem 8.7. Assume the activity times from Problem 8.7 apply here.

Solution: Robot cycle time \( T_c = 3.3 + 5.0 + 3.0 + 1.7 = 13 \text{ sec} \)

Machine tool cycle = 33 (machining) + 6 (tool change) + 5 (robot unload/load) = 44 sec. = 0.733 min.

Assume no interference since 13 sec is so much less than 33 sec.

\[ R_p = \frac{60}{0.7333}(1.0 - 0.02) = 80.182 \text{ pc/hr} \]

With two machines, production rate is doubled, adjusted for robot efficiency.

\[ R_p = 2(80.182)(1 - 0.03) = 155.55 \text{ pc/hr} \]

8.10 The arc-on time is a measure of efficiency in an arc welding operation. As indicated in our discussion of arc welding in Section 8.5.2, typical arc-on times in manual welding range between 20% and 30%. Suppose that a certain welding operation is currently performed using a welder and a fitter. Production requirements are steady at 500 units per week. The fitter's job is to load the component parts into the fixture and clamp them in position for the welder. The welder then welds the components in two passes, stopping to reload the welding rod between the two passes. Some time is also lost each cycle for repositioning the welding rod on the work. The fitter's and welder's activities are done sequentially, with times for the various elements as follows:

<table>
<thead>
<tr>
<th>Seq.</th>
<th>Worker and activity</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fitter: load and clamp parts</td>
<td>4.2 min.</td>
</tr>
<tr>
<td>2</td>
<td>Welder: weld first pass</td>
<td>2.5 min.</td>
</tr>
<tr>
<td>3</td>
<td>Welder: reload weld rod</td>
<td>1.8 min.</td>
</tr>
<tr>
<td>4</td>
<td>Welder: weld second pass</td>
<td>2.4 min.</td>
</tr>
<tr>
<td>5</td>
<td>Welder: repositioning time</td>
<td>2.0 min.</td>
</tr>
<tr>
<td>6</td>
<td>Delay time between work cycles</td>
<td>1.1 min.</td>
</tr>
</tbody>
</table>

Because of fatigue, the welder must take a 20 minute rest at mid-morning and mid-afternoon, and a 40 minute lunch break around noon. The fitter joins the welder in these rest breaks. The nominal time of the work shift is eight hours, but the last 20 minutes of the shift is non-productive time for clean-up at each workstation. A proposal has been made to install a robot welding cell to perform the operation. The cell would be set up with two fixtures, so that the robot could be welding one job (the set of parts to be welded) while the fitter is unloading the previous job and loading the next job. In this way, the welding robot and the human fitter could be working simultaneously rather than sequentially. Also, a continuous wire feed would be used rather than individual welding rods. It has been estimated that the continuous wire feed must be changed only once every 40 parts and the lost time will be 20 minutes to make the wire change. The times for the various activities in the regular work cycle are as follows:

<table>
<thead>
<tr>
<th>Seq.</th>
<th>Fitter and robot activities</th>
<th>Times</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fitter: Load and clamp parts</td>
<td>4.2 min.</td>
</tr>
<tr>
<td>2</td>
<td>Robot: Weld complete</td>
<td>4.0 min.</td>
</tr>
<tr>
<td>3</td>
<td>Repositioning time</td>
<td>1.0 min</td>
</tr>
<tr>
<td>4</td>
<td>Delay time between work cycles</td>
<td>0.3 min.</td>
</tr>
</tbody>
</table>

A 10 minute break would be taken by the fitter in the morning and another in the afternoon, and 40 minutes would be taken for lunch. Clean-up time at the end of the shift is 20 minutes. In your calculations, assume that the proportion uptime of the robot will be 98%. Determine the following: (a) arc-on times (expressed as a percent, using the eight hour shift as the base) for the manual welding operation and the robot welding station, and (b) hourly production rate on average throughout the eight-hour shift for the manual welding operation and the robot welding station.

Solution: (a) Manual cycle arc-on time:

\[ T_c = 4.2 + 2.5 + 1.8 + 2.4 + 2.0 + 1.1 = 14.0 \text{ min} \]
Time arc is on = 2.5 + 2.4 = 4.9 min
Out of 8 hours, time available = 480 - 20 - 20 - 40 - 20 = 380 min/shift.
Number of cycles in 380 min = 380/14 = 27.143 cycles/shift
Time arc is on during shift = 27.143(4.9) = 133 min/shift
Arc-on time = 133/480 = 0.277 = 27.7%

Robot cycle arc-on time:
Cycle time $T_c = \text{Max}((4.2 + .3), (5.0 + .3)) = 5.3$ min/cycle
Time arc is on each cycle = 4.0 min
Out of 8 hours, time available = 480 - 10 - 10 - 40 - 20 = 400 min/shift.
Number of cycles in 400 min = 400/5.3 = 75.472 cycles/shift
Time arc is on during shift = 75.472(4.0) = 301.9 min/shift
Arc-on time = 301.9/480 = 0.629 = 62.9%

(b) Manual cycle production rate $R_p = (27.14 \text{ units}/\text{shift})/(8 \text{ hr}) = 3.393 \text{ units/hr}$
Robot cycle production rate $R_p = (75.47 \text{ units}/\text{shift})/(8 \text{ hr}) = 9.434 \text{ units/hr}$

Programming Exercises

Note: Problems 8.11 through 8.17 are all programming exercises to be performed on robots available. The solutions depend on the particular programming methods or languages used.

8.11 The setup for this problem requires a felt-tipped pen mounted to the robot's end-of-arm (or held securely in the robot's gripper). Also required is a thick cardboard, mounted on the surface of the worktable. Pieces of plain white paper will be pinned or taped to the cardboard surface. The exercise is the following: Program the robot to write your initials on the paper with the felt-tipped pen.

8.12 As an enhancement of the previous programming exercise, consider the problem of programming the robot to write any letter that is entered at the alphanumeric keyboard. Obviously, a textual programming language is required to accomplish this exercise.

8.13 Apparatus required for this exercise consists of two wood or plastic blocks of two different colors that can be grasped by the robot gripper. The blocks should be placed in specific positions (call the positions A and B on either side of a center location (call it position C). The robot should be programmed to do the following: (1) pick up the block at position A and place it at the central position C; (2) pick up the block at position B and place it at position A; (3) pick up the block at position C and place it at position B. (4) Repeat steps (1), (2), and (3) continually.

8.14 Apparatus for this exercise consists of a cardboard box and a dowel about 4 inches long (any straight thin cylinder will suffice, e.g., pen, pencil, etc.). The dowel is attached to the robot’s end-of-arm or held in its gripper. The dowel is intended to simulate an arc welding torch, and the edges of the cardboard box are intended to represent the seams that are to be welded. The programming exercise is the following: With the box oriented with one of its corners pointing towards the robot, program the robot to weld the three edges that lead into the corner. The dowel (welding torch) must be continuously oriented at a $45\degree$ angle with respect to the edge being welded. See Figure P8.14.

8.15 This exercise is intended to simulate a palletizing operation. The apparatus includes: six wooden (or plastic or metal) cylinders approximately 20 mm in diameter and 75 mm in length, and a 20 mm thick wooden block approximately 100 mm by 133 mm. The block is to have six holes of diameter 25 mm drilled in it as illustrated in Figure P8.15. The wooden cylinders represent workparts and the wooden block represents a pallet. (As an alternative to the wooden block, the layout of the pallet can be sketched on a plain piece of paper attached to the work table.) The programming exercise is the following: Using the powered leadthrough programming method, program the robot to pick up the parts from a fixed position on the work table and place them into the six positions in the pallet. The fixed position on the table might be a stop point on a conveyor. (The student may have to manually place the parts at the position if a real conveyor is not available.)

8.16 This is the same problem as the previous exercise, except that a robot programming language should be used, and the positions of the pallet should be defined by calculating their x and y coordinates by whatever method is available in the particular programming language used.

8.17 Repeat Problem 8.16 only in the reverse order to simulate a depalletizing operation.
8.18 The linear joint (type L) of a certain industrial robot is actuated by a piston mechanism. The length of the joint when fully retracted is 500 mm and when fully extended is 850 mm. If the robot's controller has an 8-bit storage capacity, determine the control resolution for this robot.

**Solution:** Range \( L = 850 \text{ mm} - 500 \text{ mm} = 350 \text{ mm} \). Given: \( n = 8 \) bit storage capacity

Control resolution \( CR = \frac{L}{2^n-1} = \frac{350}{255} = 1.37 \text{ mm} \)

8.19 In the previous problem, the mechanical errors associated with the linear joint form a normal distribution in the direction of the joint actuation with standard deviation = 0.08 mm. Determine (a) spatial resolution, (b) accuracy, and (c) repeatability for the robot.

**Solution:** Refers to Problem 7.30. Additional data: \( \sigma = 0.08 \text{ mm} \).

Spatial resolution \( SR = 1.57 + 6(0.08) = 2.05 \text{ mm} \)

Accuracy = \( \frac{CR}{2} + 3\sigma = \frac{1.57}{2} + 3(0.08) = 1.025 \text{ mm} \)

Repeatability = \( \pm 3\sigma = \pm 3(0.08) = \pm 0.24 \text{ mm} \)

8.20 The revolving joint (type V) of an industrial robot has a range of 240° rotation. The mechanical errors in the joint and the input/output links can be described by a normal distribution with its mean at any given addressable point, and a standard deviation of 0.25°. Determine the number of storage bits required in the controller memory so that the accuracy of the joint is as close as possible to, but less than, its repeatability. Use six standard deviations as the measure of repeatability.

**Solution:** Repeatability = \( 6\sigma = 6(0.25) = 1.5 \text{°} \) and Accuracy = \( 0.5 \text{ SR} = 0.5 \text{ CR} + 3\sigma \)

Find bit storage capacity \( n \) so that \( 0.5 \text{ CR} + 3\sigma = \text{approx} \) \( 6\sigma \)

Set \( 0.5 \text{ CR} + 3\sigma - 6\sigma = 0 \)

\( 0.5 \text{ CR} = 3\sigma \)

\( 2^n = (240 \text{°})/(1.5 \text{°}) = 160 \)

\( n \ln(2) = \ln(160), \quad 0.69315 n = 5.07517, \quad n = 7.3 \rightarrow n = 8 \text{ bits} \)

Accuracy = \( 0.5(0.9412) + 3(0.25) = 1.221 \text{°} \) which is \( \leq \) repeatability = \( 1.5 \text{°} \)

8.21 A cylindrical robot has a T-type wrist axis that can be rotated a total of three rotations (each rotation is a full 360°). It is desired to be able to position the wrist with a control resolution of 0.5° between adjacent addressable points. Determine the number of bits required in the binary register for that axis in the robot's control memory.

**Solution:** Range \( L = 3(360) = 1080 \text{°} \)

Specification: \( CR = 0.5 \text{°} \) or better, Find \( n \)

\( CR = \frac{1080}{2^n-1} = 0.5 \text{°} \).

Rearranging, \( 2^n - 1 = 1080/0.5 = 2160 \)

\( 2^n = 2161 \)

\( n \ln(2) = \ln(2161), \quad 0.69315 n = 7.6783, \quad n = 11.08 \rightarrow n = 12 \text{ bits} \)

8.22 One axis of an RRL robot is a linear slide with a total range of 950 mm. The robot's control memory has an 10-bit capacity. It is assumed that the mechanical errors associated with the arm are normally distributed with a mean at the given taught point and an isotropic standard deviation of 0.10 mm. Determine (a) the control resolution for the axis under consideration, (b) the spatial resolution for the axis, (c) the defined accuracy, (d) the repeatability.

**Solution:** Joint range \( L = 950 \text{ mm} \)

(a) \( CR = (950 \text{ mm})/(2^n-1) = 950/1023 = 0.929 \text{ mm} \)

(b) \( SR = 0.929 + 6(0.10) = 0.929 + 0.60 = 1.529 \text{ mm} \)
(c) Accuracy = 0.5 \( SR = 0.764 \text{ mm} \)

(d) Repeatability = ± 3\(\sigma\) = 6\(\sigma\) = \(0.60 \text{ mm}\).

8.23 A TLR robot has a rotational joint (type R) whose output link is connected to the wrist assembly. Considering the design of this joint only, the output link is 600 mm long, and the total range of rotation of the joint is 40°. The spatial resolution of this joint is expressed as a linear measure at the wrist, and is specified to be ±0.5 mm. It is known that the mechanical inaccuracies in the joint result in an error of ±0.018° rotation, and it is assumed that the output link is perfectly rigid so as to cause no additional errors due to deflection. (a) Determine the minimum number of bits required in the robot's control memory in order to obtain the spatial resolution specified. (b) With the given level of mechanical error in the joint, show that it is possible to achieve the spatial resolution specified.

Solution: \( SR = ±0.5 \text{ mm} \) at end of output link. Mechanical errors = ± 0.018° = ± 3\(\sigma\)

(a) Converting spatial resolution to an angular measure, we get
\[
SR = (1.0 \times 360)/(2 \times \pi \times 600) = 0.0955°
\]

\( SR = CR + 6\sigma \). Rearranging, \( CR = SR - 6\sigma = 0.0955 - 2(0.018) = 0.0595° \)

Given joint range \( L = 40° \), \( CR = (40°)/(2^n-1) = 0.0595° \)

\( 2^n - 1 = 40/0.0595 = 672.35 \), \( n \ln(2) = \ln(673.35) \), \( n = 9.395 \rightarrow 10 \text{ bits} \)

(b) It is therefore possible to achieve the spatial resolution specified.
Chapter 9
DISCRETE CONTROL USING PROGRAMMABLE LOGIC
CONTROLLERS AND PERSONAL COMPUTERS

REVIEW QUESTIONS

9.1 Briefly define the two categories of discrete process control?
   **Answer:** Discrete process control can be divided into two categories: (1) logic control, which is concerned with event-driven changes in the system; and (2) sequencing, which is concerned with time-driven changes in the system.

9.2 What is an AND gate? How does it operate on two binary inputs?
   **Answer:** An AND gate outputs a value of 1 if all of the inputs are 1, and 0 otherwise.

9.3 What is an OR gate? How does it operate on two binary inputs?
   **Answer:** An OR gate outputs a value of 1 if either of the inputs has a value of 1, and 0 otherwise.

9.4 What is Boolean algebra? What was its original purpose?
   **Answer:** Boolean algebra is a special form of algebra based on the logic elements (AND, OR, and NOT) that was developed around 1847 by George Boole. Its original purpose was to provide a symbolic means of testing whether complex statements of logic were TRUE or FALSE.

9.5 What is the difference between a delay-off timer and a delay-on timer?
   **Answer:** A delay-off timer switches power on immediately in response to a start signal, and then switches power off after a specified time delay, whereas a delay-on timer waits a specified length of time before switching power on when it receives a start signal.

9.6 What is the difference between an up counter and a down counter?
   **Answer:** An up counter starts at zero and increments its contents (the count total) by one in response to each pulse. When a preset value has been reached, the up counter can be reset to zero. A down counter starts with a preset value and decrements the total by one for each pulse received.

9.7 What is a ladder logic diagram?
   **Answer:** A ladder logic diagram shows the various logic elements and other components along horizontal lines or rungs connected on either end to two vertical rails. The diagram has the general configuration of a ladder, hence its name. The elements and components are contacts (representing logical inputs) and loads, also known as coils (representing outputs).

9.8 The two types of components in a ladder logic diagram are contacts and coils. Give two examples of each type.
   **Answer:** Contacts include switches and relay contacts, and coils include motors, lamps, and alarms.

9.9 What is a programmable logic controller?
   **Answer:** A programmable logic controller is a microcomputer-based controller that uses stored instructions in programmable memory to implement logic, sequencing, timing, counting, and arithmetic functions through digital or analog input/output (I/O) modules, for controlling machines and processes.

9.10 What are the advantages of using a PLC rather than conventional relays, timers, counters, and other hard-wired control components?
   **Answer:** The advantages listed in the text are (1) programming the PLC is easier than wiring the relay control panel; (2) the PLC can be reprogrammed, whereas conventional controls must be rewired and are often scrapped instead; (3) PLCs take less floor space than relay control panels; (4) reliability is greater, and maintenance is easier; (5) the PLC can be connected to computer systems more easily than relays; and (6) PLCs can perform a greater variety of control functions than can relay controls.

9.11 What are the five basic components of a PLC?
The five basic components of a PLC are the following: (1) processor, (2) memory unit, (3) power supply, (4) I/O module, and (5) programming device.

9.12 The typical operating cycle of the PLC, called a scan, consists of three parts: (1) input scan, (2) program scan, and (3) output scan. Briefly describe what is accomplished in each part.

Answer: During the input scan, the inputs to the PLC are read by the processor and the status of these inputs is stored in memory. Next, the control program is executed during the program scan. The input values stored in memory are used in the control logic calculations to determine the values of the outputs. Finally, during the output scan, the outputs are updated to agree with the calculated values.

9.13 Name the five PLC programming methods identified in the International Standard for Programmable Controllers (IEC 1131–3).

Answer: The standard specifies three graphical languages and two text-based languages for programming PLCs, respectively: (1) ladder logic diagrams, (2) function block diagrams, (3) sequential functions charts, (4) instruction list, and (5) structured text.

9.14 What are three of the reasons and factors that explain why personal computers are being used with greater and greater frequency for industrial control applications?

Answer: Some of the reasons given in the text are the following: (1) The technological evolution of PLCs has not kept pace with the development of PCs. (2) New generations of PCs are introduced with much greater frequency than PLCs, making it difficult to mix and match components from different vendors. (3) There is much more proprietary software and architecture in PLCs than in PCs, and the gap is increasing. (5) PCs are now available in more-sturdy enclosures for the dirty and noisy plant environment. (6) PCs can be equipped with membrane-type keyboards for protection against factory moisture, oil, and dirt. (7) PCs can be ordered with I/O cards and related hardware to provide the necessary devices to connect to the plant’s equipment and processes. (8) Operating systems designed to implement real-time control applications can be installed in addition to traditional office software.

9.15 Name the two basic approaches used in PC-based control systems.

Answer: The two approaches are soft logic and hard real-time control. In the soft logic configuration, the PC’s operating system is Windows, and control algorithms are installed as high-priority programs under the operating system. However, it is possible to interrupt the control tasks in order to service certain system functions in Windows, such as network communications and disk access. When this happens, the control function is delayed, with possible negative consequences to the process. By contrast, in a hard real-time control system, the PC’s operating system is the real-time operating system, and the control software takes priority over all other software. Windows tasks are executed at a lower priority under the real-time operating system. Windows cannot interrupt the execution of the real-time controller. If Windows locks up, it does not affect the controller operation. Also, the real-time operating system resides in the PC’s active memory, so a failure of the hard disk has no effect in a hard real-time control system.

PROBLEMS

9.1 Write the Boolean logic expression for the pushbutton switch of Example 9.2 using the following symbols: X1 = START, X2 = STOP, Y1 = MOTOR, and Y2 = POWER-TO-MOTOR.

Solution: Let X1 = start, X2 = stop, Y1 = motor, Y2 = power-to-motor.

Boolean logic expression: Y2 = (X1 + Y1) · X2

9.2 Construct the ladder logic diagram for the robot interlock system in Example 9.1.

Solution: Ladder logic diagram.
9.3 In the circuit of Figure 9.1, suppose a photodetector were used to determine whether the lamp worked. If the lamp does not light when both switches are closed, the photodetector causes a buzzer to sound. Construct the ladder logic diagram for this system.

**Solution:** Ladder logic diagram.

![Ladder logic diagram](image)

9.4 Construct the ladder logic diagrams for (a) the NAND gate and (b) the NOR gate.

**Solution:** Ladder logic diagrams.

(a) NAND

![NAND ladder diagram](image)

(b) NOR

![NOR ladder diagram](image)

9.5 Construct the ladder logic diagrams for the following Boolean logic equations: (a) \( Y = (X_1 + X_2) \cdot X_3 \), (b) \( Y = (X_1 + X_2) \cdot (X_3 + X_4) \), and (c) \( Y = (X_1 \cdot X_2) + X_3 \).

**Solution:** Ladder logic diagrams.

(a) \( Y = (X_1 + X_2) \cdot X_3 \)

![Ladder logic diagram](image)
9.6 Write the low level language statements for the robot interlock system in Example 9.1 using the instruction set in Table 9.10.

**Solution:**

```
STR X1
AND X2
AND X3
OUT Y
```

9.7 Write the low level language statements for the lamp and photodetector system in Problem 9.4 using the instruction set in Table 9.10.

**Solution:**

```
STR X1
AND X2
OUT Y
STR X1
AND X2
AND NOT X3
OUT Y1
```

9.8 Write the low level language statements for the fluid filling operation in Example 9.6 using the instruction set in Table 9.10.

**Solution:**

```
STR X1
OR C1
AND NOT FS
OUT C1
STR C1
OUT S1
STR FS
OR C2
AND NOT T2
OUT C2
STR C2
TMR T1 120
STR T1
OUT S2
STR T1
TMR T2 90
```

(120 specifies timer delay in sec)

9.9 Write the low level language statements for the four parts of Problem 9.5 using the instruction set in Table 9.10.
Solution:  (a) STR X1
OR X2
AND X3
OUT Y
(c) STR X1
AND X2
OR X3
OUT Y

(b) STR X3
OR X4
OUT Y1
STR X1
OR X2
AND Y1
OUT Y
(d) STR X1
AND X2
OUT Y

9.10 In the fluid filling operation of Example 9.6, suppose a sensor (e.g., a submerged float switch) is used to determine whether the contents of the tank have been evacuated, rather than rely on timer T2 to empty the tank.
(a) Construct the ladder logic diagram for this revised system. (b) Write the low level language statements for the system using the PLC instruction set in Table 9.10.

Solution: (a) Ladder logic diagram. Assume FS2 (new float switch) is open when tank is empty. FS1 is the tank full float switch.

(b) Low level language statements:
STR X1
OR C1
AND NOT FS1
OUT C1
STR C1
OUT S1
STR FS1
OR C2
AND NOT FS2
OUT C2
STR C2
TMR T1 120  (120 specifies timer delay in sec)
9.11 In the manual operation of a sheet metal stamping press, a two button safety interlock system is often used to prevent the operator from inadvertently actuating the press while his hand is in the die. Both buttons must be depressed to actuate the stamping cycle. In this system, one pressbutton is located on one side of the press while the other button is located on the opposite side. During the work cycle the operator inserts the part into the die and depresses both pushbuttons, using both hands. (a) Write the truth table for this interlock system. (b) Write the Boolean logic expression for the system. (c) Construct the logic network diagram for the system. (d) Construct the ladder logic diagram for the system.

**Solution:** Let $X1 =$ button one, $X2 =$ button 2, and $Y =$ safety interlock

(a) Truth table

<table>
<thead>
<tr>
<th>$X1$</th>
<th>$X2$</th>
<th>$Y$</th>
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(b) Boolean logic expression: $Y = X1 \cdot X2$

(c) Logic network diagram

(d) Ladder logic diagram

9.12 An emergency stop system is to be designed for a certain automatic production machine. A single "start" button is used to turn on the power to the machine at the beginning of the day. In addition, there are three "stop" buttons located at different locations around the machine, any one of which can be pressed to immediately turn off power to the machine. (a) Write the truth table for this system. (b) Write the Boolean logic expression for the system. (c) Construct the logic network diagram for the system. (d) Construct the ladder logic diagram for the system.

**Solution:** Let $X1 =$ start button, $X2 =$ stop button 1, $X3 =$ stop button 2, $X4 =$ stop button 3, $Y1 =$ machine, and $Y2 =$ power-to-machine.

(a) Truth table:

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<tr>
<th>$X1$</th>
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<th>$X4$</th>
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An industrial robot performs a machine loading and unloading operation. A PLC is used as the robot cell controller. The cell operates as follows: (1) a human worker places a workpart into a nest, (2) the robot reaches over and picks up the part and places it into an induction heating coil, (3) a time of 10 seconds is allowed for the heating operation, and (4) the robot reaches in and retrieves the part and places it on an outgoing conveyor. A limit switch X1 (normally open) will be used in the nest to indicate part presence in step (1). Output contact Y1 will be used to signal the robot to execute step (2) of the work cycle. This is an output contact for the PLC, but an input interlock for the robot controller. Timer T1 will be used to provide the 10 second delay in step (3). Output contact Y2 will be used to signal the robot to execute step (4). (a) Construct the ladder logic diagram for the system. (b) Write the low level language statements for the system using the PLC instruction set in Table 9.10.

**Solution:** (a) Ladder logic diagram
A PLC is used to control the sequence in an automatic drilling operation. A human operator loads and clamps a raw workpart into a fixture on the drill press table and presses a start button to initiate the automatic cycle. The drill spindle turns on, feeds down into the part to a certain depth (the depth is determined by limit switch), and then retracts. The fixture then indexes to a second drilling position, and the drill feed-and-retract is repeated. After the second drilling operation, the spindle turns off, and the fixture moves back to the first position. The worker then unloads the finished part and loads another raw part.

(a) Specify the input/output variables for this system operation and define symbols for them (e.g., X1, X2, C1, Y1, etc.).

(b) Construct the ladder logic diagram for the system.

(c) Write the low level language statements for the system using the PLC instruction set in Table 9.10.

Solution: (a) Let

X1 = spindle up
X2 = spindle at desired depth
X3 = fixture at position 1
X4 = fixture at position 2
X5 = start button
Y1 = spindle on
Y2 = spindle down
Y3 = fixture to position 2
C1 = drill cycle permit
C2 = hole 1 drilled
C3 = hole 2 drilled.

(b) Ladder logic diagram:
(c) Low level language:
STR NOT C3
OR NOT X1
OUT C10
STR X5
AND X1
AND X3
OR C1
AND C10
OUT C1
STR X2
AND Y2
AND X3
OR C2
AND C1
OUT C2
STR X2
AND Y2
AND X4
OR C3
AND C2
OUT C3

(C10 used to facilitate parallel circuit)
An industrial furnace is to be controlled as follows: The contacts of a bimetallic strip inside the furnace close if the temperature falls below the set point, and open when the temperature is above the set point. The contacts regulate a control relay which turns on and off the heating elements of the furnace. If the door to the furnace is opened, the heating elements are temporarily turned off until the door is closed. (a) Specify the input/output variables for this system operation and define symbols for them (e.g., X1, X2, C1, Y1, etc.). (b) Construct the ladder logic diagram for the system. (c) Write the low level language statements for the system using the PLC instruction set in Table 9.10.

Solution: (a) Let X1 = temperature below set point, X2 = door closed, Y1 = furnace on.
(b) Ladder logic diagram:

(c) Low level language:

\[
\text{STR X1} \\
\text{AND X2} \\
\text{OUT Y1}
\]
Chapter 10
MATERIAL TRANSPORT SYSTEMS

REVIEW QUESTIONS

10.1 Provide a definition of material handling.

**Answer:** Material handling is defined by the Material Handling Industry of America (MHIA) as “the movement, storage, protection and control of materials throughout the manufacturing and distribution process including their consumption and disposal.”

10.2 How does material handling fit within the scope of logistics?

**Answer:** Material handling is concerned with internal logistics – the movement and storage of material in a facility. By contrast, external logistics is concerned with the transportation of materials between facilities by rail, truck, seaway, air transport, and/or pipelines.

10.3 Name the four major categories of material handling equipment.

**Answer:** As identified in the text, the four categories of material handling equipment are (1) material transport equipment, (2) storage systems, (3) unitizing equipment, and (4) identification and tracking systems.

10.4 What is included within the term *unitizing equipment*?

**Answer:** As defined in the text, unitizing equipment refers to the containers used to hold individual items during handling and the equipment used to load and package the containers.

10.5 What is the unit load principle?

**Answer:** The unit load principle recommends that the unit load should be designed to be as large as is practical for the material handling system that will move or store it, subject to considerations of safety, convenience, and access to the materials making up the unit load.

10.6 What are the five categories of material transport equipment commonly used to move parts and materials inside a facility?

**Answer:** The five categories identified in the text are (1) industrial trucks, manual and powered, (2) automated guided vehicles, (3) monorails and other rail guided vehicles, (4) conveyors, and (5) cranes and hoists.

10.7 Give some examples of industrial trucks used in material handling.

**Answer:** Examples given in the text include nonpowered trucks such as dollies and pallet trucks, and powered trucks such as walkie trucks, forklift rider trucks, and towing tractors.

10.8 What is an automated guided vehicle system (AGVS)?

**Answer:** As defined in the text, an automated guided vehicle system is a material handling system that uses independently operated, self-propelled vehicles guided along defined pathways. The vehicles are powered by on-board batteries.

10.9 Name three categories of automated guided vehicles.

**Answer:** The three categories are (1) driverless trains, consisting of a towing vehicle that pulls one or more trailers, (2) pallet trucks, used to move palletized loads, and (3) unit load carriers, which move unit loads.

10.10 What features distinguish self-guided vehicles from conventional AGVs?

**Answer:** Conventional AGVs use either imbedded guide wires in the floor or paint strips on the floor surface as the guidance technology, whereas self-guided vehicles use a combination of dead reckoning, which refers to the capability of the vehicle to follow a given route by counting its own wheel rotations along a specified trajectory, and beacons located throughout the facility that serve to verify the vehicle’s location in the facility.

10.11 What is forward sensing in AGVS terminology?

**Answer:** Forward sensing involves the use of one or more sensors on each vehicle to detect the presence of other vehicles and obstacles ahead on the guide path. Sensor technologies include optical and ultrasonic devices. When the on-board sensor detects an obstacle in front of it, the vehicle is programmed to stop.
10.12 What are some of the differences between rail-guided vehicles and automated guided vehicles?

**Answer:** Rail-guided vehicles ride on tracks on the floor or overhead, whereas AGVs ride on the building floor without rails. Rail-guided vehicles are guided by the tracks, whereas AGVs are guided by imbedded wires in the floor that emit a magnetic field, or by paint strips, or other means that do not rely on rails. Rail-guided vehicles obtain their electrical power from a “third rail”, whereas AGVs carry batteries as their electrical power source.

10.13 What is a conveyor?

**Answer:** As defined in the text, a conveyor is a mechanical apparatus for moving items or bulk materials, usually inside a facility. Conveyors are used when material must be moved in relatively large quantities between specific locations over a fixed path, which may be in-the-floor, above-the-floor, or overhead. Conveyors divide into two basic categories: (1) powered and (2) non-powered.

10.14 Name some of the different types of conveyors used in industry.

**Answer:** The conveyor types listed in the text include roller, skate wheel, belt, chain, in-floor towline, overhead trolley, and cart-on-track.

10.15 What is a recirculating conveyor?

**Answer:** A recirculating conveyor is a closed-loop conveyor that allow parts or loads to remain on the return loop for one or more revolutions.

10.16 What is the difference between a hoist and a crane?

**Answer:** A hoist is a mechanical device for lifting and lowering loads vertically, whereas a crane is a mechanical apparatus for horizontal movement of loads. A crane invariably includes one or more hoists.

**PROBLEMS**

**Analysis of Vehicle-based Systems**

10.1 A flexible manufacturing system is being planned. It has a ladder layout as pictured in Figure P10.1 and uses a rail guided vehicle system to move parts between stations in the layout. All workparts are loaded into the system at station 1, moved to one of three processing stations (2, 3, or 4), and then brought back to station 1 for unloading. Once loaded onto its RGV, each workpart stays onboard the vehicle throughout its time in the FMS. Load and unload times at station 1 are each 1.0 min. Processing times at other stations are: 5.0 min at station 2, 7.0 min at station 3, and 9.0 min at station 4. Hourly production of parts through the system is: 7 parts through station 2, 6 parts through station 3, and 5 parts through station 4. (a) Develop the from-to Chart for trips and distances using the same format as Table 10.5. (b) Develop the network diagram for this data similar to Figure 10.13. (c) Determine the number of rail guided vehicles that are needed to meet the requirements of the flexible manufacturing system, if vehicle speed = 60 m/min and the anticipated traffic factor = 0.85. Assume reliability = 100%.

**Solution:** (a) First develop the distances from the FMS layout.
Distance from 1 to 2: 10 + 10 + 10 = 30 m
Distance from 2 to 1: 5 + 10 + 5 = 20 m
Distance from 1 to 3: 10 + 20 + 10 = 40 m
Distance from 3 to 1: 5 + 20 + 5 = 30 m
Distance from 1 to 4: 10 + 30 + 10 = 50 m
Distance from 4 to 1: 5 + 30 + 5 = 40 m

From-To chart:

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<th>2</th>
<th>3</th>
<th>4</th>
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<tbody>
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<td>6/40</td>
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<tr>
<td>4</td>
<td>5/40</td>
<td>-</td>
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</table>

(b) Network diagram:
In Example 10.2 in the text, suppose that the vehicles operate according to the following scheduling rules: (1) vehicles delivering raw workparts from station 1 to stations 2, 3, and 4 must return empty to station 5; and (2) vehicles picking up finished parts at stations 2, 3, and 4 for delivery to station 5 must travel empty from station 1. (a) Determine the empty travel distances associated with each delivery and develop a from-to Chart in the format of Table 10.5 in the text. (b) Suppose the AGVs travel at a speed of 50 m/min, and the traffic factor = 0.90. Assume reliability = 100%. As determined in Example 10.2, the delivery distance \( L_d = 103.8 \text{ m} \). Determine the value of \( L_e \) for the layout based on your table. (c) How many automated guided vehicles will be required to operate the system?

**Solution:** (a) Enumeration of empty trips:

<table>
<thead>
<tr>
<th>Deliveries</th>
<th>Associated empty trips</th>
<th>Frequency</th>
<th>Empty distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 2</td>
<td>2 to 1</td>
<td>9</td>
<td>110</td>
</tr>
<tr>
<td>2 to 5</td>
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<td>9</td>
<td>50 + 30</td>
</tr>
<tr>
<td>1 to 3</td>
<td>3 to 1</td>
<td>5</td>
<td>200</td>
</tr>
<tr>
<td>3 to 5</td>
<td>1 to 3 and 5 to 1</td>
<td>3</td>
<td>120 + 30</td>
</tr>
<tr>
<td>1 to 4</td>
<td>4 to 1</td>
<td>6</td>
<td>115</td>
</tr>
<tr>
<td>3 to 4</td>
<td>1 to 3 and 4 to 1</td>
<td>2</td>
<td>120 + 115</td>
</tr>
<tr>
<td>4 to 5</td>
<td>1 to 4 and 5 to 1</td>
<td>8</td>
<td>205 + 30</td>
</tr>
</tbody>
</table>

From-To chart:

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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
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<tr>
<td>4</td>
<td>8/115</td>
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<td>20/30</td>
<td>-</td>
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<td>-</td>
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</tr>
</tbody>
</table>

(b) \( L_e = \frac{9(50) + 5(120) + 8(205) + 9(110) + 5(200) + 8(115) + 20(30)}{42} = \frac{6200}{42} = 147.6 \text{ m} \)
10.3 In Example 10.2 in the text, suppose that the vehicles operate according to the following scheduling rule in order to minimize the distances the vehicles travel empty: vehicles delivering raw workparts from station 1 to stations 2, 3, and 4 must pick up finished parts at these respective stations for delivery to station 5. (a) Determine the empty travel distances associated with each delivery and develop a from-to Chart in the format of Table 10.5 in the text. (b) Suppose the AGVs travel at a speed of 40 m/min, and the traffic factor = 0.90. Assume reliability = 100%. As determined in Example 10.2, the delivery distance $L_d = 103.8$ m. Determine the value of $L_e$ for the layout based on your table. (c) How many automated guided vehicles will be required to operate the system?

Solution: (a) Enumeration of empty trips:

<table>
<thead>
<tr>
<th>Deliveries</th>
<th>Associated empty trips</th>
<th>Frequency</th>
<th>Empty distance</th>
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From-To chart:

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<tr>
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<td>20/30</td>
<td>-</td>
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</table>

(b) $L_e = \frac{20(30)}{42} = 14.3$ m

(c) $T_e = 1.0 + \frac{103.8}{40} + \frac{14.3}{40} = 3.95$ min

$R_{dv} = \frac{60(0.90)}{3.95} = 13.66$ del/hr per vehicle

$c = 42/13.66 = 3.07 \rightarrow 4$ vehicles

10.4 A planned fleet of forklift trucks has an average travel distance per delivery = 500 ft loaded and an average empty travel distance = 350 ft. The fleet must make a total of 60 deliveries per hour. Load and unload times are each 0.5 min and the speed of the vehicles = 300 ft/min. The traffic factor for the system = 0.85. Availability = 0.95, and worker efficiency = 90%. Determine (a) ideal cycle time per delivery, (b) the resulting average number of deliveries per hour that a forklift truck can make, and (c) how many trucks are required to accomplish the 60 deliveries per hour.

Solution: (a) $T_i = 0.5 + \frac{500}{300} + 0.5 + \frac{350}{300} = 3.83$ min/delivery

(b) Ideally, $R_{dv} = \frac{60}{3.83} = 15.66$ deliveries/hr per truck

Accounting for traffic factor, availability, and worker efficiency, $R_{dv} = 15.66(0.85)(0.95)(0.90) = 11.39$ deliveries/hr per truck

(c) $c = 60/11.39 = 5.27 \rightarrow 6$ forklift trucks

10.5 An automated guided vehicle system has an average travel distance per delivery = 200 m and an average empty travel distance = 150 m. Load and unload times are each 24 s and the speed of the AGV = 1 m/s. Traffic factor =
0.9. How many vehicles are needed to satisfy a delivery requirement of 30 deliveries/hour? Assume that availability = 0.95.

**Solution:**

\[ T_c = 24 + \frac{200}{1} + 24 + \frac{150}{1} = 398 \text{ s} = 6.63 \text{ min} \]

\[ R_{dv} = \frac{60 \times 0.90 \times 0.95}{6.63} = 7.73 \text{ deliveries/hr per vehicle} \]

\[ n_c = \frac{30}{7.73} = 3.88 \rightarrow 4 \text{ vehicles} \]

10.6 Four forklift trucks are used to deliver pallet loads of parts between work cells in a factory. Average travel distance loaded is 350 ft and the travel distance empty is estimated to be the same. The trucks are driven at an average speed of 4 miles/hr when loaded and 5 miles/hr when empty. Terminal time per delivery averages 1.0 min (load = 0.5 min and unload = 0.5 min). If the traffic factor is assumed to be 0.90, availability = 100%, and worker efficiency = 0.95, what is the maximum hourly delivery rate of the four trucks?

**Solution:**

When loaded,

\[ v_c = \left(4 \text{ miles/hr}\right) \left( \frac{5280 \text{ ft}}{1 \text{ mile}} \times \frac{1 \text{ hr}}{60 \text{ min}} \right) = 352 \text{ ft/min} \]

When empty,

\[ v_c = \left(5 \text{ miles/hr}\right) \left( \frac{5280 \text{ ft}}{1 \text{ mile}} \times \frac{1 \text{ hr}}{60 \text{ min}} \right) = 440 \text{ ft/min} \]

\[ T_c = 1.0 + \frac{350}{352} + \frac{350}{440} = 2.79 \text{ min/delivery} \]

\[ R_{dv} = \frac{60 \times 0.90 \times 0.95}{2.79} = 18.39 \text{ deliveries/hr per vehicle} \]

With four trucks,

\[ R_d = 4 \times 18.39 = 73.6 \text{ deliveries/hr}. \]

10.7 An AGVS has an average loaded travel distance per delivery = 400 ft. The average empty travel distance is not known. Required number of deliveries per hour = 60. Load and unload times are each 0.6 min and the AGV speed = 125 ft/min. Anticipated traffic factor = 0.85 and availability = 0.95. Develop an equation that relates the number of vehicles required to operate the system as a function of the average empty travel distance \( L_e \).

**Solution:**

\[ T_c = 0.6 + \frac{400}{125} + 0.6 + \frac{L_e}{125} = 4.4 + \frac{L_e}{125} \]

\[ AT = 60 \times 0.95 \times 0.85 \times 1.0 = 48.45 \text{ min/hr per vehicle} \]

\[ WL = 50 \left(4.4 + \frac{L_e}{125}\right) = 220 + 0.4 L_e \]

\[ n_c = \frac{220 + 0.4 L_e}{48.45} \]

\[ n_c = 4.54 + 0.00825 L_e \]

10.8 A rail-guided vehicle system is being planned as part of an assembly cell. The system consists of two parallel lines, as in Figure P10.8. In operation, a base part is loaded at station 1 and delivered to either station 2 or 4, where components are added to the base part. The RGV then goes to either station 3 or 5, respectively, where further assembly of components is accomplished. From stations 3 or 5, the product moves to station 6 for removal from the system. Vehicles remain with the products as they move through the station sequence; thus, there is no loading and unloading of parts at stations 2, 3, 4, and 5. After unloading parts at station 6, the vehicles then travel empty back to station 1 for reloading. The hourly moves (parts/hr) and distances (ft) are listed in the table below. RGV speed = 100 ft/min. Assembly cycle times at stations 2 and 3 = 4.0 min each, and at stations 4 and 5 = 6.0 min each. Load and unload times at stations 1 and 6 respectively are each 0.75 min. Traffic factor = 1.0 and availability = 1.0. How many vehicles are required to operate the system?

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<th>4</th>
<th>5</th>
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<tbody>
<tr>
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<td>14L/200</td>
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<td>9L/150</td>
<td>0/NA</td>
</tr>
<tr>
<td>2</td>
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<td>0/NA</td>
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<tr>
<td>4</td>
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<td>0/NA</td>
<td>0/0</td>
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<td>5</td>
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</tr>
</tbody>
</table>
**Solution**: Assembly through stations 2 and 3:

\[ T_c = 0.75 + \frac{200}{100} + \frac{50}{100} + \frac{4.0 + \frac{50}{100} + \frac{0.75 + \frac{400}{100}}{100}}{100} = 16.5 \text{ min} \]

\[ R_{av} = \frac{60}{16.5} = 3.636 \text{ deliveries/hr per vehicle} \]

\[ n_c = \frac{14}{3.636} = 3.85 \text{ vehicles.} \]

Assembly through stations 2 and 3:

\[ T_c = 0.75 + \frac{150}{100} + \frac{6.0 + \frac{50}{100} + \frac{6.0 + \frac{100}{100} + \frac{0.75 + \frac{400}{100}}{100}}{100}}{100} = 20.5 \text{ min} \]

\[ R_{av} = \frac{60}{20.5} = 2.927 \text{ deliveries/hr per vehicle} \]

\[ n_c = \frac{9}{2.927} = 3.07 \text{ vehicles.} \]

Total vehicles \( n_c = 3.85 + 3.07 = 6.92 \Rightarrow 7 \text{ vehicles} \)

10.9 An AGVS will be used to satisfy material flows indicated in the from-to Chart in the table below, which shows deliveries per hour between stations (above the slash) and distances in meters between stations (below the slash). Moves indicated by "L" are trips in which the vehicle is loaded, while "E" indicates moves in which the vehicle is empty. It is assumed that availability \( = 0.90 \), traffic factor \( = 0.85 \), and efficiency \( = 1.0 \). Speed of an AGV \( = 1.1 \text{ m/s} \). If load handling time per delivery cycle \( = 1.0 \text{ min} \), determine the number of vehicles needed to satisfy the indicated deliveries per hour? Assume that availability \( = 0.90 \).

<table>
<thead>
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<td>9E/75</td>
<td>0/NA</td>
<td>0/NA</td>
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</table>

**Solution**: \( v_c = 1.1 \text{ m/s}(60 \text{ s/min}) = 66 \text{ m/min} \)

Route 1 \( \rightarrow 2 \rightarrow 1 \): \( T_c = 1.0 + (90 + 90)/66 = 3.73 \text{ min, 5 deliveries.} \)

Route 1 \( \rightarrow 3 \rightarrow 1 \): \( T_c = 1.0 + (120 + 120)/66 = 4.64 \text{ min, 7 deliveries.} \)

Route 1 \( \rightarrow 4 \rightarrow 1 \): \( T_c = 1.0 + (75 + 75)/66 = 3.27 \text{ min, 5 deliveries.} \)

Route 2 \( \rightarrow 4 \rightarrow 1^* \): \( T_c = 1.0 + (80 + 75)/66 = 3.35 \text{ min, 4 deliveries.} \)

Route 1 \( \rightarrow 2^* \): \( T_c = 1.0 + 90/66 = 2.36 \text{ min, 4 deliveries.} \)

* Assumes vehicles on route 1 \( \rightarrow 2 \) are used to make deliveries on route 2 \( \rightarrow 4 \rightarrow 1 \).

Average \( T_c = \frac{5(3.73) + 7(4.64) + 5(3.27) + 4(3.35) + 4(2.36)}{25} = 3.613 \text{ min/delivery cycle} \)

\[ R_{av} = \frac{60(0.85)}{3.613} = 14.12 \text{ deliveries/hr per vehicle} \]

Including effect of availability factor, \( R_{av} = 14.12(0.90) = 12.7 \text{ deliveries/hr per vehicle} \)

\[ n_c = \frac{25/12.7 = 1.97}{2} \Rightarrow 2 \text{ vehicles} \]

10.10 An automated guided vehicle system is being proposed to deliver parts between 40 workstations in a factory. Loads must be moved from each station about once every hour; thus, the delivery rate \( = 40 \text{ loads per hour.} \)

Average travel distance loaded is estimated to be 250 ft and travel distance empty is estimated to be 300 ft. Vehicles move at a speed \( = 200 \text{ ft/min.} \) Total handling time per delivery \( = 1.5 \text{ min (load = 0.75 min and unload = 0.75 min).} \) Traffic factor \( F_T \) becomes increasingly significant as the number of vehicles \( n_c \) increases; this can be modeled as:

\[ F_T = 1.0 - 0.05(n_c - 1) \quad \text{for } n_c = \text{Integer} > 0 \]

Determine the minimum number of vehicles needed in the factory to meet the flow rate requirement. Assume that availability \( = 1.0 \) and worker efficiency \( = 1.0 \).

**Solution**: \( T_c = 1.5 + \frac{250 + 300}{200} = 4.25 \text{ min/cycle} \)

\[ R_{av} = \frac{60(1.0 - 0.05(n_c - 1))}{4.25} = \frac{60(1.05 - 0.05n_c)}{4.25} = 14.824 - 0.706 n_c \text{ deliveries/hr per vehicle} \]
Material Transport-3e-SI  10-05, 12/06, 06/04/07, 09/13/07

\[ n_c = \frac{40}{14.824 - 0.706 n_c} \]
\[ n_c (14.824 - 0.706 n_c) = 40 \]
\[ 14.824 n_c - 0.706 n_c^2 = 40 \]
\[ 0.706 n_c^2 - 14.824 n_c + 40 = 0 \]

Use quadratic equation to find roots:
\[ n_c = \frac{-(-14.824) \pm \sqrt{14.824^2 - 4(0.706)(40)}}{2(0.706)} = 17.82 \text{ or } 3.18 \rightarrow \text{Use } n_c = 4 \text{ vehicles} \]

**Check:** \( F_I = 1.0 - 0.05(4 - 1) = 1.0 - 0.15 = 0.85 \)
\[ R_{d_i} = \frac{60(0.85)}{4.25} = 12 \text{ deliveries/hr per vehicle,} \]
\[ n_c = 40/12 = 3.33 \rightarrow \text{Use } n = 4 \text{ vehicles} \]

10.11 An automated guided vehicle system is being planned for a warehouse complex. The AGVS will be a driverless train system, and each train will consist of the towing vehicle plus four carts. Speed of the trains will be 160 ft/min. Only the pulled carts carry loads. The average loaded travel distance per delivery cycle is 2000 ft and empty travel distance is the same. Anticipated travel factor = 0.95. Assume reliability = 1.0. The load handling time per delivery is expected to be 10 min. If the requirements on the AGVS are 25 cart loads per hour, determine the number of trains required.

**Solution:** \( T_c = 10 + \frac{2000 + 2000}{160} = 35.0 \text{ min/delivery cycle} \)
\[ R_{d_i} = \frac{60(0.95)}{35.0} = 1.629 \text{ deliveries/hr per vehicle} \]
\[ R_f = \frac{25\text{ cartloads/hr}}{4\text{ carts/load/train}} = 6.25 \text{ trainloads/hr} = 6.25 \text{ deliveries/hr} \]
\[ n_c = 6.25/1.629 = 3.84 \rightarrow \text{Use } n_c = 4 \text{ AGV trains.} \]

10.12 The from-to Chart in the table below indicates the number of loads moved per 4-hour period (above the slash) and the distances in ft (below the slash) between departments in a particular factory. Fork lift trucks are used to transport materials between departments. They move at an average speed = 350 ft/min (loaded) and 400 ft/min (empty). Load handling time per delivery is 1.5 min, and anticipated traffic factor = 0.9. Use an availability factor = 95% and worker efficiency = 100%. Determine the number of trucks required under each of the following assumptions: (a) the trucks never travel empty; and (b) the trucks travel empty a distance equal to their loaded distance.

<table>
<thead>
<tr>
<th>To Dept</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>From Dept A</td>
<td>-</td>
<td>62/500</td>
<td>51/450</td>
<td>45/350</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>22/400</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>76/200</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>65/150</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

**Solution:** \( L_d = \frac{62(500) + 51(450) + 45(350) + 22(400) + 76(200) + 65(150)}{350 + 400} = 322.27 \text{ ft} \)

Using \( L_c = 0, T_c = 1.5 + \frac{322.27}{350} + \frac{0}{400} = 2.42 \text{ min/delivery cycle} \)
\[ R_{d_i} = \frac{60(0.95)(0.90)(1.0)}{2.42} = 21.19 \text{ deliveries/hr per vehicle} \]
\[ R_f = 321/4 = 80.25 \text{ deliveries/hr} \]
\[ n_c = 80.25/21.19 = 3.79 \rightarrow \text{Use } n_c = 4 \text{ vehicles.} \]

(b) \( L_d = 322.27 \text{ ft, same as before.} \)

Using \( L_c = L_d = 322.26 \text{ ft, } T_c = 1.5 + \frac{322.27}{350} + \frac{322.27}{400} = 3.23 \text{ min/delivery cycle} \)
\[
R_{dv} = \frac{60(0.95)(0.90)(1.0)}{3.23} = 15.9 \text{ deliveries/hr per vehicle}
\]
\[n_c = \frac{80.25}{15.9} = 5.05 \Rightarrow \text{Use } n_c = 6 \text{ vehicles.}
\]

10.13 A warehouse consists of five aisles of racks (racks on both sides of each aisle) and a loading dock. The rack system is four levels high. Forklift trucks are used to transport loads between the loading dock and the storage compartments of the rack system in each aisle. The trucks move at an average speed = 140 m/min (loaded) and 180 m/min (empty). Load handling time (loading plus unloading) per delivery totals 1.0 min per storage/retrieval delivery on average, and the anticipated traffic factor = 0.90. Worker efficiency = 100% and vehicle reliability (availability) = 96%. The average distance between the loading dock and the centers of aisles 1 through 5 are 200 m, 300 m, 400 m, 500 m, and 600 m, respectively. These values are to be used to compute travel times. The required rate of storage/retrieval deliveries is 100 per hour, distributed evenly among the five aisles, and the trucks perform either storage or retrieval deliveries, but not both in one delivery cycle. Determine the number of forklift trucks required to achieve the 100 deliveries per hour.

Solution:
\[
L_d = \frac{(200 + 300 + 400 + 500 + 600)}{5} = 400 \text{ m}, \quad L_e = L_d = 400 \text{ m}
\]
\[T_c = 1.0 + \frac{400}{140} + \frac{400}{180} = 6.08 \text{ min}
\]
\[R_{dv} = 60/6.08 = 9.87 \text{ del/hr per truck}
\]
\[n_c = \frac{100}{9.87 \times 0.90 \times 0.96} = 11.73 \text{ rounded to 12 trucks}
\]

10.14 Suppose the warehouse in the preceding problem were organized according to a class-based dedicated storage strategy based on activity level of the pallet loads in storage, so that aisles 1 and 2 accounted for 70% of the deliveries (class A) and aisles 3, 4, and 5 accounted for the remaining 30% (class B). Assume that deliveries in class A are evenly divided between aisles 1 and 2, and that deliveries in class B are evenly divided between aisles 3, 4, and 5. How many trucks would be required to achieve 100 storage/retrieval deliveries per hour?

Solution: Class A \[L_d = \frac{(200 + 300)}{2} = 250 \text{ m}, \quad L_e = L_d = 250 \text{ m}\]

Class B \[L_d = \frac{(400 + 500 + 600)}{3} = 500 \text{ m}, \quad L_e = L_d = 500 \text{ m}\]

Weighted average \[L_d = L_e = 0.70(250) + 0.30(500) = 325 \text{ m}\]
\[T_c = 1.0 + \frac{325}{140} + \frac{325}{180} = 5.13 \text{ min}
\]
\[R_{dv} = 60/5.13 = 11.69 \text{ del/hr per truck}
\]
\[n_c = \frac{100}{(11.69 \times 0.90 \times 0.96)} = 9.9 \text{ rounded to 10 trucks}
\]

10.15 Major appliances are assembled on a production line at the rate of 55 per hour. The products are moved along the line on work pallets (one product per pallet). At the final workstation the finished products are removed from the pallets. The pallets are then removed from the line and delivered back to the front of the line for reuse. Automated guided vehicles are used to transport the pallets to the front of the line, a distance of 900 ft. Return trip distance (empty) to the end of the line is also 900 ft. Each AGV carries four pallets and travels at a speed of 200 ft/min (either loaded or empty). The pallets form queues at each end of the line, so that neither the production line nor the AGVs are ever starved for pallets. Time required to load each pallet onto an AGV = 15 sec; time to release a loaded AGV and move an empty AGV into position for loading at the end of the line = 12 sec. The same times apply for pallet handling and release/positioning at the unload station located at the front of the production line. Assume the traffic factor is 1.0 since the route is a simple loop. How many vehicles are needed to operate the AGV system?

Solution: \[T_L = T_u = 12 \text{ sec} + 4(15 \text{ sec}) = 72 \text{ sec} = 1.2 \text{ min}\n\]
\[T_c = 1.2 + \frac{900}{200} + 1.2 + \frac{900}{200} = 11.4 \text{ min/delivery cycle.}
\]
\[R_{dv} = 60/11.4 = 5.26 \text{ delivery cycles/hr per vehicle}
\]
Each delivery means 4 pallets, so \[R_{dv} = 4(5.26) = 21.05 \text{ pallets/hr per vehicle}
\]
\[n_c = \frac{55}{21.05} = 2.613 \Rightarrow \text{Use } n_c = 3 \text{ vehicles.}
\]

10.16 For the production line in the previous problem, assume that a single AGV train consisting of a tractor and multiple trailers are used to make deliveries rather than separate vehicles. Time required to load a pallet onto a trailer = 15 sec; and the time to release a loaded train and move an empty train into position for loading at the end of the production line = 30 sec. The same times apply for pallet handling and release/positioning at the unload station located at the front of the production line. If each trailer is capable of carrying four pallets, how many trailers should be included in the train?
Solution: Let \( n_p \) = number of pallets per train
\[
T_L = T_u = 30 \text{ sec} + n_p (15 \text{ sec}) = 0.5 + 0.25 n_p \text{ (min)}
\]
\[
T_c = 1.0 + 0.5 n_p + 
\frac{900}{200} + 
\frac{900}{200} = 10.0 + 0.5 n_p
\]
\[
R_{dh} = \frac{60}{10 + 0.5 n_p} \text{ delivery cycles/hr per train.}
\]
Each delivery cycle means \( n_p \) pallets are delivered; thus, \( R_{dh} = \frac{60 n_p}{10 + 0.5 n_p} \) pallets/hr per train.

\[
n_c = \frac{55 \text{ pallets/hr}}{\left( \frac{60 n_p}{10 + 0.5 n_p} \right)} = 1 \text{ train (given that a single AGV train is used to satisfy delivery requirements)}
\]
\[
55 = \frac{60 n_p}{10 + 0.5 n_p}
\]
\[
55(10 + 0.5 n_p) = 60 n_p
\]
\[
550 + 27.5 n_p = 60 n_p
\]
\[
60 n_p - 27.5 n_p = 32.5 n_p = 550 \quad n_p = 16.9 \text{ round up to 17 pallets/train}
\]
With 4 pallets per trailer, the train must have 17/4 = 4.25 rounded up to 5 trailers.

An AGVS will be implemented to deliver loads between four workstations: A, B, C, and D. The hourly flow rates (loads/hr) and distances (m) within the system are given in the table below (travel loaded denoted by “L” and travel empty denoted by “E”). Load and unload times are each 0.45 min, and travel speed of each vehicle is 1.4 m/sec. A total of 43 loads enter the system at station A, and 30 loads exit the system at station A. In addition, six loads exit the system from workstation B each hour and seven loads exit the system from station D. This is why there are a total of 13 empty trips made by the vehicles within the AGVS. How many vehicles are required to satisfy these delivery requirements, assuming the traffic factor is 0.85 and the reliability (availability) is 95%?

<table>
<thead>
<tr>
<th>Hourly rate (loads/hr)</th>
<th>Distances (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>To</td>
<td>A</td>
</tr>
<tr>
<td>From</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>6E</td>
</tr>
<tr>
<td>C</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>30L, 7E</td>
</tr>
</tbody>
</table>

Solution: \( L_d = \frac{18(95)+10(80)+15(150)+12(65)+22(80)+30(150)}{18+10+15+12+22+30} \)

\[
L_d = 11,800/107 = 110.28 \text{ m}
\]
\[
L_c = \frac{6(95)+7(150)}{107} = 1620/107 = 15.14 \text{ m}
\]
\[
T_c = 0.45 + 110.28/(1.4 \times 60) + 0.45 + 15.14/(1.4 \times 60) = 2.393 \text{ min}
\]
\[
WL = 107(2.393) = 256.04 \text{ min of work per hour}
\]
\[
AT = 60(0.85)(0.95) = 48.45 \text{ min/hr per vehicle}
\]
\[
n_c = 256.04/48.45 = 5.28 \text{ rounded to 6 vehicles}
\]

Analysis of Conveyor Systems

An overhead trolley conveyor is configured as a continuous closed loop. The delivery loop has a length of 150 m and the return loop = 130 m. All parts loaded at the load station are unloaded at the unload station. Each hook on the conveyor can hold one part and the hooks are separated by 4 m. Conveyor speed = 1.75 m/s. Determine (a) maximum number of parts in the conveyor system, (b) parts flow rate; and (c) maximum loading and unloading times that are compatible with the operation of the conveyor system?
**Solution:** (a) Number of parts on the conveyor = \( \frac{150 \text{ m}}{4 \text{ m/part}} = 37.5 \text{ parts (average)} \)

(b) \( R_f = \frac{n_p v_c}{s_c} = \frac{(1 \text{ part/carrier})(1.75 \text{ m/s})}{(4 \text{ m/carrier})} = 0.4375 \text{ parts/s} = 1575 \text{ parts/hr} \)

(c) \( T_L = T_u = \frac{1}{R_f} = 1/0.4375 = 2.29 \text{ sec} \)

10.19 A 300 ft long roller conveyor, which operates at a velocity = 80 ft/min, is used to move pallets between load and unload stations. Each pallet carries 12 parts. Cycle time to load a pallet is 15 sec and one worker at the load station is able to load pallets at the rate of 4 per min. It takes 12 sec to unload at the unload station. Determine (a) center-to-center distance between pallets, (b) the number of pallets on the conveyor at one time, and (c) hourly flow rate of parts. (d) By how much must conveyor speed be increased in order to increase flow rate to 3000 parts/hour.

**Solution:** (a) \( s_c = T_L v_c = (15/60 \text{ min})(80 \text{ ft/min}) = 20 \text{ ft/carrier} \)

(b) Number pallets on conveyor = \( \frac{L_d}{s_c} = \frac{300 \text{ ft}}{20 \text{ ft/carrier}} = 15 \text{ carriers} \)

(c) \( R_f = \frac{n_p v_c}{s_c} = \frac{(12 \text{ parts/carrier})(80 \text{ ft/min})}{20 \text{ ft/carrier}} = 48 \text{ parts/min} = 2880 \text{ parts/hr} \)

(d) Increasing \( v_c \) would have no effect towards increasing \( R_f \) in this problem. The loading rate, set by \( T_L = 15 \text{ sec} \), is what limits the flow rate in this system.

10.20 A roller conveyor moves tote pans in one direction at 150 ft/min between a load station and an unload station, a distance of 200 ft. With one worker, the time to load parts into a tote pan at the load station is 3 sec per part. Each tote pan holds 8 parts. In addition, it takes 9 sec to load a tote pan onto the conveyor. Determine (a) spacing between tote pan centers flowing in the conveyor system and (b) flow rate of parts on the conveyor system. (c) Consider the effect of the unit load principle. Suppose the tote pans were smaller and could hold only one part rather than 8. Determine the flow rate in this case if it takes 7 sec to load a tote pan onto the conveyor (instead of 9 sec for the larger tote pan), and it takes the same 3 sec to load the part into the tote pan.

**Solution:** (a) \( T_L = 9 + 3(8) = 33 \text{ sec} = 0.55 \text{ min/tote pan} \)

\( s_p = (150 \text{ ft/min})(0.55 \text{ min/tote pan}) = 82.5 \text{ ft/tote pan} \)

(b) \( R_f = \frac{n_p v_c}{s_c} = \frac{(8 \text{ pc/tote pan})(150 \text{ ft/min})}{82.5 \text{ ft/tote pan}} = 14.55 \text{ pc/min} = 872.7 \text{ pc/hr} \).

(c) \( T_L = 7 + 3(1) = 10 \text{ sec} = 0.167 \text{ min/tote pan} \)

\( s_p = (150 \text{ ft/min})(0.167 \text{ min/tote pan}) = 25 \text{ ft/tote pan} \)

\( R_f = \frac{(1 \text{ pc/tote pan})(150 \text{ ft/min})}{25 \text{ ft/tote pan}} = 6.0 \text{ pc/min} = 360 \text{ pc/hr} \).

10.21 A closed loop overhead conveyor must be designed to deliver parts from one load station to one unload station. The specified flow rate of parts that must be delivered between the two stations is 600 parts per hour. The conveyor has carriers spaced at a center-to-center distance that is to be determined. Each carrier holds one part. Forward and return loops will each be 90 m long. Conveyor speed = 0.5 m/s. Times to load and unload parts at the respective stations are each = 12 s. Is the system feasible and if so, what is the appropriate number of carriers and spacing between carriers that will achieve the specified flow rate?

**Solution:** Relationships to use in this problem:

(1) \( R_f = \frac{n_p v_c}{s_c} = \frac{v_c}{s_c} = 0.5 \) for \( v_c = 0.5 \text{ m/s and } n_p = 1 \)

(2) \( T_L \leq \frac{s_c}{v_c} = \frac{s_c}{0.5} = 2 \text{ s} \) for \( v_c = 0.5 \text{ m/s} \)
(3) \( n_c s_c = 90 + 90 = 180 \text{ m} \)

Solving (1): \( R_f = 600 \text{ parts/hr} = 0.16667 \text{ parts/s} \). Rearranging, \( s_c = \frac{0.5}{0.16667} = 3 \text{ m} \)

Solving (2): \( T_L = 12 \text{ s} \leq 2 s_c = 2(3) = 6 \text{ s} \)
Solving (3): \( n_c s_c = 180 \text{ m} \). Since \( s_c = 3 \text{ m} \), \( n_c (3) = 180, n_c = 180/3 = 60 \text{ carriers} \).

**Conclusion:** The system is feasible.

10.22 Consider the previous problem, only the carriers are larger and capable of holding up to four parts \( (n_p = 1, 2, 3, \text{ or } 4) \). The loading time \( T_L = 9 + 3n_p \), where \( T_L \) is in seconds. With other parameters defined as in the previous problem, determine which of the four values of \( n_p \) are feasible. For those values that are feasible, specify the appropriate design parameters for (a) spacing between carriers and (b) number of carriers that will achieve this flow rate.

**Solution:** Try each of the four values of \( n_p \).

\( n_p = 1 \): This is the same as the previous problem. (a) \( s_c = 3 \text{ m} \), (b) \( n_c = 60 \text{ carriers} \). The system is feasible.

\( n_p = 2 \): \( T_L = 15 \text{ sec} \leq 2 s_c = 2(6) = 12 \text{ sec} \rightarrow \text{(OK)} \)
Solving (3): \( n_c s_c = 180 \text{ m} \). Since \( s_c = 6 \text{ m} \), \( n_c (6) = 180, n_c = 180/6 = 30 \text{ carriers} \)

**Conclusion:** The system is feasible.

\( n_p = 3 \): \( T_L = 9 + 3(3) = 18 \text{ sec} \)

Solving (1): \( R_f = 600 \text{ parts/hr} = 0.16667 \text{ parts/sec} = \frac{1}{s_c} \). Rearranging, \( s_c = 1/0.16667 = 6 \text{ m} \)

Solving (2): \( T_L = 18 \text{ sec} \leq 2 s_c = 2(9) = 18 \text{ sec} \rightarrow \text{(OK)} \)
Solving (3): \( n_c s_c = 180 \text{ m} \). Since \( s_c = 9 \text{ m} \), \( n_c (9) = 180, n_c = 180/9 = 20 \text{ carriers} \)

**Conclusion:** The system is feasible.

\( n_p = 4 \): \( T_L = 9 + 3(4) = 21 \text{ sec} \)

Solving (1): \( R_f = 600 \text{ parts/hr} = 0.16667 \text{ parts/sec} = \frac{1}{s_c} \). Rearranging, \( s_c = 1/0.16667 = 6 \text{ m} \)

Solving (2): \( T_L = 21 \text{ sec} \leq 2 s_c = 2(12) = 24 \text{ sec} \rightarrow \text{(OK)} \)
Solving (3): \( n_c s_c = 180 \text{ m} \). Since \( s_c = 12 \text{ m} \), \( n_c (12) = 180, n_c = 180/12 = 15 \text{ carriers} \rightarrow \text{(not OK)} \)

**Conclusion:** The system is feasible.

10.23 A recirculating conveyor has a total length of 700 ft and a speed of 90 ft/min. Spacing of part carriers = 14 ft. Each carrier can hold one part. Automatic machines load and unload the conveyor at the load and unload stations. Time to load a part is 0.10 min and unload time is the same. To satisfy production requirements, the loading and unloading rates are each 2.0 parts per min. Evaluate the conveyor system design with respect to the three principles developed by Kwo.

**Solution:** (1) Speed rule: Lower limit: \( \frac{n_p v_c}{s_c} \geq \text{Max} \{R_L, R_u\} \)

(3) \( n_c v_c = 90 + 90 = 180 \text{ m} \)

Solving (1): \( R_f = 600 \text{ parts/hr} = 0.16667 \text{ parts/s} \). Rearranging, \( s_c = \frac{0.5}{0.16667} = 3 \text{ m} \)

Solving (2): \( T_L = 12 \text{ s} \leq 2 s_c = 2(3) = 6 \text{ s} \)
Solving (3): \( n_c s_c = 180 \text{ m} \). Since \( s_c = 3 \text{ m} \), \( n_c (3) = 180, n_c = 180/3 = 60 \text{ carriers} \).

**Conclusion:** The system is feasible.
Material Transport-3e-SI  10-05, 12/06, 06/04/07, 09/13/07

\[
\frac{(1 \text{ part / carrier})(90 \text{ ft / min})}{14 \text{ ft / carrier}} = 6.428 \text{ parts/min} \geq \text{Max}\{2, 2\} \rightarrow (OK)
\]

**Upper limit:** \[\frac{v_c}{s_c} \leq \text{Min}\{\frac{1}{T_L}, \frac{1}{T_u}\}\]

\[
\frac{90\text{ ft / min.}}{14\text{ ft / carrier}} = 6.428 \text{ carrier/min} \leq \text{Min}\{\frac{1}{0.1}, \frac{1}{0.1}\} = \text{Min}\{10, 10\} \rightarrow (OK)
\]

(2) **Capacity constraint:** In this case, the flow rate is interpreted to be the specified load and unload rates, that is, \(R_l = R_u = 2 \text{ parts/min}\)

\[
\frac{n_p v_c}{s_c} = 6.428 \text{ parts/min} \geq 2 \rightarrow (OK)
\]

(3) **Uniformity principle:** The conveyor is assumed to be uniformly loaded throughout its length since \(R_l = R_u\) and the flow rate capacity is significantly greater than \(R_l\) and \(R_u\) \(\rightarrow (OK)\)

**Conclusion:** The system is feasible.

10.24 A recirculating conveyor has a total length of 200 m and a speed of 50 m/min. Spacing of part carriers = 4 m. Each carrier holds two parts. Time needed to load a part carrier = 0.12 min. Unloading time is the same. The required loading and unloading rates are 6 parts per min. Evaluate the conveyor system design with respect to the three Kwo principles.

**Solution:**

(1) **Speed rule:** Lower limit: \[\frac{n_p v_c}{s_c} \geq \text{Max}\{R_l, R_u\}\]

\[
\frac{(2 \text{ parts / carrier})(50 \text{ m / min.})}{4 \text{ m / carrier}} = 25 \text{ parts/min} \geq \text{Max}\{6, 6\} \rightarrow (OK)
\]

**Upper limit:** \[\frac{v_c}{s_c} \leq \text{Min}\{\frac{1}{T_L}, \frac{1}{T_u}\}\]

\[
\frac{50\text{ m / min.}}{4\text{ m / carrier}} = 12.5 \text{ carrier/min} \leq \text{Min}\{\frac{1}{0.12}, \frac{1}{0.12}\} = \text{Min}\{8.333, 8.333\} \rightarrow (not OK)
\]

The time to load/unload is too long relative to the speed of the conveyor as it moves past the load/unload station.

(2) **Capacity constraint:** In this case, the flow rate is interpreted to be the specified load and unload rates, that is, \(R_l = R_u = 2 \text{ parts/min}\)

\[
\frac{n_p v_c}{s_c} = 25 \text{ parts/min} \geq 6 \rightarrow (OK)
\]

(3) **Uniformity principle:** The conveyor is assumed to be uniformly loaded throughout its length since \(R_l = R_u\) and the flow rate capacity is significantly greater than \(R_l\) and \(R_u\) \(\rightarrow (OK)\)

**Conclusion:** The system is not feasible since the lower limit on the speed rule is violated.

10.25 There is a plan to install a continuous loop conveyor system with a total length of 1000 ft and a speed of 50 ft/min. The conveyor will have carriers that are separated by 25 ft. Each carrier will be capable of holding one part. A load station and an unload station are to be located 500 ft apart along the conveyor loop. Each day, the conveyor system is planned to operate as follows, starting empty at the beginning of the day. The load station will load parts at the rate of one part every 30 seconds, continuing this loading operation for 10 min, then resting for 10 min during which no loading occurs. It will repeat this 20 min cycle of loading and then resting throughout the 8-hour shift. The unload station will wait until loaded carriers begin to arrive, then will unload parts at the rate of one part every minute during the eight hours, continuing until all carriers are empty. Will the planned conveyor system work? Present calculations and arguments to justify your answer.

**Solution:** The time for a carrier to complete one loop = \[\frac{L}{v_c} = \frac{1000\text{ ft}}{50\text{ ft / min.}} = 20\text{ min}\]
**Analysis:** The time for one loading cycle = 20 min. (10 min loading, then 10 min rest). On average, loading and unloading schedules seem balanced (parts loaded in 20 min = 10 min x 2 parts/min + 10(0) = 20 parts total or 60 parts/hr, and parts unloaded in 20 min = 20 min x 1 part/min = 20 parts total or 60 parts/hr). However, due to the loading schedule, the 1000 ft conveyor length will be divided into two sections: the first 500 ft will be fully loaded when it leaves the loading station, but the second 500 ft will always be empty. When the first 500 ft flows past the unload station, only half the parts will be unloaded, leaving every other carrier loaded. When the second 500 ft flows past the unload station, all carriers are empty so there are no parts to unload. When the first 500 ft comes back around to the load station, the loading rate will be only half the intended rate since every other carrier already contains a part. Thus, the intended loading and unloading rates will be only half their planned values (10 parts in 20 min or 30 parts/hr).

**Conclusion:** The system is not feasible.
Chapter 11
STORAGE SYSTEMS

REVIEW QUESTIONS

11.1 Materials stored in manufacturing include a variety of types. Name six of the ten categories listed in Table 11.1.

Answer: The material types listed in Table 11.1 are (1) raw materials, (2) purchase parts, (3) work-in-process, (4) finished product, (5) rework and scrap, (6) refuse, (7) tooling, (8) spare parts, (9) office supplies, and (10) plant records.

11.2 Name and briefly describe four of the six measures used to assess the performance of a storage system?

Answer: The six performance measures discussed in the text are the following: (1) storage capacity, which is defined and measured either as the total volumetric space available or as the total number of storage compartments in the system available for items or loads; (2) storage density, defined as the volumetric space available for actual storage relative to the total volumetric space in the storage facility; (3) accessibility, which refers to the capability to access any desired item or load stored in the system; (4) system throughput, defined as the hourly rate at which the storage system receives and puts loads into storage and/or retrieves and delivers loads to the output station; (5) utilization, which is defined as the proportion of time that the system is actually being used for performing storage and retrieval operations compared with the time it is available, and (6) availability, defined as the proportion of time that the system is capable of operating (not broken down) compared with the normally scheduled shift hours.

11.3 Briefly describe the two basic storage location strategies.

Answer: The two basic strategies are (1) randomized storage and (2) dedicated storage. In randomized storage, items are stored in any available location in the storage system. In the usual implementation of randomized storage, incoming items are placed into storage in the nearest available open location. When an order is received for a given SKU, the stock is retrieved from storage according to a first-in-first-out policy so that the items held in storage the longest are used to make up the order. In dedicated storage, SKUs are assigned to specific locations in the storage facility. This means that enough locations are reserved for all SKUs stored in the system, and so the number of storage locations for each SKU must be sufficient to accommodate its maximum inventory level.

11.4 What is a class-based dedicated storage strategy?

Answer: A class-based dedicated storage allocation is a compromise between a randomized storage strategy and a dedicated storage strategy. The storage system is divided into several classes according to activity level, and a randomized storage strategy is used within each class. The classes containing more-active SKUs are located closer to the input/output point of the storage system for increased throughput, and the randomized locations within the classes reduce the total number of storage compartments required.

11.5 Name the four traditional (non-automated) methods for storing materials.

Answer: The four traditional methods for storing materials are (1) bulk storage, (2) rack systems, (3) shelving and bins, and (4) drawer storage.

11.6 Which of the four traditional storage methods is capable of the highest storage density?

Answer: Bulk storage is capable of the highest storage density, given that materials can be stacked on top of each other and very little allowance is made for aisle space.

11.7 What are some of the objectives and reasons behind company decisions to automate their storage operations? Name six of the ten objectives and reasons listed in Table 11.3.

Answer: The ten objectives and reasons given in Table 11.3 are to (1) increase storage capacity, (2) increase storage density, (3) recover factory floor space presently used for storing work-in-process, (4) improve security and reduce pilferage, (5) improve safety in the storage function, (6) reduce labor cost and/or increase labor productivity in storage operations, (7) improve control over inventories, (8) improve stock rotation, (9) improve customer service, and (10) increase throughput.

11.8 What are the two basic categories of automated storage systems?
11.9 What are the differences between the two basic types of automated storage systems?

**Answer:** The biggest difference between the two basic types of automated storage systems is in the construction of the equipment. The basic AS/RS consists of a rack structure for storing loads and a storage/retrieval (S/R) machine whose motions are linear (x-y-z motions). The S/R machine travels to the storage compartments to perform a storage or retrieval operation. By contrast, the carousel system uses storage baskets suspended from an overhead conveyor that revolves around an oval track loop to deliver the baskets to a load/unload station.

11.10 Identify the three application areas of automated storage/retrieval systems.

**Answer:** The three AS/RS application areas identified in the text are (1) unit load storage and handling, (2) order picking, and (3) work-in-process storage.

11.11 What are the four basic components of nearly all automated storage/retrieval systems?

**Answer:** The four basic components of nearly all automated storage/retrieval systems are (1) the storage structure, which is a rack system, (2) the S/R machine, (3) storage modules (e.g., pallets for unit loads), and (4) one or more pickup-and-deposit stations. In addition, a control system is required to operate the AS/RS.

11.12 What is the advantage of a vertical storage carousel over a horizontal storage carousel?

**Answer:** A vertical storage carousel requires less floor space.

### PROBLEMS

#### Sizing the AS/RS Rack Structure

11.1 Each aisle of a six-aisle Automated Storage/Retrieval System is to contain 50 storage compartments in the length direction and 8 compartments in the vertical direction. All storage compartments will be the same size to accommodate standard size pallets of dimensions: \( x = 36 \) in and \( y = 48 \) in. The height of a unit load \( z = 30 \) in. Using the allowances \( a = 6 \) in, \( b = 8 \) in, and \( c = 10 \) in, determine (a) how many unit loads can be stored in the AS/RS, and (b) the width, length, and height of the AS/RS. The rack structure will be built 18 in above floor level.

**Solution:**

(a) Capacity per aisle = 2(50(8)) = 800 loads/aisle
With six aisles, AS/RS capacity = 6(800) = **4800 loads**

(b) \( W = 3(x + a) = 3(36 + 6) = 126 \) in/aisle
With 6 aisles, AS/RS width = 6(126) = 756 in = **63 ft**.

\( L = n_y (y + b) = 50(48 + 8) = 2800 \) in = **233.33 ft**.

\( H = n_z (z + c) = 8(30 + 10) = 320 \) in = **26.67 ft**.

Given that the rack structure is built 18 in above floor level, \( H = 320 + 18 = 338 \) in = **28.167 ft**.

11.2 A unit load AS/RS is being designed to store 1000 pallet loads in a distribution center located next to the factory. Pallet dimensions are: \( x = 1000 \) mm, \( y = 1200 \) mm; and the maximum height of a unit load = 1300 mm. The following is specified: (1) the AS/RS will consist of two aisles with one S/R machine per aisle, (2) length of the structure should be approximately five times its height, and (3) the rack structure will be built 500 mm above floor level. Using the allowances \( a = 150 \) mm, \( b = 200 \) mm, and \( c = 250 \) mm, determine the width, length, and height of the AS/RS rack structure.

**Solution:** Assumption: the \( L/H \) ratio does not include the 500 mm foundation.

1000 pallets/ 2 aisles = 500 pallets/aisle. 500 pallets/aisle → 250 pallets per aisle side.

Thus \( n_x n_y = 250 \)

\( L = n_y (y + b) = 50(1200 + 200) = 14000 \) in = \( 1400 \) \( n_y \) (in mm) = 1.4 \( n_y \) (in m)

\( H = n_z (z + c) = 6(1300 + 250) = 15500 \) in = \( 1550 \) \( n_z \) (in mm) = 1.55 \( n_z \) (in m)

Given the specification \( L/H = 5 \)

\[
\frac{1.40n_y}{1.55n_z} = 0.9032 \quad \frac{n_y}{n_z} = 5 \quad 0.9032 \times 5 = 5.0 \quad n_z = 5.536 \times n_z = 250
\]

Combining Eqs. (1) and (2): \( n_y n_z = (5.536 n_z) n_z = 250 \)
10.1 Given the rack structure dimensions computed in Problem 11.2. Assuming that only 75% of the storage compartments are occupied on average, and that the average volume of a unit load per pallet in storage is 0.90 m³, compute the ratio of the total volume of unit loads in storage relative to the total volume occupied by the storage rack structure.

**Solution:**
Number of unit loads = 0.75(1008) = 756 unit loads on average

Volume of loads at 0.75 m³ per load: \( V_u = 756(0.90) = 680.4 \text{ m}^3 \)

Volume of rack structure, excluding elevation above floor level (using values computed in Problem 11.2):

\[
V_r = W \times L \times H = 6.9(50.4)(10.85) = 37733.2 \text{ m}^3
\]

Ratio \( \frac{V_u}{V_r} = \frac{680.4}{37733.2} = 0.1803 = 18.03\% \)

11.3 A unit load AS/RS for work-in-process storage in a factory must be designed to store 2000 pallet loads, with an allowance of no less than 20% additional storage compartments for peak periods and flexibility. The unit load pallet dimensions are: depth \( (x) = 36 \text{ in} \) and width \( (y) = 48 \text{ in} \). Maximum height of a unit load = 42 in. It has been determined that the AS/RS will consist of four aisles with one S/R machine per aisle. The maximum ceiling height (interior) of the building permitted by local ordinance is 60 ft, so the AS/RS must fit within this height limitation. The rack structure will be built 2 ft above floor level, and the clearance between the rack structure and the ceiling of the building must be at least 18 in. Determine the dimensions (height, length, and width) of the rack structure.

**Solution:**
Total number of storage compartments = 2000(1 + 0.20) = 2400 compartments.

With 4 aisles, number of compartments per aisle = 2400/4 = 600

Number of compartments per aisle side = 600/2 = 300 compartments/side.

\[ H = n_z (z + c) = n_z (42 + 10) = 52 \text{ } n_z \]

Given that the rack structure is elevated 2 ft = 24 in above floor level and that the clearance above the rack structure = 18 in, then the AS/RS rack structure itself must have a height \( H \) less than 60(12) - 24 - 18 = 678 in.

Thus,

\[ 52 \text{ } n_z \leq 678 \]

\[ n_z \leq 678/52 = 13.04 \rightarrow \text{use } n_z = 13 \]

\[ H = 52 \text{ } n_z = 52(13) = 676 \text{ in} = 56.33 \text{ ft (clearance above rack structure exceeds 18 in by 2 in)} \]

\[ n_z = 300 \]

\[ n_z = 300/13 = 23.07 \rightarrow \text{use } n_z = 24 \text{ compartments along aisle length} \]

\[ L = n_y (y + b) = 24(48 + 8) = 1344 \text{ in} = 112 \text{ ft.} \]

\[ W = 3(x + a) = 3(36 + 6) = 126 \text{ in/aisle.} \]

With 4 aisles, \( W = 4(126) = 504 \text{ in} = 42 \text{ ft.} \)

Actual capacity = 4 x 2 x 24 x 13 = 2496, which slightly exceeds the specification of 2400.

11.5 The length of the storage aisle in an AS/RS = 240 ft and its height = 60 ft. Suppose horizontal and vertical speeds of the S/R machine are 400 ft/min and 60 ft/min, respectively. The S/R machine requires 18 sec to accomplish a pick and deposit operation. Find: (a) the single-command and dual-command cycle times per aisle, and (b) throughput for the aisle under the assumptions that storage system utilization = 85% and the number of single command and dual command cycles are equal.

**Solution:**
(a) \[ T_{cs} = 2 \text{ Max} \left( \frac{0.5(240)}{400}, \frac{0.5(60)}{60} \right) + 2(18/60) = 1.6 \text{ min/cycle} \]
\[ T_{cd} = 2 \text{ Max} \left( \frac{0.75(240)}{400}, \frac{0.75(60)}{60} \right) + 4(18/60) = 2.7 \text{ min/cycle} \]

(b) \(1.6 \, R_{cs} + 2.7 \, R_{cd} = 60(0.85) = 51.0 \text{ min} \)

Given \( R_{cs} = R_{cd} \), \( 1.6 \, R_{cs} + 2.7 \, R_{cs} = 51 \) \( R_{cs} = 11.86 \text{ cycles/hr} \)

\( R_{cd} = R_{cs} = 11.86 \text{ cycles/hr} \)

\( R_t = R_{cs} + 2 \, R_{cd} = 11.86 + 2(11.86) = \text{35.58 S/R transactions/hr} \)

11.6 Solve Problem 11.5 except that the ratio of single-command to dual-command cycles is 2:1 instead of 1:1.

Solution: (a) \( T_{cs} = 2 \text{ Max} \left( \frac{0.5(240)}{400}, \frac{0.5(60)}{60} \right) + 2(18/60) = 1.6 \text{ min/cycle} \)

\[ T_{cd} = 2 \text{ Max} \left( \frac{0.75(240)}{400}, \frac{0.75(60)}{60} \right) + 4(12/60) = 2.7 \text{ min/cycle} \]

(b) \(1.6 \, R_{cs} + 2.7 \, R_{cd} = 60(0.85) = 51.0 \text{ min} \)

Given \( R_{cs} = 2 \, R_{cd} \), \( 1.6 \, (2 \, R_{cd}) + 2.7 \, R_{cd} = 5.9 \, R_{cd} = 51 \) \( R_{cd} = 8.644 \text{ cycles/hr} \)

\( R_{cs} = 2 \, R_{cd} = 2(8.644) = 17.288 \text{ cycles/hr} \)

\( R_t = R_{cs} + 2 \, R_{cd} = 17.288 + 2(8.644) = \text{34.6 S/R transactions/hr} \)

11.7 An AS/RS is used for work-in-process storage in a manufacturing facility. The AS/RS has five aisles, each aisle being 120 ft long and 40 ft high. The horizontal and vertical speeds of the S/R machine are 400 ft/min and 50 ft/min, respectively. The S/R machine requires 12 sec to accomplish a pick and deposit operation. The number of single command cycles equals the number of dual command cycles. If the requirement is that the AS/RS must have a throughput rate of 200 S/R transactions per hour during periods of peak activity, will the AS/RS satisfy this requirement? If so, what is the utilization of the AS/RS during peak hours.

Solution: \( T_{cs} = 2 \text{ Max} \left( \frac{0.5(120)}{400}, \frac{0.5(40)}{50} \right) + 2(0.25) = 1.2 \text{ min/cycle} \)

\[ T_{cd} = 2 \text{ Max} \left( \frac{0.75(120)}{400}, \frac{0.75(40)}{50} \right) + 4(0.5) = 2.0 \text{ min/cycle} \]

1.2 \( R_{cs} + 2.0 \, R_{cd} = 60 \)

Given \( R_{cs} = R_{cd} \), \( 1.2 \, R_{cs} + 2.0 \, R_{cs} = 3.2 \, R_{cs} = 60 \) \( R_{cs} = 18.75 \text{ cycles/hr} \)

\( R_{cd} = R_{cs} = 18.75 \text{ cycles/hr} \)

\( R_t = 5( R_{cs} + 2 \, R_{cd} ) = 5(3 \times 18.75) = \text{281.25 S/R transactions/hr} \)

\( U = 200/281.25 = 0.711 = 71.1\% \)

11.8 An automated storage/retrieval system installed in a warehouse has five aisles. The storage racks in each aisle are 30 ft high and 150 ft long. The S/R machine for each aisle travels at a horizontal speed of 350 ft/min and a vertical speed of 60 ft/min. The pick and deposit time = 0.25 min. Assume that the number of single command cycles per hour is equal to the number of dual command cycles per hour and that the system operates at 75% utilization. Determine the throughput rate (loads moved/hour) of the AS/RS.

Solution: \( T_{cs} = 2 \text{ Max} \left( \frac{0.5(150)}{350}, \frac{0.5(30)}{60} \right) + 2(0.25) = 1.00 \text{ min/cycle} \)

\[ T_{cd} = 2 \text{ Max} \left( \frac{0.75(150)}{350}, \frac{0.75(30)}{60} \right) + 4(0.5) = 1.75 \text{ min/cycle} \]

1.00 \( R_{cs} + 1.75 \, R_{cd} = 60(0.75) = 45 \text{ min} \)

Given \( R_{cs} = R_{cd} \), \( 1.00 \, R_{cs} + 1.75 \, R_{cs} = 2.75 \, R_{cs} = 45.0 \) \( R_{cd} = 16.36 \text{ cycles/hr} \)

\( R_t = R_{cs} + 2 \, R_{cd} = 16.36 + 2(16.36) = 49.1 \text{ transactions/hr} \)

With 5 aisles, \( R_t = 5(49.1) = \text{245.5 transactions/hr} \)

11.9 A 10-aisle automated storage/retrieval system is located in an integrated factory-warehouse facility. The storage racks in each aisle are 20 m high and 110 m long. The S/R machine for each aisle travels at a horizontal speed of 2.5 m/s and a vertical speed of 0.5 m/s. Pick and deposit time = 15 s. Assume that the number of single command cycles per hour is one-half the number of dual command cycles per hour and that the system operates at 80% utilization. Determine the throughput rate (loads moved/hour) of the AS/RS.
11.10 An automated storage/retrieval system for work-in-process has five aisles. The storage racks in each aisle are 10 m high and 50 m long. The S/R machine for each aisle travels at a horizontal speed of 2.0 m/s and a vertical speed of 0.4 m/s. Pick and deposit time = 15 s. Assume that the number of single command cycles per hour is equal to three times the number of dual command cycles per hour and that the system operates at 90% utilization. Determine the throughput rate (loads moved/hour) of the AS/RS.

**Solution:**

\[
T_{cs} = 2 \text{ Max} \left( \frac{0.5(110)}{2.5}, \frac{0.5(20)}{40} \right) + 2(15) = 55 \text{ s/cycle} = 0.9167 \text{ min/cycle}
\]

\[
T_{cd} = 2 \text{ Max} \left( \frac{0.75(110)}{2.5}, \frac{0.75(20)}{40} \right) + 4(15) = 97.5 \text{ s/cycle} = 1.625 \text{ min/cycle}
\]

\[
0.9167 \text{ } R_{cs} + 1.625 \text{ } R_{cd} = 60(0.90) = 54.0 \text{ min}
\]

Given \( R_{cs} = 3 \text{ R}_{cd} \), \( 0.9167 \text{ } (3 \text{ R}_{cd}) + 1.625 \text{ } R_{cd} = 4.375 \text{ } R_{cd} = 54.0 \text{ min} \)

\( R_{cs} = 3 \text{ R}_{cd} = 3(12.34) = 37.03 \text{ cycles/hr.} \)

\( R_{o} = R_{cs} + 2\text{ R}_{cd} = 37.03 + 2(12.34) = 61.71 \text{ transactions/hr per aisle} \)

With 5 aisles, \( R_{t} = 5(61.71) = 308.5 \text{ transactions/hr} \)

11.11 The length of one aisle in an AS/RS is 100 m and its height is 20 m. Horizontal travel speed is 4.0 m/s. The vertical speed is specified so that the storage system is "square in time," which means that \( \frac{L}{v_y} = \frac{H}{v_z} \). The pick-and-deposit time is 12 s. Determine the expected throughput rate (transactions per hour) for the aisle if the expected ratio of the number of transactions performed under single-command cycles to the number of transactions performed under dual-command cycles is 2:1. The system operates continuously during the hour.

**Solution:**

\[
T_{cs} = 2 \left( \frac{0.5(100)}{4.0} \right) + 2(12) = 49 \text{ s/cycle} = 0.817 \text{ min/cycle}
\]

\[
T_{cd} = 2 \left( \frac{0.75(100)}{4.0} \right) + 4(12) = 85.5 \text{ s/cycle} = 1.425 \text{ min/cycle}
\]

\( T_{so} = T_{cs} = 0.817 \text{ min since one transaction is accomplished during each single command cycle.} \)

\( T_{sd} = T_{cs}/2 = 0.7125 \text{ min since two transactions are accomplished during each dual command cycle.} \)

\( R_{o} = 2 \text{ R}_{cd} + 0.817 \text{ R}_{cd} + 0.7125 \text{ R}_{cd} = 60 \text{ transactions/hr} \)

\( R_{cs} = 2 \text{ R}_{cd} = 2(25.57) = 51.14 \text{ trans./hr} \)

\( R_{cd} = 2 \text{ R}_{cd} = 2(25.57) = 51.14 \text{ trans./hr} \)

\( R_{o} = R_{cs} + R_{cd} = 51.14 + 51.14 = 76.71 \text{ transactions/hr} \)

11.12 An automated storage/retrieval system has five aisles. The storage racks in each aisle are 40 ft high and 200 ft long. The S/R machine for each aisle travels at a horizontal speed of 400 ft/min and a vertical speed of 60 ft/min. If the pick and deposit time = 0.25 min, determine the throughput rate (loads moved/hour) of the AS/RS, under the assumption that time spent each hour performing single command cycles is twice the time spent performing dual command cycles, and that the AS/RS operates at 90% utilization.

**Solution:**

\[
T_{cs} = 2 \text{ Max} \left( \frac{0.5(200)}{400}, \frac{0.5(40)}{60} \right) + 2(0.25) = 1.167 \text{ min/cycle}
\]

\[
T_{cd} = 2 \text{ Max} \left( \frac{0.75(200)}{400}, \frac{0.75(40)}{60} \right) + 4(0.25) = 2.0 \text{ min/cycle}
\]

\( 1.167 \text{ } R_{cs} + 2 \text{ R}_{cd} = 60(0.90) = 54.0 \text{ min} \)

Given \( R_{cs} \), \( T_{cs} = 2(0.25) = 1.167 \text{ min/cycle} \)

\( 1.167 \text{ } R_{cs} + 2 \text{ R}_{cd} = 60(0.90) = 54.0 \text{ min} \)

Given \( R_{cs} \), \( T_{cd} = 2 \text{ R}_{cd} + 4(0.25) = 2 \text{ min/cycle} \)

\( 1.167 \text{ } R_{cs} + 2 \text{ R}_{cd} = 60(0.90) = 54.0 \text{ min} \)

Given \( R_{cs} \), \( T_{cs} = 2(0.25) = 1.167 \text{ min/cycle} \)

\( 1.167 \text{ } R_{cs} + 2 \text{ R}_{cd} = 60(0.90) = 54.0 \text{ min} \)

Given \( R_{cs} \), \( T_{cd} = 2 \text{ R}_{cd} + 4(0.25) = 2 \text{ min/cycle} \)
\[ R_{cs} = 3.428 R_{cd} \]
\[ 1.167 (3.428 R_{cd}) + 2.0 R_{cd} = 6.00 R_{cd} = 54 \quad R_{cd} = 9.0 \text{ cycles/hr.} \]
\[ R_{cs} = 3.428(9.0) = 30.852 \text{ cycles/hr.} \]
\[ R_t = R_{cs} + 2 R_{cd} = 30.852 + 2(9.0) = 48.85 \text{ transactions/hr.} \]

**Check:**
- Time performing single command cycles = \( R_{cs} T_{cs} = 30.852(1.167) = 36.0 \text{ min} \)
- Time performing dual command cycles = \( R_{cd} T_{cd} = 9(2.0) = 18.0 \text{ min.} \) This is a 2:1 ratio.

With 5 aisles, \( R_t = 5(48.85) = 244.25 \text{ transactions/hr} \)

11.13 An AS/RS with one aisle is 300 ft long and 60 ft high. The S/R machine has a maximum speed of 300 ft/min in the horizontal direction. It accelerates from zero to 300 ft/min in a distance of 15 ft. On approaching its target position (where the S/R machine will transfer a load onto or off of its platform), it decelerates from 300 ft/min to a full stop in 15 ft. The maximum vertical speed is 60 ft/min, and the acceleration and deceleration distances are each 3 ft. Assume simultaneous horizontal and vertical movement, and that the rates of acceleration and deceleration are constant in both directions. The pick and deposit time = 0.3 min. Using the general approach of the MHI method for computing cycle time but adding considerations for acceleration and deceleration, determine the single command and dual command cycle times.

**Solution:**
\[ v = \int_0^t a \, dt = at = 300 \text{ ft/min, } a = 300/t \]
\[ y = \int_0^t \frac{1}{2} a \, dt = \frac{1}{2} \frac{1}{t^2} = 0.5(300/t) \, t^2 = 150 \, t = 15 \text{ ft.} \]
\[ t = 15/150 = 0.1 \text{ min} \]

Because of the square-in-time feature, we need to consider only one direction to calculate travel time, since both \( y \) and \( z \) travel times are equal.
\[ T_{cs} = 4(0.1) + 2 \left( \frac{0.5(300) - 2(15)}{300} \right) + 2(0.3) = 1.8 \text{ min/cycle} \]
\[ T_{cd} = 6(0.1) + 2 \left( \frac{0.75(300) - 3(15)}{300} \right) + 4(0.3) = 3.0 \text{ min/cycle} \]

11.14 An AS/RS with four aisles is 80 m long and 18 m high. The S/R machine has a maximum speed of 1.6 m/s in the horizontal direction. It accelerates from zero to 1.6 m/s in a distance of 2.0 m. On approaching its target position (where the S/R machine will transfer a load onto or off of its platform), it decelerates from 1.6 m/s to a full stop in 2.0 m. The maximum vertical speed is 0.5 m/s, and the acceleration and deceleration distances are each 0.3 m. Rates of acceleration and deceleration are constant in both directions. Pick and deposit time = 12 s. Utilization of the AS/RS is assumed to be 90%, and the number of dual command cycles = the number of single command cycles. (a) Calculate the single command and dual command cycle times, including considerations for acceleration and deceleration. (b) Determine the throughput rate for the system.

**Solution:**
(a) Horizontal travel:
\[ v = \int_0^t a \, dt = at = 1.6 \text{ m/s, } a = 1.6/t \]
\[ y = \int_0^t \frac{1}{2} a \, dt = \frac{1}{2} \frac{1}{t^2} = 0.5(1.6/t) \, t^2 = 0.8 \, t = 2 \text{ m} \]
\[ t = 2/0.8 = 2.5 \text{ s.} \]

Vertical travel:
\[ z = \int_0^t a \, dt = at = 0.5 \text{ m/s, } a = 0.5/t \]
\[ z = \int_0^t \frac{1}{2} a \, dt = \frac{1}{2} \frac{1}{t^2} = 0.25 \, t = 0.3 \text{ m} \]
\[ t = 0.3/0.25 = 1.2 \text{ s.} \]

\[ T_{cs} = 2 \text{ Max} \left( \frac{0.5(80) - 2(2)}{16} + 2(2.5), \frac{0.5(18) - 2(0.3)}{0.5} + 2(1.2) \right) + 2(12) = 79 \text{ s/cycle} = 1.3167 \text{ min/cycle} \]
\[ T_{cd} = 2 \text{ Max} \left( \frac{0.75(80) - 3(2)}{16} + 3(2.5), \frac{0.75(18) - 3(0.3)}{0.5} + 3(1.2) \right) + 4(12) = 130.5 \text{ s/cycle} = 2.175 \text{ min/cycle} \]

(b) \( R_{cs} \) \( T_{cs} + R_{cd} T_{cd} = 60(0.90) = 54 \text{ min} \)

Given \( R_{cs} = R_{cd}, 1.3167 R_{cs} + 2.175 R_{cs} = 3.4917 R_{cs} = 54.0 \quad R_{cs} = 15.465 \text{ cycles/hr} \)
\( R_{cd} = R_{cs} = 15.465 \text{ cycles/hr} \)
\( R_t = R_{cs} + 2 R_{cd} = 15.465 + 2(15.465) = 46.396 \text{ transactions/hr per aisle} \)
With 4 aisles, \( R_t = 4(46.396) = 185.6 \text{ transactions/hr} \)

11.15 Your company is seeking proposals for an automated storage/retrieval system that will have a throughput rate of 275 storage/retrieval transactions/hour during the one 8-hour shift per day. The request for proposal indicates that the number of single command cycles is expected to be four times the number of dual command cycles. The first proposal received is from a vendor who specifies the following: ten aisles, each aisle 150 ft long and 50 ft high; horizontal and vertical speeds of the S/R machine = 200 ft/min and 66.67 ft/min, respectively; and pick and deposit time = 0.3 min. As the responsible engineer for the project, you must analyze the proposal and make recommendations accordingly. One of the difficulties you see in the proposed AS/RS is the large number of S/R machines that would be required - one for each of the 10 aisles. This makes the proposed system very expensive. Your recommendation is to reduce the number of aisles from 10 to 6 and to select a S/R machine with horizontal and vertical speeds of 300 ft/min and 100 ft/min, respectively. Although each high speed S/R machine is slightly more expensive than the slower model, reducing the number of machines from 10 to 6 will significantly reduce total cost. Also, fewer aisles will reduce the cost of the rack structure even though each aisle will be somewhat larger since total storage capacity must remain the same. The problem is that throughput rate will be adversely affected by the larger rack system. (a) Determine the throughput rate of the proposed 10-aisle AS/RS and calculate its utilization relative to the specified 300 transactions/hour. (b) Determine the length and height of a six-aisle AS/RS whose storage capacity would be the same as the proposed 10-aisle system. (c) Determine the throughput rate of the 6-aisle AS/RS and calculate its utilization relative to the specified 300 transactions/hour. (d) Given the dilemma now confronting you, what other alternatives would you analyze and recommendations would you make to improve the design of the system?

**Solution:**

(a) 
\[
T_{cs} = 2 \left( \frac{0.5(150)}{200} \right) + 2(0.3) = 1.35 \text{ min/cycle}
\]
\[
T_{cd} = 2 \left( \frac{0.75(150)}{200} \right) + 4(0.3) = 2.325 \text{ min/cycle}
\]
\[
1.35 R_{cs} + 2.325 R_{cd} = 60
\]
Given \( R_{cs} = 4 R_{cd} \),
\[
1.35(4 R_{cd}) + 2.325 R_{cd} = 7.725 R_{cd} = 60
\]
\[
R_{cd} = 7.767 \text{ cycles/hr.}
\]
\[
R_{cs} = 4(7.767) = 31.068 \text{ cycles/hr.}
\]
\[
R_t = R_{cs} + 2 R_{cd} = 31.068 + 2(7.767) = 46.6 \text{ transactions/hr per aisle}
\]
With 10 aisles, \( R_t = 10(46.6) = 466 \text{ transactions/hr} \). Given the specification \( R_t = 275 \text{ transactions/hr} \),
\[
U = \frac{275}{466} = 0.590 = 59.0\%
\]
This utilization is somewhat lower than desirable.

(b) Assume capacity is a function of (# aisles) \( L H \). Let subscript 1 represent the 10 aisle AS/RS. Let subscript 2 represent the 6 aisle AS/RS. Then, \( 6 L_2 H_2 = 10 L_1 H_1 = 10(150)(50) = 75,000 \)
To maintain square-in-time proportions for the 6-aisle system, \( L_2 H_2 = L_1 H_1 = 150/50 = 3.0 \)
Thus, \( L_2 = 3 H_2 \). Thus, \( 6(3 H_2) H_2 = 18(H_2)^2 = 75,000 \)
\[
(H_2)^2 = \frac{75,000}{18} = 4166.67
\]
\[
H_2 = 64.55 \text{ ft and } L_2 = 3 H_2 = 3(64.55) = 193.65 \text{ ft}. \]

(c) 
\[
T_{cs} = 2 \left( \frac{0.5(193.65)}{300} \right) + 2(0.3) = 1.246 \text{ min/cycle}
\]
\[
T_{cd} = 2 \left( \frac{0.75(193.65)}{300} \right) + 4(0.3) = 2.168 \text{ min/cycle}
\]
\[
1.246 R_{cs} + 2.168 R_{cd} = 60
\]
Given \( R_{cs} = 4 R_{cd} \),
\[
1.246(4 R_{cd}) + 2.168 R_{cd} = 7.152 R_{cd} = 60
\]
\[
R_{cd} = 8.389 \text{ cycles/hr.}
\]
\[
R_{cs} = 4(8.389) = 33.556 \text{ cycles/hr.}
\]
\[
R_t = R_{cs} + 2 R_{cd} = 33.556 + 2(8.389) = 50.334 \text{ transactions/hr per aisle.}
\]
With 6 aisles, \( R_t = 6(50.334) = 302.0 \text{ transactions/hr} \). Given the specification of 275 transactions/hr for the AS/RS, \( U = \frac{275}{302} = 0.911 = 91.1\% \)
This utilization is acceptable but perhaps a little high.

(d) Other alternatives and recommendations:
- Investigate the possibility of an AS/RS with 7 or 8 aisles. The throughput performance should be between the two alternatives analyzed above.
- Improve scheduling of the AS/RS to achieve \( R_{cs} = R_{cd} \) rather than \( R_{cs} = 4 R_{cd} \) as given in problem statement.
• Operate a 9-hour shift rather than an 8-hour shift. Although hourly throughput will not be improved, the extra hour of AS/RS operation will improve daily throughput rates.

11.16 A unit load automated storage/retrieval system has five aisles. The storage racks are 60 ft high and 280 ft long. The S/R machine travels at a horizontal speed of 200 ft/min and a vertical speed of 80 ft/min. The pick and deposit time = 0.30 min. Assume that the number of single command cycles per hour is four times the number of dual command cycles per hour and that the system operates at 80% utilization. A class-based dedicated storage strategy is used for organizing the stock, in which unit loads are separated into two classes, according to activity level. The more active stock is stored in the half of the rack system located closest to the input/output station, and the less active stock is stored in the other half of the rack system (farther away from the input/output station). Within each half of the rack system, random storage is used. The more active stock accounts for 75% of the transactions, and the less active stock accounts for the remaining 25% of the transactions. Determine the throughput rate (loads moved/hour into and out of storage) of the AS/RS, basing your computation of cycle times on the same types of assumptions used in the MHI method. Assume that when dual command cycles are performed the two transactions per cycle are both in the same class.

**Solution:** Class 1 stock (75%):  
\[ T_{c1} = 2 \text{ Max} \left( \frac{0.5(140)}{200}, \frac{0.75(60)}{80} \right) + 2(0.30) = 1.35 \text{ min/cycle} \]

\[ T_{c1} = 2 \text{ Max} \left( \frac{0.75(140)}{200}, \frac{0.75(60)}{80} \right) + 4(0.30) = 2.325 \text{ min/cycle} \]

Class 2 stock (25%):  
\[ T_{c2} = 2 \text{ Max} \left( \frac{140 + 0.5(140)}{200}, \frac{0.75(60)}{80} \right) + 2(0.30) = 2.7 \text{ min/cycle} \]

\[ T_{c2} = 2 \text{ Max} \left( \frac{140 + 0.75(140)}{200}, \frac{0.75(60)}{80} \right) + 4(0.30) = 3.65 \text{ min/cycle} \]

1.35 \[ R_{c1} + 2.325 R_{cd1} + 2.7 R_{c2} + 3.65 R_{cd2} = 60(0.80) = 48.0 \text{ min} \]

Given: \[ R_{c1} = 4 R_{cd1} \text{ and } R_{c2} = 4 R_{cd2} \text{ Also, due to 75%: 25%, } R_{c1} = 3 R_{c2} \text{ and } R_{cd1} = 3 R_{cd2} \]

1.35 (4 \[ R_{cd1} ] + 2.325 R_{cd1} + 2.7(4 \[ R_{cd2} ] + 3.65 R_{cd2} = 48.0 \]

(5.4 + 2.325) \[ R_{cd1} ] + (10.8 + 3.65) R_{cd2} = 7.725 R_{cd1} + 14.45 R_{cd2} = 48.0 \]

7.725(3 \[ R_{cd2} ] + 14.45 R_{cd2} = 37.625 R_{cd2} = 48.0 \]

\[ R_{cd2} = 1.276 \text{ cycles/hr} \]

\[ R_{cd1} = 3(1.276) = 3.827 \text{ cycles/hr} \]

\[ R_{c1} = 4(3.827) = 15.309 \text{ cycles/hr} \]

\[ R_{c2} = 4(1.276) = 5.103 \text{ cycles/hr} \]

Throughput per aisle \[ R_t = R_{c1} + R_{c2} + 2(R_{cd1} + R_{cd2}) = (15.309 + 5.103) + 2(3.827 + 1.276) \]

\[ R_t = 30.62 \text{ transactions/hr per aisle} \]

AS/RS throughput \[ R_t = 5(30.62) = 153.1 \text{ transactions/hr} \]

11.17 The AS/RS aisle of Problem 11.5 will be organized following a class-based dedicated storage strategy. There will be two classes, according to activity level. The more active stock is stored in the half of the rack system that is located closest to the input/output station, and the less active stock is stored in the other half of the rack system farther away from the input/output station. Within each half of the rack system, random storage is used. The more active stock accounts for 80% of the transactions, and the less active stock accounts for the remaining 20%. Assume that system utilization = 85% and the number of single command cycles = the number of dual command cycles in each half of the AS/RS. (a) Determine the throughput of the AS/RS, basing the computation of cycle times on the same kinds of assumptions used in the MHI method. (b) A class-based dedicated storage strategy is supposed to increase throughput. Why is throughput less here than in Problem 11.5?

**Solution:** Length \[ L \] is divided into 2 halves of 120 ft each.

Class 1 stock (80%):  
\[ T_{c1} = 2 \text{ Max} \left( \frac{0.5(120)}{400}, \frac{0.5(60)}{60} \right) + 2(18/60) = 1.6 \text{ min/cycle} \]

\[ T_{c1} = 2 \text{ Max} \left( \frac{0.75(120)}{400}, \frac{0.75(60)}{60} \right) + 4(18/60) = 2.7 \text{ min/cycle} \]

Class 2 stock (20%):  
\[ T_{c2} = 2 \text{ Max} \left( \frac{120 + 0.5(120)}{400}, \frac{0.5(60)}{60} \right) + 2(18/60) = 1.8 \text{ min/cycle} \]

\[ T_{c2} = 2 \text{ Max} \left( \frac{120 + 0.75(120)}{400}, \frac{0.75(60)}{60} \right) + 4(18/60) = 2.7 \text{ min/cycle} \]
Carousel Storage Systems

11.18 A single carousel storage system is located in a factory making small assemblies. It is 25 m long and 1.0 m wide. The pick and deposit time is 0.25 min. The speed at which the carousel operates is 0.5 m/s. The storage system has a 90% utilization. Determine the hourly throughput rate.

Solution: \( C = 2(L - W) + \pi W = 2(25 - 1) + 1\pi = 51.14 \text{ m} \)

\[ T_c = \frac{C}{4v_c} + T_{pd} = \frac{51.14}{4(0.5)} + 0.25(60) = 40.57 \text{ sec} = 0.676 \text{ min} \]

\[ R_t = 60/0.676 = 88.7 \text{ transaction/hr} \]

11.19 A storage system serving an electronics assembly plant has three storage carousels, each with its own manually operated pick and deposit station. The pick and deposit time is 0.30 min. Each carousel is 60 ft long and 2.5 ft wide. The speed at which the system revolves is 85 ft/min. Determine the throughput rate of the storage system.

Solution: \( C = 2(L - W) + \pi W = 2(60 - 2.5) + 2.5\pi = 122.84 \text{ ft} \)

\[ T_c = \frac{C}{4v_c} + T_{pd} = \frac{122.85}{4(85)} + 0.30 = 0.661 \text{ min} \]

\[ R_t = 60/0.661 = 90.73 \text{ transaction/hr} \]

With 3 carousels, \( R_t = 3(90.73) = 272.2 \text{ transaction/hr} \)

11.20 A single carousel storage system has an oval rail loop that is = 30 ft long and 3 ft wide. Sixty carriers are equally spaced around the oval. Suspended from each carrier are 5 bins. Each bin has a volumetric capacity = 0.75 ft\(^3\). Carousel speed = 100 ft/min. Average pick and deposit time for a retrieval = 20 sec. Determine (a) volumetric capacity of the storage system and (b) hourly retrieval rate of the storage system.

Solution: (a) Total number of bins = \( n_c, n_b = 60(5) = 300 \) bins

Total volume capacity = 300(0.75) = 225 ft\(^3\)

(b) \( C = 2(L - W) + \pi W = 2(30 - 3) + 3\pi = 63.42 \text{ ft} \)

\[ T_c = \frac{C}{4v_c} + T_{pd} = \frac{63.42}{4(100)} + 20/60 = 0.4916 \text{ min} \]

\[ R_t = 60/0.4916 = 122.1 \text{ transaction/hr} \]

11.21 A carousel storage system is to be designed to serve a mechanical assembly plant. The specifications on the system are that it must have a total of 400 storage bins and a throughput of at least 125 storage and retrieval transactions per hour. Two alternative configurations are being considered: (1) a one-carousel system and (2) a two-carousel system. In either case, the width of the carousel is to be 4.0 ft and the spacing between carriers = 2.5 ft. One picker-operator will be required for the one-carousel system and two picker-operators will be required for the two-carousel system. In either system \( v_c = 100 \text{ ft/min.} \) For the convenience of the picker-operator, the height of the carousel will be limited to 5 bins. The standard time for a pick and deposit operation at the load/unload station = 0.4 min if one part is picked or stored per bin and 0.6 min if more than one part is picked or stored. Assume that 50% of the transactions will involve more than one component. Determine (a) the required length of the one-carousel system and (b) the corresponding throughput rate; (c) the required length of the two-carousel system and (d) the corresponding throughput rate. (e) Which system better satisfies the design specifications?

Solution: Total bins = 400 = \( n_c, n_b \). Given \( n_b = 5 \) bins, thus \( n_c = 400/5 = 80 \) carriers on the carousel.

Circumference \( C = 80(2.5 \text{ ft/carrier}) = 200 \text{ ft} \)

Given \( W = 4 \text{ ft} \), \( C = 2(L - W) + \pi W = 2(4 - 4) + 4\pi = 200 \text{ ft} \)

88
2L = 200 + 8 - 4\pi = 195.43 \quad L = 97.7 \text{ ft}

(b) Average \( T_{pd} = 0.5(0.4) + 0.5(0.6) = 0.5 \text{ min} \)

\[ T_c = \frac{200}{4(100)} + 0.5 = 1.0 \text{ min/transaction} \quad R_c = 60/1.0 = 60 \text{ transactions/hr} \]

(c) Total bins = 400. With 2 carousels, bins/carousel = 200/5 = 40 carriers on each carousel

Circumference \( C = 40(2.5 \text{ ft/carrier}) = 100 \text{ ft} \)

Given \( W = 4 \text{ ft}, \frac{C}{2} = 2(L - W) + \pi W = 2(L - 4) + 4\pi = 100 \text{ ft} \)

\[ 2L = 100 + 8 - 4\pi = 95.43 \quad L = 47.7 \text{ ft} \]

(d) \( T_c = \frac{100}{4(100)} + 0.5 = 0.75 \text{ min/transaction} \quad R_c = 60/0.75 = 80 \text{ transactions/hr} \)

With 2 carousels, \( R_c = 2(80) = 160 \text{ transactions/hr} \)

(e) Only the two-carousel system satisfies the throughput specification of 125 per hour.

11.22 Given your answers to Problem 11.21, the costs of the two carousel systems are to be compared. The one-carousel system has an installed cost of $50,000, and the comparable cost of the two-carousel system is $75,000. Labor cost for a picker-operator is $20/hour, including fringe benefits and applicable overhead. The storage systems will be operated 250 days per year for 7 hours per day, although the operators will be paid for 8 hours. Using a 3 year period in your analysis, and a 25% rate of return, determine (a) the equivalent annual cost for the two design alternatives, assuming no salvage value at the end of three years; and (b) the average cost per storage/retrieval transaction.

**Solution:**

(a) One-carousel system:

\[ EUAC = 50,000(A/P,25\%,3) + 250(8)(\$15) = 25,615 + 30,000 = \$55,615/yr \]

Two-carousel system:

\[ EUAC = 75,000(A/P,25\%,3) + 250(8)(2)(\$15) = 38,422 + 60,000 = \$98,422/yr \]

(b) One-carousel system: Annual \( R_c = 250(7)(51.43) = 90,002 \text{ transactions/yr} \)

Cost/transaction = \( \frac{55,615}{90,002} = \$0.618/transaction \)

Two-carousel system: Annual \( R_c = 250(7)(144.0) = 252,000 \text{ transactions/yr} \)

Cost/transaction = \( \frac{98,422}{252,000} = \$0.391/transaction \)
Chapter 12
AUTOMATIC IDENTIFICATION AND DATA CAPTURE

REVIEW QUESTIONS

12.1 What is automatic identification and data capture?

Answer: The definition given in the text is the following: Automatic identification and data capture (AIDC) refers to the technologies that provide direct entry of data into a computer or other microprocessor controlled system without using a keyboard.

12.2 What are the drawbacks of manual collection and entry of data?

Answer: Three drawbacks are identified in the text: (1) Errors. Errors occur in both data collection and keyboard entry of the data when accomplished manually. (2) Time factor. Manual methods are inherently more time consuming than automated methods. Also, when manual methods are used, there is a time delay between when the activities and events occur and when the data on status are entered into the computer. (3) Labor cost. The full-time attention of human workers is required in manual data collection and entry, with the associated labor cost.

12.3 What are the three principal components in automatic identification technologies?

Answer: The three components given in the text are (1) Data encoder. The data are translated into a machine-readable code. A label or tag containing the encoded data is attached to the item that is to be later identified. (2) Machine reader or scanner. This device reads the encoded data, converting them to alternative form, usually an electrical analog signal. (3) Data decoder. This component transforms the electrical signal into digital data and finally back into the original alphanumeric characters.

12.4 Name four of the six categories of AIDC technologies that are identified in the text.

Answer: The six categories of AIDC technologies identified in the text are (1) optical, such as bar codes and optical character recognition, (2) electromagnetic, such as RFID, (3) magnetic, used in plastic credit cards, (4) smart cards, which are imbedded with microchips capable of containing large amounts of data, (5) touch techniques, such as touch screens, and (6) biometric, such as voice recognition and fingerprint analysis.

12.5 Name five common applications of AIDC technologies in production and distribution?

Answer: The applications listed in the text are (1) receiving, (2) shipping, (3) order picking, (4) finished goods storage, (5) manufacturing processing, (6) work-in-process storage, (7) assembly, and (8) sortation.

12.6 There are two forms of linear bar codes. Name them, and indicate what the difference is.

Answer: The two forms of linear bar codes are (a) width-modulated, in which the symbol consists of bars and spaces of varying width; and (b) height-modulated, in which the symbol consists of evenly spaced bars of varying height.

12.7 What was the major industry to first use the Universal Product Code (UPC)?

Answer: The major industry to first use the Universal Product Code was the grocery industry, starting in 1973.

12.8 What are the two basic types of two-dimensional bar codes?

Answer: The two basic types of two-dimensional bar codes are (1) stacked bar codes and (2) matrix symbologies.

12.9 What does RFID stand for?

Answer: RFID stands for radio frequency identification.

12.10 What is a transponder in RFID?

Answer: The RFID identification tag is a transponder. A transponder is defined as a device that emits a signal of its own when it receives a signal from an external source.

12.11 What is the difference between a passive tag and an active tag?
Answer: A passive tag has no internal power source; it derives its electrical power for transmitting a signal from radio waves generated by the reader when in close proximity. An active tag includes its own battery power packs.

12.12 What are the relative advantages of RFID over bar codes?

Answer: The relative advantages of RFID over bar codes are (1) read-write capability, (2) large storage capacity, (3) line-of-sight reading is not required, (4) not susceptible to dirt or scratching that would destroy the label, and (5) the tags can be reused.

12.13 What are the relative advantages of bar codes over RFID?

Answer: The relative advantages of bar codes over RFID are (1) lower cost and (2) the technology is widely available.

12.14 What are the reasons why magnetic stripes are not widely used in factory floor operations?

Answer: Three reasons are given in the text: (1) The magnetic stripe must be in contact with the scanning equipment for reading to be accomplished, (2) unavailability of convenient shop floor encoding methods to write data into the stripe, and (3) the magnetic stripe labels are more expensive than bar code labels.

12.15 What is the advantage of optical character recognition technology over bar code technology?

Answer: The advantage is that OCR symbols can be read by humans, whereas bar codes cannot.

12.16 What is the principal application of machine vision in industry?

Answer: The principal application of machine vision is automated inspection.
Chapter 13
INTRODUCTION TO MANUFACTURING SYSTEMS

REVIEW QUESTIONS

13.1 What is a manufacturing system?

**Answer:** The definition given in the text is the following: A manufacturing system is a collection of integrated equipment and human resources, whose function is to perform one or more processing and/or assembly operations on a starting raw material, part, or set of parts.

13.2 Name the four components of a manufacturing system.

**Answer:** As listed in the text, the four components are (1) production machines plus tools, fixtures, and other related hardware, (2) a material handling system, (3) a computer system to coordinate and/or control the preceding components, and (4) human workers to operate and manage the system.

13.3 What are the three classifications of production machines, in terms of worker participation?

**Answer:** In terms of worker participation, the machines can be classified as (1) manually operated, (2) semi-automated or (3) fully automated.

13.4 What are the five material handling functions that must be provided in a manufacturing system?

**Answer:** The five material handling functions that must be provided in a manufacturing system are (1) loading work units at each station, (2) positioning the work units at the station, (3) unloading the work units from the station, (4) transporting work units between stations in manufacturing systems comprised of multiple workstations, and (5) temporary storage of work units to prevent starving of workstations.

13.5 What is the difference between fixed routing and variable routing in manufacturing systems consisting of multiple workstations?

**Answer:** In fixed routing, the work units always flow through the same sequence of workstations. This means that the work units are identical or similar enough that the processing sequence is identical. In variable routing, work units are transported through a variety of different station sequences. This means that the manufacturing system processes or assembles different types of work units.

13.6 What is a pallet fixture in work transport in a manufacturing system?

**Answer:** A pallet fixture is a workholder that is designed to be transported by the material handling system. The part is accurately attached to the fixture on the upper face of the pallet, and the under portion of the pallet is designed to be moved, located, and clamped in position at each workstation in the system.

13.7 A computer system is an integral component in a modern manufacturing system. Name four of the eight functions of the computer system listed in the text.

**Answer:** The eight functions of the computer system identified in the text are (1) communicate instructions to workers, (2) download part programs to computer-controlled machines, (3) control the material handling system, (4) schedule production, (5) failure diagnosis, (6) safety monitoring, (7) quality control, and (8) operations management.

13.8 What are the five factors that can be used to distinguish manufacturing systems in the classification scheme proposed in the chapter?

**Answer:** The five factors identified in the text are (1) types of operations performed, (2) number of workstations, (3) system layout, (4) automation and manning level, and (5) part or product variety.

13.9 Why is manning level inversely correlated with automation level in a manufacturing system?

**Answer:** Manning level is inversely correlated with automation level in a manufacturing system because the number of workers required to operate the system tends to be reduced as the level of automation increases.

13.10 Name the three cases of part or product variety in manufacturing systems. Briefly define each of the three cases.

**Answer:** The three cases of part or product variety in manufacturing systems are (1) single model, (2) batch model, and (3) mixed model. In the single-model case, all parts or products made by the manufacturing
system are identical. In the batch-model case, different parts or products are made by the system, but they are made in batches because the physical setup and/or equipment programming must be changed over between models. In the mixed-model case, different parts or products are made by the system, but the differences are not significant, so the system is able to handle them without the need for time-consuming changeovers in setup or program.

13.11 What is flexibility in a manufacturing system?

**Answer:** Flexibility is the attribute that allows a mixed-model manufacturing system to cope with a certain level of variation in part or product style without interruptions in production for changeovers between models.

13.12 What are the three capabilities that a manufacturing system must possess in order to be flexible?

**Answer:** As identified in the text, the three capabilities are (1) identification of the different work units, (2) quick changeover of operating instructions, and (3) quick changeover of the physical setup.
Chapter 14
SINGLE STATION MANUFACTURING CELLS

REVIEW QUESTIONS

14.1 Name three reasons why single-station manned cells are so widely used in industry.

Answer: The reasons given in the text are the following: (1) It requires the shortest amount of time to implement. (2) It requires the least capital investment of all manufacturing systems. (3) Technologically, it is the easiest system to install and operate. Its maintenance requirements are usually minimal. (4) For many situations, particularly for low quantities, it results in the lowest cost per unit produced. (5) In general, it is the most flexible manufacturing system with regard to changeovers from one part or product style to the next.

14.2 What does the term semi-automated station mean?

Answer: As defined in the text, a semi-automated station is a machine that is controlled by some form of program during a portion of the work cycle, and the worker’s function is simply to load and unload the machine each cycle, and periodically change cutting tools.

14.3 What is a single-station automated cell?

Answer: A single station automated cell is a fully-automated machine capable of unattended operation for a time period longer than one machine cycle. A worker is not required to be at the machine except periodically to load and unload parts or otherwise tend it.

14.4 What are the five enablers that are required for unattended operation of a single-model or batch-model automated production cell?

Answer: As given in the text, the five enablers of unattended operation for a single-model or batch-model automated production cell are the following: (1) a programmed cycle that allows the machine to perform every step of the processing or assembly cycle automatically; (2) a parts storage subsystem and a supply of parts that permit continuous operation beyond one machine cycle; (3) automatic transfer of workparts between the storage system and the machine (automatic unloading of finished parts from the machine and loading of raw workparts to the machine); (4) periodic attention of a worker who performs the necessary machine tending functions (e.g., parts loading and unloading of the storage subsystem) for the particular processing or assembly operation; and (5) built-in safeguards that protect the system against operating under conditions that may be unsafe or self-destructive to itself or destructive to the work units being processed or assembled.

14.5 What are the additional three enablers that are required for unattended operation of a mixed-model automated production cell?

Answer: As given in the text, the three enablers of unattended operation for a mixed-model automated production cell are (1) a work identification subsystem that can distinguish the different starting work units entering the station, so that the correct processing sequence can be used for that part or product style; (2) a program downloading capability to transfer the machine cycle program corresponding to the identified part or product style; and (3) a quick setup changeover capability so that the necessary workholding devices and other tools for each part are available on demand.

14.6 What is an automatic pallet changer?

Answer: An automatic pallet changer is a part handling subsystem that is used to exchange pallet fixtures between the machine tool worktable and the load/unload position or part storage system.

14.7 What is a machining center?

Answer: As defined in the text, a machining center is a machine tool capable of performing multiple machining operations on a workpart in one setup under NC program control. Typical cutting operations performed on a machining center are milling, drilling, reaming, and tapping.

14.8 What are some of the features on a NC machining center used to reduce nonproductive time in the work cycle?

Answer: The text lists the following features: (1) automatic tool-changer; (2) automatic workpart positioner; and (3) automatic pallet changer.
14.9 What is a machine cluster?

**Answer:** As defined in the text, a machine cluster is a collection of two or more machines producing parts or products with identical cycle times and serviced (usually loaded and unloaded) by one worker.

**PROBLEMS**

**Unattended Operation**

14.1 A CNC machining center has a programmed cycle time = 25.0 min for a certain part. The time to unload the finished part and load a starting work unit = 5.0 min. (a) If loading and unloading are done directly onto the machine tool table and no automatic storage capacity exists at the machine, what are the cycle time and hourly production rate? (b) If the machine tool has an automatic pallet changer so that unloading and loading can be accomplished while the machine is cutting another part, and the repositioning time = 30 sec, what are the total cycle time and hourly production rate? (c) If the machine tool has an automatic pallet changer that interfaces with a parts storage unit whose capacity is 12 parts, and the repositioning time = 30 sec, what are the total cycle time and hourly production rate? Also, how long does it take to perform the loading and unloading of the 12 parts by the human worker, and what is the time the machine can operate unattended between parts changes?

**Solution:** (a) \( T_c = 25.0 + 5.0 = 30.0 \text{ min/pc} \)
\( R_c = \frac{60}{30} = 2.0 \text{ pc/hr} \)

(b) \( T_c = \text{Max}(25.0, 5.0) + 0.5 = 25.5 \text{ min/pc} \)
\( R_c = \frac{60}{25.5} = 2.35 \text{ pc/hr} \)

(c) \( T_c = \text{Max}(25.0, 5.0) + 0.5 = 25.5 \text{ min/pc} \)
\( R_c = \frac{60}{25.5} = 2.35 \text{ pc/hr} \)

Time to load/unload = 12(5.0) = 60 min
\( UT = 12(25.5) - 60 = 306 - 60 = 246.0 \text{ min} = 4.1 \text{ hr} \)

**Determining Workstation Requirements**

14.2 A total of 7000 stampings must be produced in the press department during the next three days. Manually operated presses will be used to complete the job and the cycle time is 27 sec. Each press must be set up before production starts. Setup time for this job is 2.0 hr. How many presses and operators must be devoted to this production during the three days, if there are 7.5 hours of available time per day?

**Solution:** The workload consists of 7000 stampings at 27 sec per piece
\( WL = 7000(27/60) + 2(60)n = 3150 + 120 \ n \ \text{(min)} = 52.5 + 2 \ n \ \text{(hr)} \)
Time available per press during the three days \( AT = 3(7.5) = 22.5 \text{ hr} \)
\( n = \frac{52.5 + 2n}{22.5} \)
\( 22.5n = 52.5 + 2n \)
\( 20.5n = 52.5 \)
\( n = 52.5/20.5 = 2.56 \text{ rounded up to 3 presses and operators} \)

14.3 A stamping plant must be designed to supply an automotive engine plant with sheet metal stampings. The plant will operate one 8-hour shift for 250 days per year and must produce 20,000,000 good quality stampings annually. Batch size = 10,000 good stampings produced per batch. Scrap rate = 5%. On average it takes 3.0 sec to produce each stamping when the presses are running. Before each batch, the press must be set up, and it takes 4 hr to accomplish each setup. Presses are 90% reliable during production and 100% reliable during setup. How many stamping presses will be required to accomplish the specified production?

**Solution:** Production: \( WL = \frac{20,000,000(3/3600)}{1-0.05} = 17,543.9 \text{ hr/yr} \)
\( AT = 250(8)(0.90) = 1800 \text{ hr/yr per press} \)
Setup: number batches/yr = \( \frac{20,000,000}{10,000} = 2000 \text{ batches} = 2000 \text{ setups} \)
\( WL = 2000(4) = 8000 \text{ hr/yr} \)
\( AT = 250(8) = 2000 \text{ hr/yr per press} \)
A new forging plant must supply parts to the automotive industry. Because forging is a hot operation, the plant will operate 24 hr per day, five days per week, 50 weeks per year. Total output from the plant must be 10,000,000 forgings per year in batches of 1250 parts per batch. Anticipated scrap rate = 3%. Each forging cell will consist of a furnace to heat the parts, a forging press, and a trim press. Parts are placed in the furnace an hour prior to forging; they are then removed and forged and trimmed one at a time. On average the forging and trimming cycle takes 0.6 min to complete one part. Each time a new batch is started, the forging cell must be changed over, which consists of changing the forging and trimming dies for the next part style. It takes 2.0 hr on average to complete a changeover between batches. Each cell is considered to be 96% reliable during operation and 100% reliable during changeover. Determine the number of forging cells that will be required in the new plant.

Solution: Production: \( WL = \frac{10,000,000(0.6/60)}{1 - 0.03} = 103,092.8 \text{ hr/yr} \)
\( AT = 50(5)(3)(8)(0.96) = 5760 \text{ hr/yr}. \)
Setup: number batches/yr = \( \frac{10,000,000}{1250} = 8000 \text{ batches/yr = 8000 setups/yr} \)
\( WL = 8000(2) = 16,000 \text{ hr/yr per cell} \)
\( AT = 50(5)(3)(8) = 6000 \text{ hr/yr}. \)
\( n = \frac{103,092.8}{5760} + \frac{16,000}{6000} = 17.90 + 2.67 = 20.57 \rightarrow 21 \text{ forging cells} \)

A plastic injection molding plant will be built to produce 6 million molded parts per year. The plant will run three 8-hour shifts per day, five days per week, 50 weeks per year. For planning purposes, the average batch size = 6000 moldings, average changeover time between batches = 6 hrs, and average molding cycle time per part = 30 sec. Assume scrap rate = 2 percent, and average uptime proportion (reliability) per molding machine = 97 %, which applies to both run time and changeover time. How many molding machines are required in the new plant?

Solution: Production: \( WL = \frac{6,000,000(30/3600)}{1 - 0.02} = 51,020.4 \text{ hr/yr} \)
Setup: number batches/yr = \( \frac{6,000,000}{6000} = 1000 \text{ batches = 1000 setups} \)
\( WL = 1000(6) = 6000 \text{ hr/yr} \)
\( AT = 3(5)(50)(8)(0.97) = 5820 \text{ hr/yr per machine} \)
\( n = \frac{51,020.4 + 6000}{5820} = 8.766 + 1.031 = 9.797 \rightarrow 10 \text{ molding machines} \)

A plastic extrusion plant will be built to produce 25 million meters of plastic extrusions per year. The plant will run three 8-hour shifts per day, 360 days per year. For planning purposes, the average run length = 3000 meters of extruded plastic. The average changeover time between runs = 2.5 hr, and average extrusion speed = 15 m/min. Assume scrap rate = 1%, and average uptime proportion per extrusion machine = 95% during run time. Uptime proportion during changeover is assumed to be 100%. If each extrusion machine requires 500 sq. ft of floor space, and there is an allowance of 50% for aisles and office space, what is the total area of the extrusion plant?

Solution: Production: \( WL = \frac{25,000,000}{15(60)(1-0.01)} = 28,058.4 \text{ hr/yr} \)
\( AT = 360(3)(8)(0.95) = 8208 \text{ hr/yr}. \)
Changeover: number runs/yr = \( \frac{25,000,000}{3000} = 8,333 \text{ runs/yr = 8,333 changeovers/yr} \)
\( WL = 8,333(2.5) = 20,833 \text{ hr/yr} \)
\( AT = 360(3)(8) = 8640 \text{ hr/yr per machine} \)
Future production requirements in a machine shop call for several automatic bar machines to be acquired to produce three new parts (A, B, and C) that have been added to the shop’s product line. Annual quantities and cycle times for the three parts are given in the table below. The machine shop operates one 8-hour shift for 250 days per year. The machines are expected to be 95% reliable, and the scrap rate is 3%. How many automatic bar machines will be required to meet the specified annual demand for the three new parts?

<table>
<thead>
<tr>
<th>Part</th>
<th>Annual demand</th>
<th>Machining cycle time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>25,000</td>
<td>5.0 min</td>
</tr>
<tr>
<td>B</td>
<td>40,000</td>
<td>7.0 min</td>
</tr>
<tr>
<td>C</td>
<td>50,000</td>
<td>10.0 min</td>
</tr>
</tbody>
</table>

Solution: \[ AT = 250(8)(0.95) = 1900 \text{ hr/yr per machine} \]
\[ \begin{align*}
WL &= 
\left( \frac{25000}{5/60} + \frac{40000}{7/60} + \frac{50000}{10/60} \right) \left( 1 - 0.03 \right) \\
&= 2147.7 + 4811.0 + 8591.1 \\
&= 15,549.8 \text{ hr/yr}
\end{align*} \]
\[ n = 15,549.8 / 1900 = 8.184 \rightarrow 9 \text{ machines} \]

A certain type of machine will be used to produce three products: A, B, and C. Sales forecasts for these products are: 52,000, 65,000, and 70,000 units per year, respectively. Production rates for the three products are, respectively, 12, 15, and 10 pc/hr; and scrap rates are, respectively, 5%, 7%, and 9%. The plant will operate 50 weeks per year, 10 shifts per week, and 8 hr per shift. It is anticipated that production machines of this type will be down for repairs on average 10 percent of the time. How many machines will be required to meet demand?

Solution: \[ AT = 50(10)(8)(1 - 0.10) = 3600 \text{ hr/yr per machine} \]
\[ WL = \left( \frac{52000}{12(1-0.05)} + \frac{65000}{15(1-0.07)} + \frac{70000}{10(1-0.09)} \right) = 4561.4 + 4659.5 + 7692.3 = 16,913.2 \text{ hr/yr} \]
\[ n = 16,913.2 / 3600 = 4.67 \rightarrow 5 \text{ machines} \]

An emergency situation has occurred in the milling department, because the ship carrying a certain quantity of a required part from an overseas supplier sank on Friday evening. A certain number of machines in the department must therefore be dedicated to the production of this part during the next week. A total of 1000 of these parts must be produced, and the production cycle time per part = 16.0 min. Each milling machine used for this emergency production job must first be set up, which takes 4.0 hr. A scrap rate of 2% can be expected. (a) If the production week consists of 5 shifts at 8.0 hr per shift, how many machines will be required? (b) It so happens that only two milling machines can be spared for this emergency job, due to other priority jobs in the department. To cope with the emergency situation, plant management has authorized a three-shift operation for six days next week. Can the 1000 replacement parts be completed within these constraints?

Solution: 
(a) \[ WL = \frac{1000(16/60)}{(1-0.02)} = 272.1 \text{ hr/wk} \]
\[ AT = 5(8) - 40 - 4 = 36 \text{ hr/wk per machine} \]
\[ n = 272.1 / 36 = 7.56 \rightarrow 8 \text{ milling machines} \]

(b) \[ AT = 6(3)(8) - 4 = 140 \text{ hr/wk per machine} \]
\[ n = 272.1 / 140 = 1.94 \rightarrow 2 \text{ milling machines} \]

A machine shop has dedicated one CNC machining center to the production of two parts (A and B) used in the final assembly of the company’s main product. The machining center is equipped with an automatic pallet changer and a parts carousel that holds ten parts. One thousand units of the product are produced per year, and one of each part is produced in the product. Part A has a machining cycle time of 50 min. Part B has a machining cycle time of 80 min. These cycle times include the operation of the automatic pallet changer. No other changeover time is lost between parts. The anticipated scrap rate is zero. The machining center is 95% reliable. The machine shop operates 250 days per year. How many hours must the CNC machining center be operated each day on average to supply parts for the product?
Solution: Annual $WL = 1000(50 + 80)/60 = 2166.67$ hr/yr
At 250 days per year, daily workload $WL = 2166.67/250 = 8.67$ hr/day.

Machine Clusters

14.11 The CNC grinding section has a large number of machines devoted to grinding shafts for the automotive industry. The grinding machine cycle takes 3.6 min. At the end of this cycle an operator must be present to unload and load parts, which takes 40 sec. (a) Determine how many grinding machines the worker can service if it takes 20 sec to walk between the machines and no machine idle time is allowed. (b) How many seconds during the work cycle is the worker idle? (c) What is the hourly production rate of this machine cluster?

Solution: (a) $n = \frac{3.6(60) + 40}{40 + 20} = \frac{256}{60} = 4.27$ Use $n_1 = 4$ grinding machines

(b) Worker idle time $IT = 256 - 4(60) = 256 - 240 = 16$ sec

(c) $T_c = 256$ sec $R_c = 4\left(\frac{60}{4.267}\right) = 56.25$ pc/hr

14.12 A worker is currently responsible for tending two machines in a machine cluster. The service time per machine is 0.35 min and the time to walk between machines is 0.15 min. The machine automatic cycle time is 1.90 min. If the worker's hourly rate = $15/hr and the hourly rate for each machine = $20/hr, determine (a) the current hourly rate for the cluster, and (b) the current cost per unit of product, given that two units are produced by each machine during each machine cycle. (c) What is the % idle time of the worker? (d) What is the optimum number of machines that should be used in the machine cluster, if minimum cost per unit of product is the decision criterion?

Solution: (a) $C_o = 15 + 2(20) = \$55.00/hr$

(b) $T_i = T_m + T_s = 1.90 + 0.35 = 2.25$ min/cycle

$R_c = 2(2)\left(\frac{60}{2.25}\right) = 106.67$ pc/hr $C_{pc} = \frac{55}{106.67} = \$0.516/pc$

(c) Worker engagement time/cycle = 2($T_s + T_r$) = 2(0.35 + 0.15) = 1.0 min

Idle time $IT = \frac{2.25 - 1.0}{2.25} = 0.555 = 55.5\%$

(d) $n = \frac{1.90 + 0.35}{0.35 + 0.15} = 2.25/0.5 = 4.5$ machines

$n_1 = 4$ machines: $C_{pc}(4) = 0.5((15/60)/4 + (20/60)(2.25)) = \$0.406/pc$

$n_2 = 5$ machines: $C_{pc}(5) = 0.5(15/60 + 20x5/60)(0.50) = \$0.479/pc$

Use $n_1 = 4$ machines

14.13 In a machine cluster, the appropriate number of production machines to assign to the worker is to be determined. Let $n$ = the number of machines. Each production machine is identical and has an automatic processing time $T_m = 4.0$ min. The servicing time $T_s = 12$ sec for each machine. The full cycle time for each machine in the cell is $T_c = T_s + T_m$. The repositioning time for the worker is given by $T_r = 5 + 3n$, where $T_r$ is in sec. $T_r$ increases with $n$ because the distance between machines increases with more machines. (a) Determine the maximum number of machines in the cell if no machine idle time is allowed. For your answer, compute (b) the cycle time and (c) the worker idle time expressed as a percent of the cycle time?

Solution: (a) $n = \frac{4.0(60) + 12}{12 + 5 + 3n} = \frac{252}{17 + 3n}$

$n(17+3n) = 252$ $3n^2 + 17n - 252 = 0$

Use quadratic equation to find $n$.

$n = \frac{-17 \pm \sqrt{17^2 - 4(3)(-252)}}{2(3)} = -2.83 \pm 9.59 = 6.76$ or -12.43

Use $n = 6.76$ (ignore $n = -12.43$) $\rightarrow n_1 = 6$ machines
(b) \( T_c = 252 \text{ sec} \)

(c) Worker portion of cycle = \( 6(17 + 3 \times 6) = 210 \text{ sec} \)

Worker idle time \( IT = \frac{252 - 210}{252} = 0.167 = 16.7\% \)

14.14 An industrial robot will service \( n \) production machines in a machine cluster. Each production machine is identical and has an automatic processing time \( T_m = 130 \text{ sec} \). The robot servicing and repositioning time for each machine is given by the equation \( (T_s + T_r) = 15 + 4n \), where \( T_s \) is the servicing time (sec), \( T_r \) is the repositioning time (sec), and \( n = \) number of machines that the robot services. \( (T_s + T_r) \) increases with \( n \) because more time is needed to reposition the robot arm as \( n \) increases. The full cycle time for each machine in the cell is \( T_c = T_s + T_m \).

(a) Determine the maximum number of machines in the cell such that machines are not kept waiting. For your answer, (b) what is the machine cycle time, and (c) what is the robot idle time expressed as a percent of the cycle time \( T_c \)?

Solution: (a) Given \( T_m = 130 \text{ sec}, T_c = T_m + T_s = 130 + T_s \)

\[
n = \frac{130 + T_s}{15 + 4n}
\]

We can deduce that if there were only one machine \((n = 1)\), then repositioning time would be zero \((T_r = 0)\). Thus, for \( n = 1 \),

\[
(T_s + T_r) = (T_s + 0) = T_s = 15 + 4(1) = 19 \text{ sec}
\]

Substituting this value into the equation for \( n \), we have

\[
n = \frac{130 + 19}{15 + 4n} = \frac{149}{15 + 4n}
\]

\[
15n + 4n^2 = 149
\]

\[
4n^2 + 15n - 149 = 0
\]

Use quadratic equation to find \( n \).

\[
n = \frac{-15 \pm \sqrt{15^2 - 4(4)(-149)}}{2(4)} = -1.875 \pm 6.38 = 4.51 \text{ or } -8.26
\]

Use \( n = 4.51 \) (ignore \( n = -8.26 \)) \( \rightarrow \) For no machine waiting, \( n_1 = 4 \) machines

(b) \( T_c = 130 + 19 = 149 \text{ sec} \)

(c) Robot work time = \( n(T_s + T_r) = 4(15 + 4 \times 4) = 4(31) = 124 \text{ sec} \)

Robot idle time % = \( \frac{149 - 124}{149} = 0.168 = 16.8\% \)

14.15 A factory production department consists of a large number of work cells. Each cell consists of one human worker performing electronics assembly tasks. The cells are organized into sections within the department, and one foreman supervises each section. It is desired to know many work cells should be assigned to each foreman. The foreman’s job consists of two tasks: (1) provide each cell with a sufficient supply of parts that it can work for 4.0 hr before it needs to be resupplied and (2) prepare production reports for each workcell. Task (1) takes 15.0 min on average per workcell and must be done twice per day. The foreman must schedule the resupply of parts to every cell so that no idle time occurs in any cell. Task (2) takes 10.0 min per workcell and must be done once per day. The plant operates one shift which is 8.0 working hr, and neither the workers nor the foreman are allowed to work more than 8.0 hr per day. Each day, the cells continue production from where they stopped the day before. (a) What is the maximum number of work cells that should be assigned to a foreman, with the proviso that the work cells are never idle? (b) With the number of work cells from part (a), how many idle minutes does the foreman have each day?

Solution: Since the foreman must resupply each cell twice in an 8.0 hour day and also prepare a report on each cell once each day, the foreman’s day can be modeled as follows:

\[
2 n(15) + 1 n (10) = 80n
\]

\[
30n + 10n = 480 \hspace{1cm} 40n = 480 \hspace{1cm} n = 12 \text{. Use } 12 \text{ cells.}
\]

(b) Foreman’s idle time each day = \( 480 - 40(12) = 480 - 480 = 0 \text{ min (no idle time)} \)
Chapter 15
MANUAL ASSEMBLY LINES

REVIEW QUESTIONS

15.1 Name three of the four factors that favor the use of manual assembly lines.

Answer: The four factors listed in the text are the following: (1) Demand for the product is high or medium. (2) The products made on the line are identical or similar. (3) The total work required to assemble the product can be divided into small work elements. (4) It is technologically impossible or economically infeasible to automate the assembly operations.

15.2 What are the four reasons given in the text that explain why manual assembly lines are so productive compared to alternative methods in which multiple workers each perform all of the tasks to assemble the product?

Answer: The four reasons are the following: (1) Specialization of labor, which asserts that when a large job is divided into small tasks and each task is assigned to one worker, the worker becomes highly proficient at performing the single task. (2) Interchangeable parts, in which each component is manufactured to sufficiently close tolerances that any part of a certain type can be selected for assembly with its mating component. (3) Work flow principle, which involves moving the work to the worker rather than vice versa. (4) Line pacing, in which workers on an assembly line are usually required to complete their assigned tasks within a certain cycle time.

15.3 What is a manual assembly line?

Answer: The definition given in the text is the following: A manual assembly line is a production line that consists of a sequence of workstations where assembly tasks are performed by human workers. Products are assembled as they move along the line. At each station, a portion of the total work is performed on each unit.

15.4 What is meant by the term manning level in the context of a manual assembly line?

Answer: The manning level is the number of workers per station for a single station. For the entire line, it is the total number of workers on the line divided by the number of stations.

15.5 What do the terms starving and blocking mean?

Answer: Starving is the situation in which the assembly operator has completed the assigned task on the current work unit, but the next unit has not yet arrived at the station. The worker is thus starved for work. Blocking means that the operator has completed the assigned task on the current work unit but cannot pass the unit to the downstream station because that worker is not yet ready to receive it. The operator is therefore blocked from working.

15.6 Identify and briefly describe the three major categories of mechanized work transport systems used in production lines?

Answer: The three major categories of mechanized work transport systems are (1) continuous transport, which uses a continuously moving conveyor that operates at constant speed to transport work units; (2) synchronous transport, also known as intermittent transport, in which all work units are moved simultaneously between stations with a quick discontinuous motion; and (3) asynchronous transport, in which work units are moved independently rather than synchronously between stations.

15.7 To cope with product variety, three types of assembly line are described in the text. Name the three types and explain the differences between them.

Answer: The three types of assembly line are (1) single model line, in which only one product is made and there is no variation in the product; (2) batch model line, in which each type of product is produced in batches and the line setup is changed over between each batch; and (3) mixed model line, in which different models are produced simultaneously on the same line but no changeover is required between models.

15.8 What does the term line efficiency mean in production line terminology?

Answer: Line efficiency is the proportion uptime on the production line. It is the ratio of the theoretical cycle time $T_c$ to the actual average production time $T_p$ when downtime on the line is averaged in.
15.9 The theoretical minimum number of workers on an assembly line \( w^* \) is the minimum integer that is greater than the ratio of the work content time \( T_{wc} \) divided by the cycle time \( T_c \). Two factors are identified in the text that make it difficult to achieve this minimum value in practice. Name the two factors.

**Answer:** The two factors are (1) repositioning losses, in which either the worker or the work unit must be positioned at the start of each work cycle, and (2) the line balancing problem, which refers to the difficulty encountered in allocating all of the work elements in the work content time equally among workers on the line.

15.10 What is the difference between the cycle time \( T_c \) and the service time \( T_s \)?

**Answer:** The cycle time \( T_c \) is the time interval between arrivals of work units at a station, while service time \( T_s \) is the actual amount of time available at the station to perform the assigned task. The difference is the repositioning time \( T_r \). That is, \( T_r = T_c - T_s \).

15.11 What is a minimum rational work element?

**Answer:** As defined in the text, a minimum rational work element is a small amount of work that has a specific limited objective, such as adding a component to the base part or joining two components. A minimum rational work element cannot be subdivided any further without loss of practicality.

15.12 What is meant by the term precedence constraint?

**Answer:** Precedence constraints are restrictions on the order in which the work elements can be performed. Some elements must be done before others. For example, to create a threaded hole, the hole must be drilled before it can be tapped.

15.13 What is meant by the term balance efficiency?

**Answer:** The balance efficiency \( E_b \) is the work content time divided by the total available service time on the line. It can be computed as \( E_b = T_{wc} / w T_s \) where \( T_{wc} \) = work content time, min; \( T_s \) = the maximum available service time on the line (Max\{\( T_{si} \)\}), min/cycle; and \( w \) = number of workers.

15.14 What is the difference between how the largest candidate rule works and how the Kilbridge and Wester method works?

**Answer:** In the largest candidate rule, the algorithm begins with the work elements listed in descending order of their time values, whereas in the Kilbridge and Wester method, the algorithm operates on the work elements listed according to their precedence order in the precedence diagram.

15.15 In a mixed-model assembly line, what is the difference between variable-rate launching and fixed-rate launching?

**Answer:** In variable-rate launching, the time interval between the launching of the current base part and the next is set equal to the cycle time of the current unit. Since different models have different work content times and thus different task times per station, their launch time intervals vary. In fixed-rate launching, the time interval between two consecutive launches is constant. The time interval in fixed-rate launching is an average based on the product mix and production rates of models on the line.

15.16 What are storage buffers and why are they sometimes used on a manual assembly line?

**Answer:** A storage buffer is a location in the production line where work units are temporarily stored. As identified in the text, the reasons to include one or more storage buffers in a production line include: (1) to accumulate work units between two stages of the line when their production rates are different; (2) to smooth production between stations with large task time variations; and (3) to permit continued operation of certain sections of the line when other sections are temporarily down for service or repair.

**PROBLEMS**

**Single Model Assembly Lines**

15.1 A product whose work content time = 47.5 min is to be assembled on a manual production line. The required production rate is 30 units per hour. From previous experience, it is estimated that the manning level will be 1.25, proportion uptime = 0.95, and repositioning time = 6 sec. Determine (a) cycle time, and (b) ideal minimum number of workers required on the line. (c) If the ideal number in part (b) could be achieved, how many workstations would be needed?
Solution: (a) \( T_c = \frac{60(0.95)}{30} = 1.9 \text{ min} \)

(b) \( w = \text{Minimum Integer} \geq \frac{47.5}{1.9} = 25 \text{ workers} \)

(c) \( n = 25/1.25 = 20 \text{ workstations} \)

15.2 A manual assembly line has 17 workstations with one operator per station. Work content time to assemble the product = 28.0 min. Production rate of the line = 30 units per hour. The proportion uptime = 0.94, and repositioning time = 6 sec. Determine the balance delay.

Solution: \( T_c = \frac{60(0.94)}{30} = 1.88 \text{ min}, T_s = 1.88 - 0.1 = 1.78 \text{ min} \)

\( w = n = 17 \text{ workers and 17 stations} \)

\( E_b = \frac{28.0}{17(1.78)} = 0.9253, \quad d = 1 - 0.9253 = 0.0747 = 7.47\% \)

15.3 A manual assembly line must be designed for a product with annual demand = 80,000 units. The line will operate 50 wks/year, 5 shifts/wk, and 7.5 hr/shift. Work units will be attached to a continuously moving conveyor. Work content time = 42.0 min. Assume line efficiency = 0.96, balancing efficiency = 0.92, and repositioning time = 6 sec. Determine (a) hourly production rate to meet demand, and (b) number of workers required.

Solution: (a) \( R_p = \frac{80,000}{50(5)(7.5)} = 42.667 \text{ pc/hr} \)

(b) \( T_c = \frac{60(0.96)}{42.667} = 1.35 \text{ min}, \quad T_s = 1.35 - 0.1 = 1.25 \text{ min} \)

\( w = \text{Minimum Integer} \geq \frac{42.0}{0.92(1.25)} = 36.52 \rightarrow 37 \text{ workers} \)

15.4 A single model assembly line is being planned to produce a consumer appliance at the rate of 200,000 units per year. The line will be operated 8 hours per shift, two shifts per day, five days per week, 50 weeks per year. Work content time = 35.0 min. For planning purposes, it is anticipated that the proportion uptime on the line will be 95%. Determine (a) average hourly production rate, (b) cycle time, and (c) theoretical minimum number of workers required on the line. (d) If the balance efficiency is 0.93 and the repositioning time = 6 sec, how many workers will actually be required?

Solution: (a) \( R_p = \frac{200,000}{10(8)(50)} = 50 \text{ pc/hr} \)

(b) \( T_c = \frac{60(0.95)}{50} = 1.14 \text{ min} \)

(c) \( w = \text{Minimum Integer} \geq \frac{35.0}{1.14} = 30.7 \rightarrow 31 \text{ workers} \).

(d) \( T_c = 1.14 - 0.10 = 1.04 \text{ min} \)

\( E_r = 1.04/1.14 = 0.9123 \)

\( w = \text{Minimum Integer} \geq \frac{35.0(50)}{60(0.95)(0.93)(0.9123)} = 36.2 \rightarrow 37 \text{ workers} \).

15.5 The required production rate = 50 units per hour for a certain product whose assembly work content time = 1.2 hours. It is to be produced on a production line that includes four workstations that are automated. Because the automated stations are not completely reliable, the line will have an expected uptime efficiency = 90%. The remaining manual stations will each have one worker. It is anticipated that 8% of the cycle time will be lost due to repositioning at the bottleneck station. If the balance delay is expected to be 0.07, determine (a) the cycle
time, (b) number of workers, (c) number of workstations needed for the line, (d) average manning level on the line, including the automated stations, and (e) labor efficiency on the line.

Solution: (a) $T_c = \frac{60(0.90)}{50} = 1.08$ min

(b) $T_i = 0.08T_c$, therefore, $T_i = 0.92T_c$, therefore, $E_i = 0.92$

$E_b = 1 - d = 1 - 0.07 = 0.93$

$w = \text{Minimum Integer} \geq \frac{12(60)}{(0.93)(0.92)(1.08)} = 77.9 \rightarrow 78 \text{ workers.}$

(c) $n = 78 + 4 = 82 \text{ workstations.}$

(d) $M = 78/82 = 0.951$

(e) Labor efficiency = $EE_bE_i = 0.90(0.93)(0.92) = 0.77 = 77\%$

15.6 A final assembly plant for a certain automobile model is to have a capacity of 225,000 units annually. The plant will operate 50 weeks/yr, two shifts/day, 5 days/week, and 7.5 hours/shift. It will be divided into three departments: (1) body shop, (2) paint shop, (3) general assembly department. The body shop welds the car bodies using robots, and the paint shop coats the bodies. Both of these departments are highly automated. General assembly has no automation. There are 18.0 hours of work content time on each car in this third department, where cars are moved by a continuous conveyor. Determine (a) hourly production rate of the plant, (b) number of workers and workstations required in trim-chassis-final if no automated stations are used, the average manning level is 2.5, balancing efficiency = 90%, proportion uptime = 95%, and a repositioning time of 0.15 min is allowed for each worker.

Solution: (a) $R_p = \frac{225,000}{50(2)(5)(7.5)} = 60 \text{ cars/hr.}$

(b) $T_c = \frac{60(0.95)}{60} = 0.95 \text{ min, } T_i = 0.95 - 0.15 = 0.80 \text{ min}$

$T_{wc} = 18(60) = 1080 \text{ min of direct labor}$

$w = \text{Minimum Integer} \geq \frac{1080}{0.90(0.80)} = 1500 \text{ workers, and } n = \frac{1500}{2.5} = 600 \text{ stations}$

15.7 Production rate for a certain assembled product is 47.5 units per hour. The assembly work content time = 32 min of direct manual labor. The line operates at 95% uptime. Ten workstations have two workers on opposite sides of the line so that both sides of the product can be worked on simultaneously. The remaining stations have one worker. Repositioning time lost by each worker is 0.2 min/cycle. It is known that the number of workers on the line is two more than the number required for perfect balance. Determine (a) number of workers, (b) number of workstations, (c) balance efficiency, and (d) average manning level.

Solution: (a) $T_c = \frac{60(0.95)}{47.5} = 1.2 \text{ min, } T_i = 1.2 - 0.2 = 1.0 \text{ min}$

For perfect balance, $E_b = 1.0$. $w = \text{Minimum Integer} \geq \frac{32.0}{1.0(1.0)} = 32 \text{ workers.}$

With 2 more workers than required for perfect balance, $w = 32 + 2 = 34 \text{ workers.}$

(b) $n = 20/2 + (34 - 20) = 10 + 14 = 24 \text{ stations.}$

(c) $E_b = \frac{32.0}{34(1.0)} = 0.941 = 94.1\%$

(d) $M = 34/24 = 1.417$

15.8 The work content for a product assembled on a manual production line is 48 min. The work is transported using a continuous overhead conveyor that operates at a speed of 5 ft/min. There are 24 workstations on the line, one-third of which have two workers; the remaining stations each have one worker. Repositioning time per
worker is 9 sec, and uptime efficiency of the line is 95%. (a) What is the maximum possible hourly production rate if the line is assumed to be perfectly balanced? (b) If the actual production rate is only 92% of the maximum possible rate determined in part (a), what is the balance delay on the line?

Solution: (a) \( w = \frac{T_s}{E_b T_w} \), therefore, \( T_s = \frac{w E_b}{E_s w} \)

If the line is perfectly balanced, the \( E_b = 1.0 \). \( T_s = \frac{48.0}{1.0(32)} = 1.5 \) min, \( T_s = 1.5 + 0.15 = 1.65 \) min

\( R_p = \frac{60(0.95)}{1.65} = 34.55 \) \( \text{pc/hr} \) (at \( E = 0.95 \) and \( E_b = 1.0 \))

(b) Actual \( R_p = 0.92(34.55) = 31.78 \) \( \text{pc/hr} \)

\( T_c = \frac{60(0.95)}{31.78} = 1.7935, \quad T_s = 1.7935 - 0.15 = 1.6435 \) min

\( d = \frac{32(1.6435) - 48.0}{32(1.6435)} = 0.087 = 8.7\% \)

15.9 Work content time for a product assembled on a manual production line is 45.0 min. Production rate of the line must be 50 units/hr. Work units are attached to a moving conveyor whose speed = 8 ft/min. Repositioning time per worker is 8 sec, line efficiency is 94%, and manning level = 1.25. Owing to imperfect line balancing, it is expected that the number of workers needed on the line will be about 10% more workers than the number required for perfect balance. If the workstations are arranged in a line, and the length of each station is 8 ft, (a) how long is the entire production line, and (b) what is the elapsed time a work unit spends on the line?

Solution: (a) \( T_c = \frac{60(0.94)}{50} = 1.128 \) min \( T_s = 1.128 - 0.133 = 0.995 \) min

For perfect balance, \( E_b = 1.0 \). \( w = \) Minimum Integer \( \geq \frac{45.0}{1.0(0.995)} = 45.23 \)

With 10% more workers, \( w = 1.1(45.23) = 49.7 \rightarrow 50 \) workers. \( n = \frac{50}{1.25} = 40 \) stations

\( L = (40 \text{ stations})(8 \text{ ft/station}) = 320 \) ft.

(b) Given \( L = 320 \) ft and \( v_c = 8 \) ft/min, \( ET = \frac{320}{8} = 40.0 \) min

Line Balancing (Single Model Lines)

15.10 Show that the two statements of the objective function in single model line balancing in Eq. (15.20) are equivalent.

Solution: \( nT_s \) in the first expression = \( \sum_{i=1}^{n} T_s \) in the second expression, since \( T_s \) is a constant

\( T_s = \text{Max}\{T_{s_i}\} \) in Eq. (15.11)

And \( T_w \) in the first expression = \( \sum_{i=1}^{n} T_w \) in the second expression, according to Eq. (15.15).

Therefore \( nT_s - T_w = \sum_{i=1}^{n} (T_s - T_w) \) Q.E.D.

15.11 The table below defines the precedence relationships and element times for a new model toy. (a) Construct the precedence diagram for this job. (b) If the ideal cycle time = 1.1 min. repositioning time = 0.1 min, and uptime proportion is assumed to be 1.0, what is the theoretical minimum number of workstations required to minimize the balance delay under the assumption that there will be one worker per station? (c) Use the largest candidate rule to assign work elements to stations. (d) Compute the balance delay for your solution.

<table>
<thead>
<tr>
<th>Work element</th>
<th>( T_e ) (min)</th>
<th>Immediate predecessors</th>
</tr>
</thead>
</table>

105
1 0.5 -
2 0.3 1
3 0.8 1
4 0.2 2
5 0.1 2
6 0.6 3
7 0.4 4,5
8 0.5 3,5
9 0.3 7,8
10 0.6 6,9

Solution: (a) Precedence diagram:

(b) $T_s = T_c - T_r = 1.1 - 0.1 = 1.0$ min

With $M = 1.0$, $n = w = $ Minimum Integer $\geq \frac{T_w}{T_s} = 4.3 \div 1.0 = 4.3$, Use $n = 5$ stations

(c) Line balancing solution using the largest candidate rule.

<table>
<thead>
<tr>
<th>Element</th>
<th>$T_e$ (min)</th>
<th>Predecessors</th>
<th>Station</th>
<th>Element</th>
<th>$T_e$</th>
<th>$\Sigma T_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>0.5 min</td>
</tr>
<tr>
<td>6</td>
<td>0.6</td>
<td>3</td>
<td>2</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.6</td>
<td>6, 9</td>
<td>4</td>
<td>0.2</td>
<td>1.0</td>
<td>1.0 min</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>-</td>
<td>2</td>
<td>3</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.5</td>
<td>3, 5</td>
<td>5</td>
<td>0.1</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.4</td>
<td>4, 5</td>
<td>3</td>
<td>6</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.3</td>
<td>7, 8</td>
<td>7</td>
<td>0.4</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.2</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.1</td>
<td>2</td>
<td>9</td>
<td>0.3</td>
<td>0.8</td>
<td></td>
</tr>
</tbody>
</table>

(d) Balance delay $d = \frac{5(1.0) - 4.3}{5(1.0)} = 0.14 = 14%$

15.12 Solve the previous problem using the Kilbridge and Wester method in part (c).

Solution: (a) Precedence diagram same as in Problem 15.11.

(b) Same as in Problem 15.11: $n = 5$ stations.

(c) Line balancing solution using the Kilbridge & Wester method:
15.13 Solve the previous problem using the ranked positional weights method in part (c).

**Solution:**
(a) Precedence diagram same as in Problem 15.11.

(b) Same as in Problem 15.11: \( n = 5 \) stations.

(c) Line balancing solution using the Kilbridge & Wester method:

<table>
<thead>
<tr>
<th>Element</th>
<th>( T_e ) (min)</th>
<th>Column</th>
<th>Allocation of elements to stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>I</td>
<td>Station 1 1 0.5 min</td>
</tr>
<tr>
<td>2</td>
<td>0.3</td>
<td>II</td>
<td>Station 2 2 0.3 min</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td>II</td>
<td>Station 4 3 0.2 min 1.0 min</td>
</tr>
<tr>
<td>4</td>
<td>0.2</td>
<td>III</td>
<td>Station 5 4 0.1 min 0.9 min</td>
</tr>
<tr>
<td>5</td>
<td>0.1</td>
<td>III</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.6</td>
<td>III</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.4</td>
<td>IV</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.5</td>
<td>IV</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.3</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.6</td>
<td>VI</td>
<td></td>
</tr>
</tbody>
</table>

4.3 min total

(d) Same as in Problem 15.11: \( d = 0.14 = 14\% \)

15.14 A manual assembly line is to be designed to make a small consumer product. The work elements, their times, and precedence constraints are given in the table below. The workers will operate the line for 400 min per day and must produce 300 products per day. A mechanized belt, moving at a speed of 1.25 m/min, will transport the products between stations. Because of the variability in the time required to perform the assembly operations, it has been determined that the tolerance time should be 1.5 times the cycle time of the line. (a) Determine the ideal minimum number of workers on the line. (b) Use the Kilbridge and Wester method to balance the line. (c) Compute the balance delay for your solution in part (b).

<table>
<thead>
<tr>
<th>Element</th>
<th>Time ( T_e )</th>
<th>Preceded by:</th>
<th>Element</th>
<th>Time ( T_e )</th>
<th>Preceded by:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4 min</td>
<td>-</td>
<td>6</td>
<td>0.2 min</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>0.7 min</td>
<td>1</td>
<td>7</td>
<td>0.3 min</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>0.5 min</td>
<td>1</td>
<td>8</td>
<td>0.9 min</td>
<td>4, 9</td>
</tr>
<tr>
<td>4</td>
<td>0.8 min</td>
<td>2</td>
<td>9</td>
<td>0.3 min</td>
<td>5, 6</td>
</tr>
<tr>
<td>5</td>
<td>1.0 min</td>
<td>2, 3</td>
<td>10</td>
<td>0.5 min</td>
<td>7, 8</td>
</tr>
</tbody>
</table>

**Solution:**
(a) \( T_c = \frac{400 \text{ min/day}}{300 \text{ asbys/day}} = 1.333 \text{ min/asby} \). No \( T_c \) value given. Assume \( T_c = 0 \).
\[ T_{wc} = \sum_k T_{sk} = 0.4 + 0.7 + \ldots + 0.5 = 5.6 \text{ min} \]

\[ w = \text{Minimum Integer} \geq \frac{5.6}{1.333} = 4.2 \rightarrow w = 5 \text{ workers} \]

(b) Line balancing solution using Kilbridge & Wester method. Assume \( M = 1.0 \).

Note: In the above solution, the Kilbridge & Wester method was followed very precisely, so that the solution consisted of a total of six stations. A better solution, but one that violates the K&W algorithm, would be to combine elements 9 and 8 at station 4 and elements 7 and 10 at station 5, for a total of only 5 stations.

(c) Use cycle time of 1.3 min (station 2) rather than 1.333 min. Using the six stations in the K&W solution, balance delay \( d = \frac{6(1.3) - 5.6}{6(1.3)} = 0.282 = 28.2\% \)

15.15 Solve the previous problem using the ranked positional weights method in part (b).

Solution: (a) Same solution as in Problem 15.14: \( (T_e = 1.333 \text{ min}, T_r = 0, T_{wc} = 5.6 \text{ min}) w = 5 \text{ workers} \).

(b) Line balancing solution using ranked positional weights method. Assume \( M = 1.0 \).
A manual assembly line operates with a mechanized conveyor. The conveyor moves at a speed of 5 ft/min, and the spacing between base parts launched onto the line is 4 ft. It has been determined that the line operates best when there is one worker per station and each station is 6 ft long. There are 14 work elements that must be accomplished to complete the assembly, and the element times and precedence requirements are listed in the table below. Determine (a) feed rate and corresponding cycle time, (b) tolerance time for each worker, and (c) ideal minimum number of workers on the line. (d) Draw the precedence diagram for the problem. (e) Determine an efficient line balancing solution. (f) For your solution, determine the balance delay.

<table>
<thead>
<tr>
<th>Element</th>
<th>$T_e$</th>
<th>Preceded by:</th>
<th>Element</th>
<th>$T_e$</th>
<th>Preceded by:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2 min</td>
<td>-</td>
<td>8</td>
<td>0.2 min</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>0.5 min</td>
<td>-</td>
<td>9</td>
<td>0.4 min</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>0.2 min</td>
<td>1</td>
<td>10</td>
<td>0.3 min</td>
<td>6, 7</td>
</tr>
<tr>
<td>4</td>
<td>0.6 min</td>
<td>1</td>
<td>11</td>
<td>0.1 min</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>0.1 min</td>
<td>2</td>
<td>12</td>
<td>0.2 min</td>
<td>8, 10</td>
</tr>
<tr>
<td>6</td>
<td>0.2 min</td>
<td>3, 4</td>
<td>13</td>
<td>0.1 min</td>
<td>11</td>
</tr>
<tr>
<td>7</td>
<td>0.3 min</td>
<td>4</td>
<td>14</td>
<td>0.3 min</td>
<td>12, 13</td>
</tr>
</tbody>
</table>

**Solution:**

(a) Assume $T_r = 0$, $f_p = \frac{5 \text{ ft/min}}{4 \text{ ft/asby}} = 1.25 \text{ asbys/min}$, $T_c = 0.8 \text{ min/asby}$

(b) $T_r = \frac{6 \text{ ft/station}}{5 \text{ ft/min}} = 1.2 \text{ min/station}$

(c) $T_{we} = \sum T_{r \alpha} = 0.2 + 0.5 + \ldots + 0.3 = 3.7 \text{ min}$

$w = \text{Minimum Integer} \geq \frac{3.7 \text{ min}}{0.8 \text{ min}} = 4.625 \rightarrow 5 \text{ workers}$

(d) Precedence diagram
(e) Line balancing solution using the Kilbridge and Wester method

List of elements by precedence columns

<table>
<thead>
<tr>
<th>Element</th>
<th>$T_e$ (min)</th>
<th>Column</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>I</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>I</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>II</td>
</tr>
<tr>
<td>4</td>
<td>0.6</td>
<td>II</td>
</tr>
<tr>
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<td>0.1</td>
<td>II</td>
</tr>
<tr>
<td>6</td>
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<td>III</td>
</tr>
<tr>
<td>7</td>
<td>0.3</td>
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<tr>
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<td>0.2</td>
<td>III</td>
</tr>
<tr>
<td>9</td>
<td>0.4</td>
<td>III</td>
</tr>
<tr>
<td>10</td>
<td>0.3</td>
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</tr>
<tr>
<td>11</td>
<td>0.1</td>
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<tr>
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<td>0.2</td>
<td>V</td>
</tr>
<tr>
<td>13</td>
<td>0.1</td>
<td>V</td>
</tr>
<tr>
<td>14</td>
<td>0.3</td>
<td>VI</td>
</tr>
</tbody>
</table>

Allocation of elements to stations

<table>
<thead>
<tr>
<th>Station</th>
<th>Element</th>
<th>$T_e$ (min)</th>
<th>$\Sigma T_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.2 min</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0.5 min</td>
<td>0.8 min</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0.2 min</td>
<td>0.6 min</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>0.1 min</td>
<td>0.7 min</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>0.2 min</td>
<td>0.8 min</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>0.3 min</td>
<td>0.7 min</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>0.2 min</td>
<td>0.7 min</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>0.4 min</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>0.3 min</td>
<td>0.7 min</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>0.1 min</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>12</td>
<td>0.2 min</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>13</td>
<td>0.1 min</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>14</td>
<td>0.3 min</td>
<td>3.7 min total</td>
</tr>
</tbody>
</table>

(f) Balance delay $d = \frac{5(0.8) - 3.7}{5(0.8)} = 0.075 = 7.5\%$

15.17 A new small electrical appliance is to be assembled on a single model assembly line. The line will be operated 250 days per year, 15 hours per day. The work content has been divided into work elements as defined in the table below. Also given are the element times and precedence requirements. Annual production is to be 200,000 units. It is anticipated that the line efficiency will be 0.96. Repositioning time for each worker is 0.08 min. Determine (a) average hourly production rate, (b) cycle time, and (c) theoretical minimum number of workers required to meet annual production requirements. (d) Use one of the line balancing algorithms to balance the line. For your solution, determine (e) balance efficiency and (f) overall labor efficiency on the line.

<table>
<thead>
<tr>
<th>Element No.</th>
<th>Element description</th>
<th>$T_e$ (min)</th>
<th>Preceded by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Place frame on workholder and clamp</td>
<td>0.15</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Assemble fan to motor</td>
<td>0.37</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Assemble bracket A to frame</td>
<td>0.21</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Assemble bracket B to frame</td>
<td>0.21</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Assemble motor to frame</td>
<td>0.58</td>
<td>1, 2</td>
</tr>
<tr>
<td>6</td>
<td>Affix insulation to bracket A</td>
<td>0.12</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>Assemble angle plate to bracket A</td>
<td>0.29</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>Affix insulation to bracket B</td>
<td>0.12</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>Attach link bar to motor and bracket B</td>
<td>0.30</td>
<td>4, 5</td>
</tr>
<tr>
<td>10</td>
<td>Assemble three wires to motor</td>
<td>0.45</td>
<td>5</td>
</tr>
<tr>
<td>11</td>
<td>Assemble nameplate to housing</td>
<td>0.18</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>Assemble light fixture to housing</td>
<td>0.20</td>
<td>11</td>
</tr>
<tr>
<td>13</td>
<td>Assemble blade mechanism to frame</td>
<td>0.65</td>
<td>6, 7, 8, 9</td>
</tr>
<tr>
<td>14</td>
<td>Wire switch, motor, and light</td>
<td>0.72</td>
<td>10, 12</td>
</tr>
<tr>
<td>15</td>
<td>Wire blade mechanism to switch</td>
<td>0.25</td>
<td>13</td>
</tr>
<tr>
<td>16</td>
<td>Attach housing over motor</td>
<td>0.35</td>
<td>14</td>
</tr>
<tr>
<td>17</td>
<td>Test blade mechanism, light, etc.</td>
<td>0.16</td>
<td>15, 16</td>
</tr>
<tr>
<td>18</td>
<td>Affix instruction label to cover plate</td>
<td>0.12</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>Assemble grommet to power cord</td>
<td>0.10</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>Assemble cord and grommet to cover plate</td>
<td>0.23</td>
<td>18, 19</td>
</tr>
<tr>
<td>21</td>
<td>Assemble power cord leads to switch</td>
<td>0.40</td>
<td>17, 20</td>
</tr>
</tbody>
</table>
Assembly Lines-3e-SI  07-05/06, 06/04/07, 09/16/07

22 Assemble cover plate to frame 0.33 21
23 Final inspect and remove from workholder 0.25 22
24 Package 1.75 23

Solution: (a) \( R_p = \frac{200,000}{250(15)} = 53.33 \) asbys/hr

(b) \( T_c = \frac{60(0.96)}{53.33} = 1.08 \) min, \( T_c = 1.08 - 0.08 = 1.00 \) min

(c) \( T_{wc} = \sum T_e = 8.49 \) min, \( w = \) Minimum Integer \( \geq \frac{8.49}{100} = 8.49 \rightarrow 9 \) workers

(d) Line balancing solution using ranked positional weights method (\( T_e \) expressed in min):

<table>
<thead>
<tr>
<th>Element</th>
<th>( T_e ) (min)</th>
<th>RPW</th>
<th>Station</th>
<th>Element</th>
<th>( T_e ) (min)</th>
<th>( T_s ) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.15</td>
<td>7.29</td>
<td>1</td>
<td>1</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.37</td>
<td>6.56</td>
<td>2</td>
<td>2</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.58</td>
<td>6.19</td>
<td>4</td>
<td>0.21</td>
<td>2.01</td>
<td>0.94</td>
</tr>
<tr>
<td>4</td>
<td>0.21</td>
<td>4.42</td>
<td>3</td>
<td>0.21</td>
<td>0.21</td>
<td>0.94</td>
</tr>
<tr>
<td>3</td>
<td>0.21</td>
<td>4.41</td>
<td>11</td>
<td>0.18</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.45</td>
<td>4.41</td>
<td>12</td>
<td>0.20</td>
<td>0.20</td>
<td>0.96</td>
</tr>
<tr>
<td>11</td>
<td>0.18</td>
<td>4.34</td>
<td>12</td>
<td>0.20</td>
<td>0.20</td>
<td>0.96</td>
</tr>
<tr>
<td>12</td>
<td>0.20</td>
<td>4.16</td>
<td>3</td>
<td>10</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.30</td>
<td>4.09</td>
<td>9</td>
<td>0.30</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.29</td>
<td>4.08</td>
<td>6</td>
<td>0.12</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>0.72</td>
<td>3.96</td>
<td>8</td>
<td>0.12</td>
<td>0.12</td>
<td>0.99</td>
</tr>
<tr>
<td>6</td>
<td>0.12</td>
<td>3.91</td>
<td>4</td>
<td>0.29</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.12</td>
<td>3.91</td>
<td>13</td>
<td>0.65</td>
<td>0.65</td>
<td>0.94</td>
</tr>
<tr>
<td>13</td>
<td>0.65</td>
<td>3.79</td>
<td>5</td>
<td>0.72</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>0.35</td>
<td>3.24</td>
<td>15</td>
<td>0.25</td>
<td>0.25</td>
<td>0.97</td>
</tr>
<tr>
<td>15</td>
<td>0.25</td>
<td>3.14</td>
<td>6</td>
<td>0.35</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>0.12</td>
<td>3.08</td>
<td>18</td>
<td>0.12</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>0.10</td>
<td>3.06</td>
<td>19</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.23</td>
<td>2.96</td>
<td>20</td>
<td>0.23</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>0.16</td>
<td>2.89</td>
<td>17</td>
<td>0.16</td>
<td>0.16</td>
<td>0.96</td>
</tr>
<tr>
<td>21</td>
<td>0.40</td>
<td>2.73</td>
<td>7</td>
<td>0.40</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>0.33</td>
<td>2.33</td>
<td>22</td>
<td>0.33</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>0.25</td>
<td>2.00</td>
<td>23</td>
<td>0.25</td>
<td>0.25</td>
<td>0.98</td>
</tr>
<tr>
<td>24</td>
<td>1.75/2</td>
<td>1.75</td>
<td>8, 9*</td>
<td>24</td>
<td>1.75/2</td>
<td>0.875</td>
</tr>
</tbody>
</table>

* Stations 8 and 9 are arranged in parallel to divide the time of element 24 in half.

(e) Use \( T_s = 0.99 \) min (station 3). Balance delay \( d = \frac{9(0.99) - 8.49}{9(0.99)} = 0.0471 = 4.71\% \)

(f) \( E = 0.96 \) (given), \( E_b = 1 - 0.0471 = 0.9529, E_r = 1.00/1.08 = 0.9259 \). Overall labor efficiency = \( E E_b E_r = 0.96(0.9529)(0.9259) = 0.8470 = 84.7\% \)

Mixed Model Assembly Lines

15.18 Two product models, A and B, are to be produced on a mixed model assembly line. Hourly production rate and work content time for model A are 15 units/hr and 32.0 min, respectively; and for model B are 21 units/hr and 19.0 min. Line efficiency = 0.95, balance efficiency = 0.93, repositioning time = 0.10 min, and manning level = 1. Determine how many workers and workstations must be on the production line in order to produce this workload.

Solution: \( WL = 15(32) + 21(19) = 480 + 399 = 879 \) min/hr
Assembly Lines-3e-SI  07-05/06, 06/04/07, 09/16/07

\[ R_p = 15 + 21 = 36 \text{ units/hr}, \quad T_c = \frac{60(0.95)}{36} = 1.58333 \text{ min}, \]

\[ T_s = 1.58333 - 0.1 = 1.48333 \text{ min}, \quad E_r = \frac{1.48333}{1.58333} = 0.93684 \]

\[ AT = 60(0.95)(0.93)(0.93684) = 49.662 \text{ min/hr. per worker} \]

\[ w = \frac{879}{49.662} = 17.7 \rightarrow 18 \text{ workers.} \quad \text{Since } M = 1, \quad n = w = 18 \text{ stations.} \]

15.19 Three models, A, B, and C, will be produced on a mixed model assembly line. Hourly production rate and work content time for model A are 10 units/hr and 45.0 min; for model B are 20 units/hr and 35.0 min; and for model C are 30 units/hr and 25.0 min. Line efficiency is 95%, balance efficiency is 0.94, repositioning efficiency = 0.93, and manning level = 1.3. Determine how many workers and workstations must be on the production line in order to produce this workload.

**Solution:**  \[ WL = 10(45) + 20(35) + 30(25) = 450 + 700 + 750 = 1900 \text{ min/hr} \]

\[ AT = 60(0.95)(0.94)(0.93) = 49.83 \text{ min/hr per worker} \]

\[ w = \frac{1900}{49.83} = 38.1 \rightarrow 39 \text{ workers.} \quad \text{Since } M = 1.3, \quad n = w/M = 39/1.3 = 30 \text{ stations} \]

15.20 For Problem 15.18, determine the variable rate launching intervals for models A and B.

**Solution:** For product A, \[ T_{cv}(A) = \frac{32}{18(0.93684)(0.93)} = 2.040 \text{ min} \]

For product B, \[ T_{cv}(B) = \frac{19}{18(0.93684)(0.93)} = 1.211 \text{ min} \]

15.21 For Problem 15.19, determine the variable rate launching intervals for models A, B, and C.

**Solution:** For product A, \[ T_{cv}(A) = \frac{45}{39(0.94)(0.93)} = 1.320 \text{ min} \]

For product B, \[ T_{cv}(B) = \frac{35}{39(0.94)(0.93)} = 1.027 \text{ min} \]

For product C, \[ T_{cv}(C) = \frac{25}{39(0.94)(0.93)} = 0.733 \text{ min} \]

15.22 For Problem 15.18, determine (a) the fixed rate launching interval, and (b) the launch sequence of models A and B during one hour of production.

**Solution:** \[ R_p = 12 + 20 = 32 \text{/hr.} \quad T_{cf} = \frac{1}{36}(15x32 + 21x19) = 1.557 \text{ min} \]

If product A launched, \[ T_{cjh} = T_{cAh} = \frac{32}{18(0.93684)(0.93)} = 2.040 \text{ min} \]

If product B launched, \[ T_{cjh} = T_{cBh} = \frac{19}{18(0.93684)(0.93)} = 1.211 \text{ min} \]

Note that the hourly production rates of the two models (12/hr for A and 20/hr for B) are both divisible by 4 (3 per 15 min for A and 5 per 15 min for B). Thus the sequence repeats every 8 launches. The following table indicates the solution for two cycles (16 launches):

<table>
<thead>
<tr>
<th>((\Sigma T_{cAh}-mT_{j})^2)</th>
<th>((\Sigma T_{cBh}-mT_{j})^2)</th>
<th>A or B</th>
<th>(\Sigma T_{cjh})</th>
<th>(\Sigma T_{cf})</th>
<th>(T_{cAh})</th>
<th>(T_{cBh})</th>
<th>(T_{cf})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.212</td>
<td>0.077</td>
<td>B</td>
<td>1.407</td>
<td>1.684</td>
<td>2.144</td>
<td>1.407</td>
<td>1.684</td>
</tr>
<tr>
<td><strong>0.033</strong></td>
<td>0.307</td>
<td>A</td>
<td>3.551</td>
<td>3.368</td>
<td>2.144</td>
<td>1.407</td>
<td>1.684</td>
</tr>
<tr>
<td>0.413</td>
<td><strong>0.009</strong></td>
<td>B</td>
<td>4.958</td>
<td>5.052</td>
<td>2.144</td>
<td>1.407</td>
<td>1.684</td>
</tr>
<tr>
<td><strong>0.134</strong></td>
<td>0.138</td>
<td>A</td>
<td>7.102</td>
<td>6.736</td>
<td>2.144</td>
<td>1.407</td>
<td>1.684</td>
</tr>
<tr>
<td>0.682</td>
<td><strong>0.008</strong></td>
<td>B</td>
<td>8.509</td>
<td>8.42</td>
<td>2.144</td>
<td>1.407</td>
<td>1.684</td>
</tr>
</tbody>
</table>
For Problem 15.19, determine (a) the fixed rate launching interval, and (b) the launch sequence of models A, B, and C during one hour or production.

Solution: $R_p = 10 + 20 + 30 = 60/\text{hr}$. $T_{cf} = \frac{1}{60} \left(10 \times 45 + 20 \times 35 + 30 \times 25\right) = 0.929 \text{ min}$

If product A launched, $T_{cjh} = T_{cA}h = 45 \times 39(0.93)(0.94) = 1.320 \text{ min}$

If product B launched, $T_{cjh} = T_{cB}h = 35 \times 39(0.94)(0.93) = 1.027 \text{ min}$

If product C launched, $T_{cjh} = T_{cC}h = 25 \times 39(0.94)(0.93) = 0.733 \text{ min}$

We note that the hourly production rates of the three models (10/hr for A and 20/hr for B and 30/hr for C) are all divisible by 10 (1 per 6 min for A, 2 per 6 min for B, and 3 per 6 min for C).

Thus the sequence should repeat every 6 launches. The following table indicates the solution for one cycle (see equations for first three columns following launching sequence):

<table>
<thead>
<tr>
<th>Eq. A</th>
<th>Eq. B</th>
<th>Eq. C</th>
<th>A, B, or C</th>
<th>$\Sigma T_{cjh}$</th>
<th>$\Sigma T_{cf}$</th>
<th>$T_{cA}h$</th>
<th>$T_{cB}h$</th>
<th>$T_{cC}h$</th>
<th>$T_{cf}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.15</td>
<td>1.01</td>
<td>1.04</td>
<td>B</td>
<td>1.03</td>
<td>0.93</td>
<td>1.320</td>
<td>1.027</td>
<td>0.733</td>
<td>0.929</td>
</tr>
<tr>
<td>1.24</td>
<td>2.04</td>
<td>1.01</td>
<td>C</td>
<td>1.76</td>
<td>1.86</td>
<td>1.320</td>
<td>1.027</td>
<td>0.733</td>
<td>0.929</td>
</tr>
<tr>
<td>1.09</td>
<td>2.00</td>
<td>1.59</td>
<td>A</td>
<td>3.08</td>
<td>2.79</td>
<td>1.320</td>
<td>1.027</td>
<td>0.733</td>
<td>0.929</td>
</tr>
<tr>
<td>100</td>
<td>2.15</td>
<td>1.51</td>
<td>C</td>
<td>3.81</td>
<td>3.72</td>
<td>1.320</td>
<td>1.027</td>
<td>0.733</td>
<td>0.929</td>
</tr>
<tr>
<td>100</td>
<td>2.04</td>
<td>3.01</td>
<td>B</td>
<td>4.84</td>
<td>4.65</td>
<td>1.320</td>
<td>1.027</td>
<td>0.733</td>
<td>0.929</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>3.00</td>
<td>C</td>
<td>5.57</td>
<td>5.57</td>
<td>1.320</td>
<td>1.027</td>
<td>0.733</td>
<td>0.929</td>
</tr>
</tbody>
</table>

Eq. A: $\left(\Sigma T_{cjh} - mT_{cf}\right) + \frac{R_p}{Q_{bm}}$

Eq. B: $\left(\Sigma T_{cjh} - mT_{cf}\right) + \frac{R_p}{Q_{bm}}$

Eq. C: $\left(\Sigma T_{cjh} - mT_{cf}\right) + \frac{R_c}{Q_{cm}}$

15.24 Two models A and B are to be assembled on a mixed model line. Hourly production rates for the two models are: A, 30 units/hr; and B, 20 units/hr. The work elements, element times, and precedence requirements are given in the table below. Elements 6 and 8 are not required for model A, and elements 4 and 7 are not required for model B. Assume $E = 1.0$, $E_r = 1.0$, and $M = 1$. (a) Construct the precedence diagram for each model and for both models combined into one diagram. (b) Find the theoretical minimum number of workstations required to achieve the required production rate. (c) Use the Kilbridge and Wester method to solve the line balancing problem. (d) Determine the balance efficiency for your solution in (c).
**Solution:** (a) Precedence diagrams.

![Model A: 25 units/hr](image1)

![Model B: 18 units/hr](image2)

(b) Minimum number of workstations to achieve production rates for A and B.

<table>
<thead>
<tr>
<th>Element k</th>
<th>$R_{pk}$</th>
<th>$T_{ck}$</th>
<th>$R_{pk} T_{ck}$</th>
<th>$\Sigma R_{pk} T_{ck}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.0 min</td>
<td>10.0 min</td>
<td>25 min</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>9.0 min</td>
<td>6.0 min</td>
<td>15 min</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>21.0 min</td>
<td>16.0 min</td>
<td>37 min</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>12.0 min</td>
<td>-</td>
<td>12 min</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>36.0 min</td>
<td>26.0 min</td>
<td>62 min</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>8.0 min</td>
<td>8 min</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>18.0 min</td>
<td>-</td>
<td>18 min</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>14.0 min</td>
<td>14 min</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>15.0 min</td>
<td>10.0 min</td>
<td>25 min</td>
<td>Total = 216.0 min</td>
</tr>
</tbody>
</table>

Given $M = 1, E = 1, E_r = 1$, therefore, $AT = 60$ min,

\[
n = \frac{216.0}{60} = 3.6 \rightarrow 4 \text{ stations.}
\]
(c) Kilbridge & Wester method to solve line balancing problem (We must use $TT_i = 62$ min because the $TT_k$ value for element 5 is 62 min):

<table>
<thead>
<tr>
<th>Element</th>
<th>Allocation of elements to workstations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Station</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>9</td>
</tr>
</tbody>
</table>

(d) Maximum $\{TT_{si}\} = 62$ min $E_b = \frac{216}{4(62)} = 0.871 = 87.1\%$

15.25 For the data given in previous Problem 15.24, solve the mixed model line balancing problem except use the ranked positional weights method to determine the order of entry of work elements.

Solution: (a) and (b) Same solution as Problem 15.24 (a) and (b).

(c) Ranked positional weights method to solve line balancing problem (We must use $TT_s = 62$ min because the $TT_k$ value for element 5 is 62 min):

<table>
<thead>
<tr>
<th>Element</th>
<th>Ranked positional weights</th>
<th>Station</th>
<th>Element</th>
<th>$TT_k$</th>
<th>$TT_{si}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>126 90 216</td>
<td>1</td>
<td>1</td>
<td>25 min</td>
<td>216 min</td>
</tr>
<tr>
<td>3</td>
<td>90 74 164</td>
<td>3</td>
<td>3</td>
<td>37 min</td>
<td>62 min</td>
</tr>
<tr>
<td>2</td>
<td>90 56 146</td>
<td>2</td>
<td>2</td>
<td>15 min</td>
<td>62 min</td>
</tr>
<tr>
<td>5</td>
<td>69 50 119</td>
<td>4</td>
<td>4</td>
<td>12 min</td>
<td>35 min</td>
</tr>
<tr>
<td>4</td>
<td>45 - 45</td>
<td>7</td>
<td>7</td>
<td>18 min</td>
<td>45 min</td>
</tr>
<tr>
<td>7</td>
<td>33 - 33</td>
<td>3</td>
<td>5</td>
<td>62 min</td>
<td>62 min</td>
</tr>
<tr>
<td>6</td>
<td>- 32 32</td>
<td>6</td>
<td>6</td>
<td>8 min</td>
<td>32 min</td>
</tr>
<tr>
<td>9</td>
<td>15 10 25</td>
<td>8</td>
<td>8</td>
<td>14 min</td>
<td>25 min</td>
</tr>
<tr>
<td>8</td>
<td>- 24 24</td>
<td>9</td>
<td>9</td>
<td>25 min</td>
<td>47 min</td>
</tr>
</tbody>
</table>

(d) Maximum $\{TT_{si}\} = 62$ min $E_b = \frac{216}{4(62)} = 0.871 = 87.1\%$

15.26 Three models A, B, and C are to be assembled on a mixed model line. Hourly production rates for the three models are: A, 15 units/hr; B, 10 units/hr; and C, 5 units/hr. The work elements, element times, and precedence requirements are given in the table below. Assume $E = 1.0$, $E_r = 1.0$, and $M_i = 1$. (a) Construct the precedence diagram for each model and for all three models combined into one diagram. (b) Find the theoretical minimum number of workstations required to achieve the required production rate. (c) Use the Kilbridge and Wester method to solve the line balancing problem. (d) Determine the balance efficiency for the solution in (c).

<table>
<thead>
<tr>
<th>Element</th>
<th>$T_{eAk}$</th>
<th>Preceded by</th>
<th>$T_{eBk}$</th>
<th>Preceded by</th>
<th>$T_{eCk}$</th>
<th>Preceded by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.6 min</td>
<td>-</td>
<td>0.6 min</td>
<td>-</td>
<td>0.6 min</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.5 min</td>
<td>1</td>
<td>0.5 min</td>
<td>1</td>
<td>0.5 min</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0.9 min</td>
<td>1</td>
<td>0.9 min</td>
<td>1</td>
<td>0.9 min</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>0.5 min</td>
<td>1</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td></td>
<td>0.6 min</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Solution: (a) Precedence diagrams:

Model A: 15 units/hr

Model B: 10 units/hr

Model C: 5 units/hr

Combined: A + B + C

(b) Given $M = 1$, $E = 1$, $E_r = 1$, and therefore, $AT = 60$ min,

$$n = w = \text{Minimum Integer } \geq \frac{15(4.8) + 10(6.2) + 5(6.6)}{60} = 2.78 \rightarrow 3 \text{ workplaces and 3 workers}$$

(c) Computation of workload:
<table>
<thead>
<tr>
<th>Element $k$</th>
<th>$R_{pA} T_{eAk}$</th>
<th>$R_{pB} T_{eBk}$</th>
<th>$R_{pC} T_{eCk}$</th>
<th>$\Sigma R_{p} T_{ejk}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.0 min</td>
<td>6.0 min</td>
<td>3.0 min</td>
<td>18.0 min</td>
</tr>
<tr>
<td>2</td>
<td>7.5 min</td>
<td>5.0 min</td>
<td>2.5 min</td>
<td>15.0 min</td>
</tr>
<tr>
<td>3</td>
<td>13.5 min</td>
<td>9.0 min</td>
<td>4.5 min</td>
<td>27.0 min</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>5.0 min</td>
<td>-</td>
<td>5.0 min</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>-</td>
<td>3.0 min</td>
<td>3.0 min</td>
</tr>
<tr>
<td>6</td>
<td>10.5 min</td>
<td>7.0 min</td>
<td>3.5 min</td>
<td>21.0 min</td>
</tr>
<tr>
<td>7</td>
<td>19.5 min</td>
<td>13.0 min</td>
<td>6.5 min</td>
<td>39.0 min</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>9.0 min</td>
<td>-</td>
<td>9.0 min</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>6.0 min</td>
<td>6.0 min</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>12.0 min</td>
<td>8.0 min</td>
<td>4.0 min</td>
<td>24.0 min</td>
</tr>
</tbody>
</table>

Line balancing solution using Kilbridge & Wester method:

<table>
<thead>
<tr>
<th>Element</th>
<th>$TT_k$</th>
<th>Column</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18 min</td>
<td>I</td>
</tr>
<tr>
<td>3</td>
<td>27 min</td>
<td>II</td>
</tr>
<tr>
<td>2</td>
<td>15 min</td>
<td>II</td>
</tr>
<tr>
<td>5</td>
<td>5 min</td>
<td>II</td>
</tr>
<tr>
<td>4</td>
<td>3 min</td>
<td>II</td>
</tr>
<tr>
<td>7</td>
<td>39 min</td>
<td>III</td>
</tr>
<tr>
<td>6</td>
<td>21 min</td>
<td>III</td>
</tr>
<tr>
<td>8</td>
<td>9 min</td>
<td>III</td>
</tr>
<tr>
<td>9</td>
<td>6 min</td>
<td>III</td>
</tr>
<tr>
<td>10</td>
<td>24 min</td>
<td>IV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station</th>
<th>Element</th>
<th>$TT_k$</th>
<th>$TT_{si}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>18 min</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>27 min</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>15 min</td>
<td>60 min</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>5 min</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>3 min</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>39 min</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>9 min</td>
<td>56 min</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>21 min</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>6 min</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>24 min</td>
<td>51 min</td>
</tr>
</tbody>
</table>

(d) Balance efficiency $E_b = \frac{167}{3(60)} = 0.928 = 92.8\%$

15.27 For the data given in previous Problem 15.26, (a) solve the mixed model line balancing problem except that line efficiency = 0.96 and repositioning efficiency = 0.95. (b) Determine the balance efficiency for your solution.

Solution: (a) Available time per station = 60(0.96)(0.95) = 54.72 min. Use same list of elements by column as in Problem 15.26.
Assembly Lines-3e-SI  07-05/06, 06/04/07, 09/16/07

(b) Balance efficiency $E_b = \frac{167}{4(54)} = 0.773 = 77.3\%$

15.28 For Problem 15.26, determine (a) the fixed rate launching interval and (b) the launch sequence of models A, B, and C during one hour of production.

**Solution:** (a) $R_p = 15 + 10 + 5 = 30$ units/hr

$$T_{cf} = \frac{1}{30} \left( \frac{15 \times 4.8 + 10 \times 6.2 + 5 \times 6.6}{3(1.0)(0.928)} \right) = 2.000$ min

If model A launched, $T_{cAh} = \frac{4.8}{3(0.928)} = 1.724$ min $R_{pA} = 3$

If model B launched, $T_{cBh} = \frac{6.2}{3(0.928)} = 2.227$ min $R_{pB} = 2$

If model C launched, $T_{cCh} = \frac{6.6}{3(0.928)} = 2.371$ min $R_{pB} = 1$

We note that the hourly production rates of the three models (15/hr for A and 10/hr for B and 5/hr for C) are all divisible by 5 (3 per 12 min for A, 2 per 12 min for B, and 1 per 12 min for C). Thus the sequence should repeat every 6 launches, 5 times each hour. The following table indicates the solution for one cycle (see equations for first three columns following launching sequence):

<table>
<thead>
<tr>
<th>Eq. A</th>
<th>Eq. B</th>
<th>Eq. C</th>
<th>A,B,or C</th>
<th>$\Sigma T_{cAh}$</th>
<th>$\Sigma T_{cBh}$</th>
<th>$\Sigma T_{cCh}$</th>
<th>$\Sigma T_{cf}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.076</td>
<td>1.052</td>
<td>1.138</td>
<td>B</td>
<td>2.23</td>
<td>1.724</td>
<td>2.371</td>
<td>2.000</td>
</tr>
<tr>
<td>1.002</td>
<td>2.206</td>
<td>1.358</td>
<td>A</td>
<td>3.95</td>
<td>1.724</td>
<td>2.371</td>
<td>2.000</td>
</tr>
<tr>
<td>1.606</td>
<td>2.032</td>
<td>1.104</td>
<td>C</td>
<td>6.32</td>
<td>1.724</td>
<td>2.371</td>
<td>2.000</td>
</tr>
<tr>
<td>1.502</td>
<td>2.301</td>
<td>100.48</td>
<td>A</td>
<td>8.05</td>
<td>1.724</td>
<td>2.371</td>
<td>2.000</td>
</tr>
<tr>
<td>3.053</td>
<td>2.075</td>
<td>100.17</td>
<td>B</td>
<td>10.27</td>
<td>1.724</td>
<td>2.371</td>
<td>2.000</td>
</tr>
<tr>
<td>3.000</td>
<td>100.25</td>
<td>100.41</td>
<td>A</td>
<td>12.00</td>
<td>1.724</td>
<td>2.371</td>
<td>2.000</td>
</tr>
</tbody>
</table>

**Equation A:**

$$\left( \Sigma T_{cAh} - mT_{cf} \right) + \frac{R_{pA}}{Q_{fm}}$$

**Equation B:**

$$\left( \Sigma T_{cBh} - mT_{cf} \right) + \frac{R_{pB}}{Q_{fm}}$$

**Equation C:**

$$\left( \Sigma T_{cCh} - mT_{cf} \right) + \frac{R_{pC}}{Q_{fm}}$$

15.29 Two similar models, A and B, are to be produced on a mixed model assembly line. There are four workers and four stations on the line ($M_i = 1$ for $i = 1, 2, 3, 4$). Hourly production rates for the two models are: for A, 7 units/hr; and for B, 5 units/hr. The work elements, element times, and precedence requirements for the two models are given in the table below. As the table indicates, most elements are common to both models. Element 5 is unique to model A, while elements 8 and 9 are unique to model B. Assume $E_r = 1.0$ and $E_r = 1.0$. (a) Develop the mixed model precedence diagram for the two models and for both models combined. (b) Determine a line balancing solution that allows the two models to be produced on the four stations at the specified rates. (c) Using your solution from (b), solve the fixed rate model launching problem by determining the fixed rate launching interval and constructing a table to show the sequence of model launchings during the hour.

<table>
<thead>
<tr>
<th>Work element k</th>
<th>$T_{cek}$</th>
<th>Preceded by:</th>
<th>$T_{cek}$</th>
<th>Preceded by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 min</td>
<td>-</td>
<td>1 min</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>3 min</td>
<td>1</td>
<td>3 min</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>4 min</td>
<td>1</td>
<td>4 min</td>
<td>1, 8</td>
</tr>
</tbody>
</table>
**Solution:** (a) Precedence diagrams:

(b) Preliminary computations for line balancing solution. We will use the Kilbridge & Wester method. Given $R_{pA} = 7$ units/hr, $R_{pB} = 5$ units/hr.

<table>
<thead>
<tr>
<th>Element k</th>
<th>$T_{eA}$</th>
<th>$T_{eB}$</th>
<th>$R_{pA} T_{eA}$</th>
<th>$R_{pB} T_{eB}$</th>
<th>$\Sigma R_{pA} T_{eA}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 min</td>
<td>1 min</td>
<td>7 min</td>
<td>5 min</td>
<td>12 min</td>
</tr>
<tr>
<td>2</td>
<td>3 min</td>
<td>3 min</td>
<td>21 min</td>
<td>15 min</td>
<td>36 min</td>
</tr>
</tbody>
</table>
Given $M = 1$, $E = 1$, $E_r = 1$, and therefore, $AT = 60$ min, 

\[ n = w = \text{Minimum Integer} \geq \frac{217}{60} = 3.62 \rightarrow 4 \text{ stations}. \] 4 stations given.

(c) Kilbridge & Wester method to solve line balancing problem ($TT_s = 60$ min):

<table>
<thead>
<tr>
<th>List of elements by column</th>
<th>Allocation of elements to workstations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element</td>
<td>$TT_k$</td>
</tr>
<tr>
<td>1</td>
<td>12 min</td>
</tr>
<tr>
<td>8</td>
<td>20 min</td>
</tr>
<tr>
<td>2</td>
<td>36 min</td>
</tr>
<tr>
<td>3</td>
<td>48 min</td>
</tr>
<tr>
<td>4</td>
<td>24 min</td>
</tr>
<tr>
<td>5</td>
<td>7 min</td>
</tr>
<tr>
<td>6</td>
<td>24 min</td>
</tr>
<tr>
<td>7</td>
<td>36 min</td>
</tr>
<tr>
<td>9</td>
<td>10 min</td>
</tr>
</tbody>
</table>

217 min

Line balance efficiency. Using maximum\{TT_{si}\} = 60 min \(E_b = \frac{217}{4(0.904)} = 90.4\%\)

(c) Fixed rate launching schedule. \(R_p = 7 + 5 = 12/\text{hr.}\)

\[ T_{cf} = \frac{1}{12}(7 \times 16 + 5 \times 21) = 5.00 \text{ min} \]

If product A launched, \(T_{cjh} = T_{cAh} = \frac{16}{4(0.904)} = 4.424 \text{ min}\)

If product B launched, \(T_{cjh} = T_{cBh} = \frac{21}{4(0.904)} = 5.806 \text{ min}\)

The following table indicates the solution for one cycle (one hour). The cycle repeats every hour.

<table>
<thead>
<tr>
<th>$(\Sigma T_{cAh} - mT_{c})^2$</th>
<th>$(\Sigma T_{cBh} - mT_{c})^2$</th>
<th>A or B</th>
<th>$\Sigma T_{cjh}$</th>
<th>$\Sigma T_{cBh}$</th>
<th>$T_{cAh}$</th>
<th>$T_{cBh}$</th>
<th>$T_{cf}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.332</td>
<td>0.650</td>
<td>A</td>
<td>4.424</td>
<td>5</td>
<td>4.424</td>
<td>5.806</td>
<td>5</td>
</tr>
<tr>
<td>1.327</td>
<td>0.053</td>
<td>B</td>
<td>10.23</td>
<td>10</td>
<td>4.424</td>
<td>5.806</td>
<td>5</td>
</tr>
<tr>
<td><strong>0.120</strong></td>
<td>1.073</td>
<td>A</td>
<td>14.654</td>
<td>15</td>
<td>4.424</td>
<td>5.806</td>
<td>5</td>
</tr>
<tr>
<td>0.850</td>
<td>0.212</td>
<td>B</td>
<td>20.46</td>
<td>20</td>
<td>4.424</td>
<td>5.806</td>
<td>5</td>
</tr>
<tr>
<td><strong>0.013</strong></td>
<td>1.603</td>
<td>A</td>
<td>24.884</td>
<td>25</td>
<td>4.424</td>
<td>5.806</td>
<td>5</td>
</tr>
<tr>
<td>0.479</td>
<td>0.476</td>
<td>B</td>
<td>30.69</td>
<td>30</td>
<td>4.424</td>
<td>5.806</td>
<td>5</td>
</tr>
<tr>
<td><strong>0.013</strong></td>
<td>2.238</td>
<td>A</td>
<td>35.114</td>
<td>35</td>
<td>4.424</td>
<td>5.806</td>
<td>5</td>
</tr>
<tr>
<td><strong>0.213</strong></td>
<td>0.846</td>
<td>A</td>
<td>39.538</td>
<td>40</td>
<td>4.424</td>
<td>5.806</td>
<td>5</td>
</tr>
<tr>
<td>1.077</td>
<td><strong>0.118</strong></td>
<td>B</td>
<td>45.344</td>
<td>45</td>
<td>4.424</td>
<td>5.806</td>
<td>5</td>
</tr>
</tbody>
</table>
Workstation Considerations

15.30 An overhead continuous conveyor is used to carry dishwasher base parts along a manual assembly line. The spacing between appliances = 2.2 m and the speed of the conveyor = 1.2 m/min. The length of each workstation is 2.75 m. There are a total of 28 stations and 33 workers on the line. Determine (a) elapsed time a dishwasher base part spends on the line, (b) feed rate, and (c) tolerance time.

Solution: (a) \( L = 28(2.75) = 77.0 \) m, \( ET = \frac{77}{1.2} = 64.1667 \) min

(b) \( f_p = \frac{1.2}{2.2} = 0.5455 \) parts/min

(c) \( T_t = \frac{2.75}{1.2} = 2.292 \) min/station

15.31 A moving belt line is used to assemble a product whose work content = 20 min. Production rate = 48 units/hour, and the proportion uptime = 0.96. The length of each station = 5 ft and manning level = 1.0. The belt speed can be set at any value between 1.0 and 6.0 ft/min. It is expected that the balance delay will be about 0.08 or slightly higher. Time lost for repositioning each cycle is 3 seconds. (a) Determine the number of stations needed on the line. (b) Using a tolerance time that is 50% greater than the cycle time, what would be an appropriate belt speed and spacing between parts?

Solution: (a) \( T_c = \frac{60(0.96)}{48} = 1.2 \) min

\( T_s = 1.2 - 0.05 = 1.15 \) min and \( E_b = 1 - 0.07 = 0.93 \)

Since \( M = 1.0, n = w = \) Minimum Integer \( \geq \frac{20.0}{0.93(1.15)} = 18.7 \rightarrow 19 \) workstations

(b) Use \( T_t = 1.5 T_c = 1.5(1.2) = 1.8 \) min/station

\( T_t = \frac{L}{V_c} \). Rearranging, \( V_c = \frac{L}{T_t} = \frac{5\text{ft}}{1.8\text{min}} = 2.778 \text{ ft/min} \)

\( T_c = \frac{s_p}{V_c} \). Rearranging, \( s_p = T_c V_c = 1.2(2.778) = 3.33 \) ft/part

15.32 In the general assembly department of an automobile final assembly plant, there are 500 workstations, and the cycle time = 0.95 min. If each workstation is 6.2 m long, and the tolerance time = the cycle time, determine the following: (a) speed of the conveyor, (b) center-to-center spacing between units on the line, (c) total length of the general assembly line, assuming no vacant space between stations, and (d) elapsed time a work unit spends in the general assembly department.

Solution: (a) \( T_t = T_c = 0.95 \) min

\( V_c = \frac{L}{T_t} = \frac{6.2}{0.95} = 6.52 \) m/min

(b) \( s_p = V_c T_c = 6.52(0.95) = 6.194 \) m/car

(c) \( L = 500(6.194) = 3097 \) m

(d) \( ET = \frac{L}{V_c} = \frac{3097}{6.52} = 475 \) min

Alternative method: \( ET = n T_t = 500(0.95) = 475 \) min
15.33 Total work content for a product assembled on a manual production line is 44.0 min. Production rate of the line must be 47 units/hr. Work units are attached to a moving conveyor whose speed = 7.5 ft/min. Repositioning time per worker is 6 sec, and uptime efficiency of the line is 94%. Due to imperfect line balancing, the number of workers needed on the line must be four more workers than the number required for perfect balance. Manning level = 1.5. Determine (a) the number of workers and (b) the number of workstations on the line. (c) What is the balance efficiency for this line? (d) If the workstations are arranged in a line, and the length of each station is 11 ft, what is the tolerance time in each station? (e) What is the elapsed time a work unit spends on the line?

Solution: (a) $T_c = \frac{60(0.94)}{47} = 1.2 \text{ min}$, $T_s = 1.2 - 0.1 = 1.1 \text{ min}$

For perfect balance, $E_b = 1.0$. $w = \text{Minimum Integer} \geq \frac{44.0}{1.0(1.1)} = 40 \text{ workers}$.

With 4 more workers than required for perfect balance, $w = 40 + 4 = 44 \text{ workers}$.

(b) $n = \frac{w}{M} = \frac{44}{1.5} = 29.33 \text{ rounded up to } 30 \text{ stations}$

(c) $d = \frac{44(1.1) - 44.0}{44(1.1)} = 0.091 = 9.1\%$

(d) $T_e = \frac{11}{7.5} = 1.467 \text{ min}$

(e) $ET = 30(1.467) = 44 \text{ min}$

Alternative method: $L = (30 \text{ stations})(11 \text{ ft/station}) = 330 \text{ ft}$, $ET = 330/7.5 = 44 \text{ min}$

15.34 A manual assembly line is to be designed for a certain major appliance whose assembly work content time = 2.0 hours. The line will be designed for an annual production rate of 150,000 units. The plant will operate one 10-hour shift per day, 250 days per year. A continuous conveyor system will be used and it will operate at a speed = 1.6 m/min. The line must be designed under the following assumptions: balance delay = 6.5%, uptime efficiency = 96%, repositioning time = 6 sec for each worker, and average manning level = 1.25. (a) How many workers will be required to operate the assembly line? If each station is 2.0 m long, (b) how long will the production line be, and (c) what is the elapsed time a work unit spends on the line?

Solution: (a) $R_p = \frac{150,000}{250(10)} = 60 \text{ pc/hr}$

$T_c = \frac{60(0.96)}{60} = 0.96 \text{ min}$, $T_s = 0.96 - 0.1 = 0.86 \text{ min}$

$w = \text{Minimum Integer} \geq \frac{2(60)}{(1 - 0.065)(0.86)} = 149.2 \rightarrow 150 \text{ workers}$

(b) $n = \frac{150}{1.25} = 120 \text{ stations}$, $L = (120 \text{ stations})(2 \text{ m/station}) = 240 \text{ m}$

(c) $ET = \frac{240}{1.6} = 150 \text{ min}$
Chapter 16
AUTOMATED PRODUCTION LINES

REVIEW QUESTIONS

16.1 Name three of the four conditions under which automated production lines are appropriate.

   **Answer:** The four conditions listed in the text are (1) high product demand, (2) stable product design, (3) long product life, and (4) multiple operations are required to produce the product.

16.2 What is an automated production line?

   **Answer:** As defined in the text, an automated production line consists of multiple workstations that are automated and linked together by a work handling system that transfers parts from one station to the next.

16.3 What is a pallet fixture, as the term is used in the context of an automated production line?

   **Answer:** As defined in the text, a pallet fixture is a workholding device that is designed to (1) fixture the part in a precise location relative to its base and (2) be moved, located, and accurately clamped in position at successive workstations by the transfer system.

16.4 What is a dial-indexing machine?

   **Answer:** A dial-indexing machine is an automated system consisting of multiple workstations that process workparts attached to fixtures around the periphery of a circular worktable, and the table is indexed (rotated in fixed angular amounts) to position the parts at the stations.

16.5 Why are continuous work transport systems uncommon on automated production lines?

   **Answer:** Continuous work transport systems are uncommon on automated lines due to the difficulty in providing accurate registration between the station workheads and the continuously moving parts.

16.6 Is a Geneva mechanism used to provide linear motion or rotary motion?

   **Answer:** A Geneva mechanism provides rotary motion.

16.7 What is a storage buffer as the term is used for an automated production line?

   **Answer:** As defined in the text, a storage buffer is a location in a production line where parts can be collected and temporarily stored before proceeding to subsequent (downstream) workstations.

16.8 Name three reasons for including a storage buffer in an automated production line?

   **Answer:** The text lists the following five reasons: (1) to reduce the effect of station breakdowns, (2) to provide a bank of parts to supply the line, (3) to provide a place to put the output of the line, (4) to allow for curing time or other required delay associated with processing, and (5) to smooth cycle time variations.

16.9 What are the three basic control functions that must be accomplished to operate an automated production line?

   **Answer:** The three basic control functions are (1) sequence control to coordinate the sequence of actions of the transfer system and associated workstations, (2) safety monitoring to ensure that the production line does not operate in an unsafe condition, and (3) quality control to monitor certain quality attributes of the workparts produced on the line.

16.10 Name some of the industrial applications of automated production lines.

   **Answer:** Applications listed in the text include machining, sheet metal forming and cutting, spot welding of car bodies in final assembly plants, painting and plating operations, and assembly.

16.11 What is the difference between a unitized production line and a link line?

   **Answer:** A unitized production line is an automated production line that consists of standard modules and is assembled in an appropriate configuration to satisfy the production requirements of the customer. A link line is a production line that consists of standard machine tools that are connected together by standard or special material handling devices.
16.12 What are the three problem areas that must be considered in the analysis and design of an automated production line?

**Answer**: The three problem areas identified in the text are (1) line balancing – the same basic problem as in manual assembly lines; (2) processing technology – cutting tool technology, speeds and feeds, and so on; and (3) system reliability – due to the complexity of an automated production line.

16.13 As the number of workstation on an automated production line increases, does line efficiency (a) decrease, (b) increase, or (c) remain unaffected?

**Answer**: (a). Line efficiency decreases because each additional station increases the probability of a line stop.

16.14 What is starving on an automated production line?

**Answer**: Starving on an automated production line means that a workstation is prevented from performing its cycle because it has no part to work on. When a breakdown occurs at any workstation on the line, the downstream stations will either immediately or eventually become starved for parts.

16.15 In the operation of an automated production line with storage buffers, what does it mean if a buffer is nearly always empty or nearly always full?

**Answer**: In the operation of an automated production line with storage buffers, if any of the buffers are nearly always empty or nearly always full, this indicates that the production rates of the stages on either side of the buffer are out of balance and that the storage buffer is serving little useful purpose.

**PROBLEMS**

**Transfer Mechanisms**

16.1 A rotary worktable is driven by a Geneva mechanism with five slots. The driver rotates at 48 rev/min. Determine (a) the cycle time, (b) available process time, and (c) indexing time each cycle.

**Solution**: (a) \( T_c = \frac{1}{N} = \frac{1}{48} = 0.020833 \text{ min} = 1.25 \text{ sec} \)

(b) \( \theta = \frac{360}{5} = 72^\circ \) \( T_s = \frac{180 + 72}{360(48)} = 0.01458333 \text{ min} = 0.875 \text{ sec} \)

(c) \( T_i = \frac{180 - 72}{360(48)} = 0.00625 \text{ min} = 0.375 \text{ sec} \)

16.2 A Geneva with six slots is used to operate the worktable of a dial-indexing machine. The slowest workstation on the dial-indexing machine has an operation time of 2.5 sec, so the table must be in a dwell position for this length of time. (a) At what rotational speed must the driven member of the Geneva mechanism be turned to provide this dwell time? (b) What is the indexing time each cycle?

**Solution**: (a) \( \theta = \frac{360}{6} = 60^\circ \) \( T_s = \frac{360 + 60}{360N} = \frac{0.667}{N} = 2.5 \text{ sec (given)} \)

\[ N = \frac{0.667}{2.5 \text{ sec}} = 0.2667 \text{ rev/sec} = 16 \text{ rev/min} \]

(b) \( T_i = \frac{180 - 60}{360(0.2667)} = 1.25 \text{ sec} \)

16.3 Solve the previous problem except that the Geneva has ten slots.

**Solution**: (a) \( \theta = \frac{360}{10} = 36^\circ \) \( T_s = \frac{180 + 36}{360N} = \frac{0.60}{N} = 2.5 \text{ sec (given)} \)

\[ N = \frac{0.60/2.5 = 0.241 \text{ rev/sec} = 14.4 \text{ rev/min}} \]
Automated Production Lines with No Internal Storage

16.4 A ten-station transfer machine has an ideal cycle time of 30 sec. The frequency of line stops is 0.075 stops per cycle. When a line stop occurs, the average downtime is 4.0 min. Determine (a) average production rate in pc/hr, (b) line efficiency, and (c) proportion downtime.

**Solution**: (a) \( T_p = 0.5 + 0.075(4) = 0.5 + 0.3 = 0.8 \text{ min} \)

\( R_p = \frac{1}{0.8} = 1.25 \text{ pc/min} = 75 \text{ pc/hr} \)

(b) \( E = \frac{0.5}{0.8} = 0.625 = 62.5\% \)

(c) \( D = \frac{0.3}{0.8} = 0.375 = 37.5\% \)

16.5 Cost elements associated with the operation of the ten-station transfer line in Problem 16.4 are as follows: raw workpart cost = $0.55/pc, line operating cost = $42.00/hr, and cost of disposable tooling = $0.27/pc. Compute the average cost of a workpiece produced.

**Solution**: Refers to Problem 16.4: \( C_{pc} = 0.55 + \frac{42(0.8)}{60} + 0.27 = 0.55 + 0.56 + 0.27 = $1.38/pc \)

16.6 In Problem 16.4, the line stop occurrences are due to random mechanical and electrical failures on the line. Suppose that in addition to these reasons for downtime, that the tools at each workstation on the line must be changed and/or reset every 125 cycles. This procedure takes a total of 15.0 min for all ten stations. Include this additional data to determine (a) average production rate in pc/hr, (b) line efficiency, and (c) proportion downtime.

**Solution**: Refers to Problem 16.4:

(a) \( F_1 T_d = 0.075(4.0) = 0.3 \text{ min} \)

\( F_2 T_d = \frac{15.00}{125} = 0.12 \text{ min} \)

\( T_p = 0.5 + 0.3 + 0.12 = 0.92 \text{ min} \)

\( R_p = \frac{1}{0.92} = 1.087 \text{ pc/min} = 65.22 \text{ pc/hr} \)

(b) \( E = \frac{0.5}{0.92} = 0.5435 \approx 54.35\% \)

(c) \( D = \frac{0.42}{0.92} = 0.4565 \approx 45.65\% \)

16.7 The dial indexing machine of Problem 16.2 experiences a breakdown frequency of 0.06 stops/cycle. The average downtime per breakdown is 3.5 min. Determine (a) average production rate in pc/hr and (b) line efficiency.

**Solution**: Refers to Problem 16.2:

(a) From Problem 16.2, \( T_c = T_o + T_r = 2.5 + 1.25 = 3.75 \text{ sec} \)

\( T_p = \frac{3.75}{60 + 0.06(3.5)} = 0.0625 + 0.021 = 0.2725 \text{ min} \)

\( R_p = \frac{1}{0.2725} = 3.67 \text{ pc/min} = 220.2 \text{ pc/hr} \)

(b) \( E = \frac{0.0625}{0.2725} = 0.2294 \approx 22.94\% \)

16.8 In the operation of a certain 15-station transfer line, the ideal cycle time = 0.58 min. Breakdowns occur at a rate of once every 20 cycles, and the average downtime per breakdown is 9.2 min. The transfer line is located in a plant that works an 8-hr day, 5 days per week. Determine (a) line efficiency, and (b) how many parts will the transfer line produce in a week?

**Solution**: (a) \( T_p = 0.58 + \frac{9.2}{20} = 0.58 + 0.46 = 1.04 \text{ min} \)

\( E = \frac{0.58}{1.04} = 0.5577 \approx 55.77\% \)

(b) \( R_p = \frac{60}{1.04} = 57.69 \text{ pc/hr} \quad \text{Weekly production} = 40(57.69) = 2307.7 \text{ pc/wk.} \)

16.9 A 22-station in-line transfer machine has an ideal cycle time of 0.58 min. Station breakdowns occur with a probability of 0.01. Assume that station breakdowns are the only reason for line stops. Average downtime = 8.0 min per line stop. Determine (a) ideal production rate, (b) frequency of line stops, (c) average actual production rate, and (d) line efficiency.
Transfer Lines-3e-SI  7-10/06, 06/04/07, 09/18/07

Solution: (a) \( R_c = \frac{1}{T_c} = \frac{1}{0.58} = 1.724 \text{ pc/min} = 103.45 \text{ pc/hr} \)

(b) \( F = np = 22(0.01) = 0.22 \)

(c) \( T_p = 0.58 + 0.22(8) = 0.58 + 1.76 = 2.34 \text{ min} \quad R_p = \frac{1}{2.34} = 0.4274 \text{ pc/min} = 25.64 \text{ pc/hr} \)

(d) \( E = \frac{0.58}{2.34} = 0.248 = 24.8\% \)

16.10 A ten-station rotary indexing machine performs nine machining operations at nine workstations, and the tenth station is used for loading and unloading parts. The longest process time on the line is 1.30 min and the loading/unloading operation can be accomplished in less time than this. It takes 9.0 sec to index the machine between workstations. Stations break down with a frequency of 0.007, which is considered equal for all ten stations. When these stops occur, it takes an average of 10.0 min to diagnose the problem and make repairs. Determine (a) line efficiency and (b) average actual production rate.

Solution: (a) \( F = np = 10(0.007) = 0.07 \)
\( T_c = 1.30 + 0.15 = 1.45 \text{ min} \)
\( T_p = 1.45 + 0.07(10) = 1.45 + 0.7 = 2.15 \text{ min/pc} \)
\( E = \frac{1.45}{2.15} = 0.674 = 67.4\% \)

(b) \( R_p = \frac{1}{2.15} = 0.465 \text{ pc/min} = 27.9 \text{ pc/hr} \)

16.11 A transfer machine has six stations that function as follows:

<table>
<thead>
<tr>
<th>Station</th>
<th>Operation</th>
<th>Process time</th>
<th>( p_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Load part</td>
<td>0.78 min</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Drill three holes</td>
<td>1.25 min</td>
<td>0.02</td>
</tr>
<tr>
<td>3</td>
<td>Ream two holes</td>
<td>0.90 min</td>
<td>0.01</td>
</tr>
<tr>
<td>4</td>
<td>Tap two holes</td>
<td>0.85 min</td>
<td>0.04</td>
</tr>
<tr>
<td>5</td>
<td>Mill flats</td>
<td>1.32 min</td>
<td>0.01</td>
</tr>
<tr>
<td>6</td>
<td>Unload parts</td>
<td>0.45 min</td>
<td>0</td>
</tr>
</tbody>
</table>

In addition, transfer time = 0.18 min. Average downtime per occurrence = 8.0 min. A total of 20,000 parts must be processed through the transfer machine. Determine (a) proportion downtime, (b) average actual production rate, and (c) how many hours of operation are required to produce the 20,000 parts.

Solution: (a) \( T_c = 1.32 + 0.18 = 1.50 \text{ min} \)
\( F = 0.02 + 0.01 + 0.04 + 0.01 = 0.08 \)
\( T_p = 1.50 + 0.08(8) = 1.50 + 0.64 = 2.14 \text{ min} \)
\( D = \frac{0.64}{2.14} = 0.299 = 29.9\% \)

(b) \( R_p = \frac{1}{2.14} = 0.467 \text{ pc/min} = 28.04 \text{ pc/hr} \)

(c) \( H = 20,000(2.14/60) = 713.3 \text{ hr} \)

16.12 The cost to operate a certain 20-station transfer line is $72/hr. The line operates with an ideal cycle time of 0.85 min. Downtime occurrences happen on average once per 12 cycles. Average downtime per occurrence is 10.5 min. It is proposed that a new computer system and associated sensors be installed to monitor the line and diagnose downtime occurrences when they happen. It is anticipated that this new system will reduce downtime from its present value to 7.5 min. If the cost of purchasing and installing the new system is $15,000, how many units must the system produce in order for the savings to pay for the computer system?

Solution: Current operation: \( T_p = 0.85 + \frac{1}{12}(10.5) = 0.85 + 0.85 = 1.70 \text{ min/pc} \)
\( C_{pc} = ($72.00/hr)(1.7/60) - $2.04/pc. \)
With computer system: \( T_p = 0.85 + \frac{1}{12}(7.5) = 0.85 + 0.625 = 1.475 \text{ min/pc} \)
\[ C_{pc} = (\$72.00/hr)(1.475/60) - \$1.77/pc \]
\[ 15,000 = (2.04 - 1.77) Q = 0.27 Q \]
\[ Q = 15,000/0.27 = 55,556 \text{ pc} \]

16.13 A 23-station transfer line has been logged for 5 days (total time = 2400 min). During this time there were a total of 158 downtime occurrences on the line. The accompanying table identifies the type of downtime occurrence, how many occurrences of each type, and how much total time was lost for each type. The transfer line performs a sequence of machining operations, the longest of which takes 0.42 min. The transfer mechanism takes 0.08 min to index the parts from one station to the next each cycle. Assuming no parts removal when the line jams, determine the following based on the five-day observation period: (a) how many parts were produced, (b) downtime proportion, (c) production rate, and (d) frequency rate associated with the transfer mechanism failures.

<table>
<thead>
<tr>
<th>Type of downtime</th>
<th>Number of occurrences</th>
<th>Total time lost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Associated with stations:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tool-related causes</td>
<td>104</td>
<td>520 min</td>
</tr>
<tr>
<td>Mechanical failures</td>
<td>21</td>
<td>189 min</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>7</td>
<td>84 min</td>
</tr>
<tr>
<td>Subtotal</td>
<td>132</td>
<td>793 min</td>
</tr>
<tr>
<td>Transfer mechanism</td>
<td>26</td>
<td>78 min</td>
</tr>
<tr>
<td>Totals</td>
<td>158</td>
<td>871 min</td>
</tr>
</tbody>
</table>

**Solution:**

(a) \[ T_e = 0.42 + 0.08 = 0.50 \text{ min} \]
\[ T_d = (793 + 78)/158 = 5.513 \text{ min} \]
\[ QT_p = QT_e + QFT_d = 2400 \text{ min} = 0.5Q + 158T_d \]
\[ 0.5Q + 158(5.513) = 2400 \]
\[ Q = 1529/5 = 3058 \text{ pc} \]

(b) \[ D = 871/2400 = 0.363 = 36.3\% \]

(c) \[ T_p = 2400 \text{ min}/3058 \text{ pc} = 0.785 \text{ min/pc}, R_p = 60/0.785 = 76.43 \text{ pc/hr} \]

(d) Transfer mechanism breakdown frequency: \( p = 26/3058 = 0.0085 \text{ breakdowns/pc} \)

16.14 An eight-station rotary indexing machine performs the machining operations shown in the accompanying table, together with processing times and breakdown frequencies for each station. The transfer time for the machine is 0.15 min per cycle. A study of the system was undertaken, during which time 2000 parts were completed. It was determined in this study that when breakdowns occur, it takes an average of 7.0 min to make repairs and get the system operating again. For the study period, determine (a) average actual production rate, (b) line uptime efficiency, and (c) how many hours were required to produce the 2000 parts.

<table>
<thead>
<tr>
<th>Station</th>
<th>Process</th>
<th>Process time</th>
<th>Breakdowns</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Load part</td>
<td>0.50 min</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Mill top</td>
<td>0.85 min</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>Mill sides</td>
<td>1.10 min</td>
<td>31</td>
</tr>
<tr>
<td>4</td>
<td>Drill two holes</td>
<td>0.60 min</td>
<td>47</td>
</tr>
<tr>
<td>5</td>
<td>Ream two holes</td>
<td>0.43 min</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>Drill six holes</td>
<td>0.92 min</td>
<td>58</td>
</tr>
<tr>
<td>7</td>
<td>Tap six holes</td>
<td>0.75 min</td>
<td>84</td>
</tr>
<tr>
<td>8</td>
<td>Unload part</td>
<td>0.40 min</td>
<td>0</td>
</tr>
</tbody>
</table>

**Solution:**

(a) \[ T_r = 1.10 + 0.15 = 1.25 \text{ min/cycle}, \]
\[ F = 250/2000 = 0.125 \]
\[ T_p = 1.25 + 0.125(7.0) = 2.125 \text{ min/pc} \]
\[ R_p = 60/2.125 = 28.2353 \text{ pc/hr} \]

(b) \[ E = 1.25/2.125 = 0.588 = 58.8\% \]
(c) Total time = 2000(1.25) + 250(7) = 4250 min = 70.83 hr

16.15 A 14-station transfer line has been logged for 2400 min to identify type of downtime occurrence, how many occurrences, and time lost. The results are presented in the table below. The ideal cycle time for the line is 0.80 min, including transfer time between stations. Determine (a) how many parts were produced during the 2400 min, (b) line uptime efficiency, (c) average actual production rate per hour, and (d) frequency p associated with transfer system failures.

<table>
<thead>
<tr>
<th>Type of occurrence</th>
<th>Number</th>
<th>Time lost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool changes and failures</td>
<td>70</td>
<td>350 min</td>
</tr>
<tr>
<td>Station failures: (mechanical and electrical)</td>
<td>45</td>
<td>300 min</td>
</tr>
<tr>
<td>Transfer system failures</td>
<td>25</td>
<td>150 min</td>
</tr>
</tbody>
</table>

Solution: Total downtime = 350 + 300 + 150 = 800 min
Number of downtime occurrences = 70 + 45 + 25 = 140 occurrences
(a) Total uptime = 2400 - 800 = 1600 min
Number of parts = (1600 min)/(0.80 min/pc) = 2000 pc
(b) \( E = \frac{1600}{2400} = 0.6667 = 66.67\% \)
(c) \( R_p = \frac{2000}{2400 \text{ min}} \cdot 60 = 50 \text{ pc/hr} \)
(d) Transfer system failures: \( p = \frac{25}{2000} = 0.0125 \)

16.16 A transfer machine has a mean time between failures (MTBF) = 50 minutes and a mean time to repair (MTTR) = 9 minutes. If the ideal cycle rate = 1/min (when the machine is running), what is the average hourly production rate?

Solution: \( T_c = \frac{1}{R_c} = 1 \text{ min/cycle} = 1.0 \text{ min/pc} \). Availability \( A = \frac{MTBF - MTTR}{MTBF} = \frac{50 - 9}{50} = 0.82 \)
\( E = A = 0.82 = 82\% \)
\( E = \frac{T_c}{T_p} \), therefore \( T_p = \frac{T_c}{E} = 1.0/0.82 = 1.2195 \text{ min/pc} \)
\( R_p = \frac{1}{1.2195} = 0.82 \text{ pc/min} = 49.2 \text{ pc/hr} \)

16.17 A part is to be produced on an automated transfer line. The total work content time to make the part is 36 minutes, and this work will be divided evenly amongst the workstations, so that the processing time at each station is \( \frac{36}{n} \), where \( n \) is the number of stations. In addition, the time required to transfer parts between workstations is 6 seconds. Thus, the cycle time = \( 0.1 + \frac{36}{n} \) minutes. In addition, it is known that the station breakdown frequency will be 0.005, and that the average downtime per breakdown = 8.0 minutes. (a) Given these data, determine the number of workstations that should be included in the line to maximize production rate. Also, what is the (b) production rate and (c) line efficiency for this number of stations?

Solution: (a) \( T_c = 0.1 + \frac{36}{n} \)
\( FT_d = pnT_d = 0.005n(8.0) = 0.04n \)
\( T_p = 0.1 + \frac{36}{n} + 0.04n \)
\( \frac{dT_p}{dn} = -\frac{36}{n^2} + 0.04 = 0 \), rearranging \( \frac{36}{n^2} = 0.04 \)
\( n^2 = 36 \cdot 0.04 = 900 \quad n = 30 \text{ stations} \)
(b) \( T_c = 0.1 + \frac{36}{30} + 0.04(30) = 0.1 + 1.2 = 2.5 \text{ min/pc} \).
\( R_p = \frac{1}{2.5} = \frac{0.4}{\text{pc/min}} = 24 \text{ pc/hr} \)
(c) \( E = (0.1 + 1.2)/2.5 = 1.3/2.5 = 0.52 = 52\% \)

Automated Production Lines with Storage Buffers

16.18 A 30-station transfer line has an ideal cycle time of 0.75 min, an average downtime of 8.0 min per line stop occurrence, and a station failure frequency of 0.01 for all stations. A proposal has been submitted to locate a storage buffer between stations 15 and 16 to improve line efficiency. Determine (a) the current line efficiency and production rate, and (b) the maximum possible line efficiency and production rate that would result from installing the storage buffer.
**Solution:** (a) $T_p = 0.75 + 30(0.01)(8.0) = 0.75 + 2.4 = 3.15 \text{ min}/\text{pc}$

$E = 0.75 / 3.15 = 0.238 = 23.8\%$

$R_p = 1 / 3.15 = 0.3175 \text{ pc/min} = 19.05 \text{ pc/hr}$

(b) $T_{p1} = T_{p2} = 0.75 + 15(0.01)(8.0) = 0.75 + 1.20 = 1.95 \text{ min}/\text{pc}.$

$E_\infty = 0.75 / 1.95 = 0.385 = 38.5\%$

$R_p = 1 / 1.95 = 0.5128 \text{ pc/min} = 30.77 \text{ pc/hr}$

---

16.19 Given the data in Problem 16.18, solve the problem except that (a) the proposal is to divide the line into three stages, that is, with two storage buffers located between stations 10 and 11, and between stations 20 and 21, respectively; and (b) the proposal is to use an asynchronous line with large storage buffers between every pair of stations on the line; that is a total of 29 storage buffers.

**Solution:** (a) $T_{p1} = T_{p2} = T_{p3} = 0.75 + 10(0.01)(8.0) = 0.75 + 0.80 = 1.55 \text{ min}/\text{pc}$

For each stage, $E = 0.75 / 1.55 = 0.484 = 48.4\%$

$R_p = 1 / 1.55 = 0.645 \text{ pc/min} = 38.71 \text{ pc/hr}$

(b) $T_{p1} = T_{p2} = \ldots = T_{p29} = 0.75 + 0.01(8.0) = 0.75 + 0.08 = 0.83 \text{ min}/\text{pc}$

For each stage, $E = 0.75 / 0.83 = 0.904 = 90.4\%$

$R_p = 1 / 0.83 = 1.205 \text{ pc/min} = 72.29 \text{ pc/hr}$

---

16.20 In Problem 16.18, if the capacity of the proposed storage buffer is to be 20 parts, determine (a) line efficiency, and (b) production rate of the line. Assume that the downtime ($T_d = 8.0 \text{ min}$) is a constant.

**Solution:** From previous Problem 16.18, $E_o = 0.238$ and $E_\infty = 0.385$

$D' = \frac{15(0.01)(8.0)}{1.0} = 3.15, \quad r = \frac{F_1}{F_2} = 1.0$

$h(20) = \frac{2}{2 + 1} + 4 \left( \frac{0.75}{8.0} \right)^{1 / (2 + 1)(2 + 2)} = \frac{2}{3} + \frac{4}{10.667} \left( \frac{1}{12} \right) = 0.6979$

$E = 0.238 + 0.381(0.6979)(0.385) = 0.3404 = 34.04\%$

(b) $R_p = \frac{E}{T_c} = \frac{0.3404}{0.75} = 0.4538 \text{ pc/min} = 27.23 \text{ pc/hr}$

---

16.21 Solve Problem 16.20 but assume that the downtime ($T_d = 8.0 \text{ min}$) follows the geometric repair distribution.

**Solution:** From previous Problem 16.20, $E_o = 0.238$ and $E_\infty = 0.385$

$D' = \frac{15(0.01)(8.0)}{1.0} = 3.15, \quad r = \frac{F_1}{F_2} = 1.0$

$h(20) = \frac{20(0.75 / 8.0)}{2 + (20 - 1)(0.75 / 8.0)} = \frac{1.875}{3.781} = 0.4959$

$E = 0.238 + 0.381(0.4959)(0.385) = 0.3107 = 31.07\%$

(b) $R_p = \frac{E}{T_c} = \frac{0.3107}{0.75} = 0.4143 \text{ pc/min} = 24.86 \text{ pc/hr}$

---

16.22 In the transfer line of Problems 16.18 and 16.20, suppose it is more technically feasible to locate the storage buffer between stations 11 and 12, rather than between stations 15 and 16. Determine (a) the maximum possible line efficiency and production rate that would result from installing the storage buffer, and (b) the line efficiency and production rate for a storage buffer with a capacity of 20 parts. Assume that downtime ($T_d = 6.0 \text{ min}$) is a constant.

**Solution:** $F_1 = 11(0.01) = 0.11, \quad T_{p1} = 0.75 + 0.11(8.0) = 0.75 + 0.88 = 1.63 \text{ min}/\text{pc}$

$F_2 = 19(0.01) = 0.19, \quad T_{p2} = 0.75 + 0.19(8.0) = 0.75 + 1.52 = 2.27 \text{ min}/\text{pc}$

$E_o = \text{Min}\{E_1, E_2\} = \text{Min}\{\{0.75 / 1.63\}, \{0.75 / 2.27\}\} = \text{Min}\{0.4601, 0.3304\} = 0.3304$

$R_p = 0.3304 / 0.75 = 0.4405 \text{ pc/min} = 26.43 \text{ pc/hr}$
A proposed synchronous transfer line will have 20 stations and will operate with an ideal cycle time of 0.5 min. All stations are expected to have an equal probability of breakdown, \( p = 0.01 \). The average downtime per breakdown is expected to be 5.0. An option under consideration is to divide the line into two stages, each stage having 10 stations, with a buffer storage zone between the stages. It has been decided that the storage capacity should be 20 units. The cost to operate the line is $96.00/hr. Installing the storage buffer would increase the line operating cost by $12.00/hr. Ignoring material and tooling costs, determine (a) line efficiency, production rate, and unit cost for the one-stage configuration, and (b) line efficiency, production rate, and unit cost for the optional two-stage configuration.

**Solution**:

(a) For the current line operation: 

\[
T_p = 0.5 + 20(0.01)(5) = 1.5 \text{ min}
\]

\[
E = \frac{0.5}{1.5} = 0.333 = 33.3\%
\]

\[
R_p = \frac{60}{1.5} = 40 \text{ pc/hr}
\]

\[
C_{pc} = \frac{20(4.80)}{40} = $2.40/pc
\]

(b) For the proposed two-stage line: 

\[
\frac{T_d}{T_c} = 10, \quad b = 20; \quad B = 2, \quad L = 0
\]

\[
h(25) = \frac{2}{3} = 0.6667
\]

\[
E_o = \frac{0.5}{1.5} = 0.3333, \quad E_2 = \frac{0.5}{1.0} = 0.5, \quad \text{and} \quad D'_1 = \frac{0.01(10)(10)}{1.5} = 0.3333
\]

\[
E = 0.3333 + 0.3333(0.6667)(5) = 0.4444
\]

\[
T_p = \frac{0.5}{0.4444} = 1.125 \text{ min}, \quad R_p = \frac{60}{1.125} = 53.33 \text{ pc/hr}
\]

\[
C_{pc} = \frac{(20 \times 4.80 + 12.00)}{53.33} = $2.025/pc
\]

16.24 A two-week study has been performed on a 12-station transfer line that is used to partially machine engine heads for a major automotive company. During the 80 hours of observation, the line was down a total of 28 hours, and a total of 1689 parts were completed. The accompanying table lists the machining operation performed at each station, the process times, and the downtime occurrences for each station. Transfer time between stations is 6 sec. To address the downtime problem, it has been proposed to divide the line into two stages, each consisting of six stations. The storage buffer between the stages would have a storage capacity of 20 parts. Determine (a) line efficiency and production rate of current one-stage configuration, and (b) line efficiency and production rate of proposed two-stage configuration. (c) Given that the line is to be divided into two stages, should each stage consist of six stations as proposed, or is there a better division of stations into stages? Support your answer.

<table>
<thead>
<tr>
<th>Station</th>
<th>Operation</th>
<th>Process time</th>
<th>Downtime occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Load part (manual)</td>
<td>0.50 min</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Rough mill top</td>
<td>1.10 min</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Finish mill top</td>
<td>1.25 min</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>Rough mill sides</td>
<td>0.75 min</td>
<td>23</td>
</tr>
<tr>
<td>5</td>
<td>Finish mill sides</td>
<td>1.05 min</td>
<td>31</td>
</tr>
<tr>
<td>6</td>
<td>Mill surfaces for drill</td>
<td>0.80 min</td>
<td>9</td>
</tr>
<tr>
<td>7</td>
<td>Drill two holes</td>
<td>0.75 min</td>
<td>22</td>
</tr>
<tr>
<td>8</td>
<td>Tap two holes</td>
<td>0.40 min</td>
<td>47</td>
</tr>
<tr>
<td>9</td>
<td>Drill three holes</td>
<td>1.10 min</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>Ream three holes</td>
<td>0.70 min</td>
<td>21</td>
</tr>
<tr>
<td>11</td>
<td>Tap three holes</td>
<td>0.45 min</td>
<td>30</td>
</tr>
</tbody>
</table>
12 | Unload and inspect part (manual) | 0.90 min | 0 |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Totals:</td>
<td>9.40 min</td>
<td>246</td>
<td></td>
</tr>
</tbody>
</table>

**Solution:** (a) \( T_c = 1.25 + 0.1 = 1.35 \text{ min/cycle} = 1.35 \text{ min/pc.} \)

\[
T_d = \frac{28(60)}{246} = 6.829 \text{ min/occurrence,} \quad F = \frac{246}{1689} = 0.1456
\]

\( T_p = 1.35 + 0.1456(6.829) = 1.35 + 0.994 = 2.344 \text{ min/pc.} \)

\( R_p = 1/2.344 = 0.427 \text{ pc/min} = \boxed{25.59 \text{ pc/hr}} \)

\( E_o = 1.35/2.344 = 0.576 = 57.6\% \)

(b) Stage 1: \( T_c = 1.25 + 0.1 = 1.35 \text{ min/cycle} = 1.35 \text{ min/pc.} \)

Assume \( T_d = 6.829 \text{ min/occurrence, as above, for both stages.} \)

\( T_p = 1/1.738 = 0.575 \text{ pc/min} = 34.52 \text{ pc/hr} \quad E_1 = 1.35/1.738 = 0.777 = 77.7\% \)

Stage 2: \( T_c = 1.10 + 0.1 = 1.20 \text{ min/pc.} \)

Assume \( T_d = 6.829 \text{ min/occurrence, as above.} \)

\( F_1 = (15 + 18 + 23 + 31 + 9)/1689 = 96/1689 = 0.0568 \)

\( T_p = 1.20 + 0.0568(6.829) = 1.20 + 0.606 = 1.806 \text{ min/pc.} \)

\( R_p = 1/1.806 = 0.554 \text{ pc/min} = 33.2 \text{ pc/hr} \quad E_2 = 1.20/1.806 = 0.664 = 66.4\% \)

\( D_1 = 0.388/2.344 = 0.1655 \quad r = \frac{F_1}{F_2} = \frac{0.0568}{0.0888} = 0.6396 \)

\( E = 0.576 + 0.6396(0.664) = 0.6407 \)

\( R_p = 0.6407\cdot1.275 = 0.5025 \text{ pc/min} = \boxed{30.15 \text{ pc/hr}} \)

(c) A better separation into stages would equalize \( E \) and \( R_p \) values between the two stages. Try dividing the line between stations 7 and 8 rather than between 6 and 7.

Stage 1: \( T_c = 1.35 \text{ min} \quad F_1 = (96 + 22)/1689 = 118/1689 = 0.0699 \)

Assume \( T_d = 6.829 \text{ min/occurrence, as above, for both stages.} \)

\( T_p = 1/1.738 = 0.575 \text{ pc/min} = 34.52 \text{ pc/hr} \quad E_1 = 1.35/1.738 = 0.777 = 77.7\% \)

Stage 2: \( T_c = 1.20 \text{ min} \quad F_2 = (150 - 22)/1689 = 128/1689 = 0.0758 \)

\( T_p = 1.20 + 0.0758(6.829) = 1.20 + 0.670 = 1.870 \text{ min/pc.} \)

\( R_p = 1/1.718 = 0.582 \text{ pc/min} = 34.93 \text{ pc/hr} \quad E_2 = 1.20/1.718 = 0.6985 = 69.85\% \)

\( D_1 = 0.4773/2.344 = 0.2036 \quad r = \frac{F_1}{F_2} = \frac{0.0568}{0.0758} = 0.7393 \)

Again, since \( T_{c1} \neq T_{c2} \), use average value in the calculations: \( T_c = \frac{1.35 + 1.20}{2} = 1.275 \text{ min} \)

\( h(20) = 0.5672 + 0.0214 = 0.5886 \)
\[ E = 0.576 + 0.2036(0.7536)(0.6985) = 0.6832 \]
\[ R_p = 0.6832/1.275 = 0.5358 \text{ pc/min} = 32.15 \text{ pc/hr} \]

16.25 In Problem 16.24, the current line has an operating cost of $66.00/hr. The starting workpart is a casting that costs $4.50/pc. Disposable tooling costs $1.25/pc. The proposed storage buffer will add $6.00/hr to the operating cost of the line. Does the improvement in production rate justify this $20 increase?

**Solution:** Current line: \( C_{pc} = 4.50 + 66(2.344/60) + 1.25 = 8.33/pc \).

Two stage line in which division into stages is between stations 6 and 7: \( C_{pc} = 4.50 + 72/30.15 + 1.25 = 8.14/pc \).

Two stage line in which division into stages is between stations 7 and 8. See solution of Problem 16.24(c): \( C_{pc} = 4.50 + 72/32.15 + 1.25 = 7.99/pc \).

Improvement is justified for either division.

16.26 A 16-station transfer line can be divided into two stages by installing a storage buffer between stations 8 and 9. The probability of failure at any station is 0.01. The ideal cycle time is 1.0 min and the downtime per line stop is 10.0 min. These values are applicable for both the one-stage and two-stage configurations. The downtime should be a considered constant value. The cost of installing the storage buffer is a function of its capacity. This cost function is \( C_b = 0.60b/hr = 0.01b/min \), where \( b \) = the buffer capacity. However, the buffer can only be constructed to store increments of 10 (in other words, \( b \) can take on values of 10, 20, 30, etc.). The cost to operate the line itself is $120/hr. Ignore material and tooling costs. Based on cost per unit of product, determine the buffer capacity \( b \) that will minimize unit product cost.

**Solution:**

With no buffer storage \( (b = 0) \): \( T_p = 1.0 + 16(0.01)(10) = 2.6 \text{ min/pc} \).

\( C_{pc} = 120(2.6/60) = 2.00(2.6) = 5.20/pc \),

\( E_o = 1/2.6 = 0.3846 \)

With two stages, each stage would operate the same way, with \( n = 8 \) stations

\( T_p = 1.0 + 8(0.01)(10) = 1.8 \text{ min/pc} \)

\( E1 = E2 = 1/1.8 = 0.5555 \)

\( D1' = (8x0.01x10)/(1+16x0.01x10) = 0.3077 \)

\( h(b) = \frac{B}{B+1} \), \( b = 10, 20, 30, 40, \text{ etc.} \) \( \rightarrow B = 1, 2, 3, 4, \text{ etc.} \)

\( C_{pc} = (2.0 + 0.1B)B/\text{min} \)

\( E = 0.3846 + 0.3077 \frac{B}{B+1}(0.5555) - 0.3846 + 0.1709 \frac{B}{B+1} = 0.5555B + 0.3846 \)

\( T_p = T_c/E. \)

\( C_{pc} = C_lT_p = C_lT_c/E \)

Using these terms for \( E, T_p \) and \( C_{pc} \), \( C_{pc} = (2.0 + 0.1B) \left( \frac{B+1}{0.5555B + 0.3846} \right) \)

\( B = 0 \quad C_{pc} = (2.0+1.0)(0+1) / 3.846 = 5.20/pc \)

\( B = 1 \quad C_{pc} = (2.0+1.0)(1+1) / 9.401 = 4.468/pc \)

\( B = 2 \quad C_{pc} = (2.0+1.0)(2+1) / 1.4956 = 4.413/pc \)

\( B = 3 \quad C_{pc} = (2.0+1.0)(3+1) / 2.0511 = 4.485/pc \)

\( B = 4 \quad C_{pc} = (2.0+1.0)(4+1) / 2.6066 = 4.604/pc \)

\( B = 5 \quad C_{pc} = (2.0+1.0)(5+1) / 3.1621 = 4.744/pc \)

Lowest cost is at \( B = 2 \) or \( b = 20 \) unit capacity

16.27 The uptime efficiency of a 20 station automated production line is only 40%. The ideal cycle time is 48 sec, and the average downtime per line stop occurrence is 3.0 min. Assume the frequency of breakdowns for all stations is equal \( (p_s = p \text{ for all stations}) \) and that the downtime is constant. To improve uptime efficiency, it is proposed to install a storage buffer with a 15-part capacity for $20,000. The present production cost is $4.00 per unit, ignoring material and tooling costs. How many units would have to be produced in order for the $20,000 investment to pay for itself?

**Solution:** \( F = np = 20p \quad T_p = T_c + 20pT_d \)

\( T_p = T_c/E = 0.8/0.4 = 2.0 \text{ min/pc} \)

\( T_d = 0.8 + 20p(3) = 0.8 + 60p \)

\( 60p = 2.0 \cdot 0.8 = 1.2 \quad p = 1.2/60 = 0.02 \)

\( C_{pc} = C_lT_p = $4.00 = C_l(2.0), C_l = $2.00/min \)
Two stage line each with 10 stations: 

\[ E_o = 0.4 \]
\[ E_2 = \frac{0.8}{0.8 + 10 \times 0.02 \times 3} = \frac{0.8}{1.4} = 0.5714 \]
\[ D_1' = 0.6/2.0 = 0.3 \]

With constant repair time, \( b = 15 \rightarrow B = 4, L = 0 \) and \( h(b) = h(15) = 4/(4+1) = 0.8 \)

\[ E = 0.4 + 0.3(0.8)(0.5714) = .5371 \]
\[ T_p = T_c/E = 0.8/0.5371 = 1.4895 \text{ min} \]
\[ C_{pc} = 2.00(1.4895) = 2.979/pc \]

Break-even point \( Q \): 
\[ 4.00 = 20,000 + 2.979 \]
\[ Q_{(4.00 - 2.979)Q = 20,000} \]
\[ Q = 19,589 \text{ pc} \]

16.28 An automated transfer line is divided into two stages with a storage buffer between them. Each stage consists of 9 stations. The ideal cycle time of each stage = 1.0 minute, and frequency of failure for each station is 0.01. The average downtime per stop is 8.0 minutes, and a constant downtime distribution should be assumed. Determine the required capacity of the storage buffer such that the improvement in line efficiency \( E \) compared to a zero buffer capacity would be 80% of the improvement yielded by a buffer with infinite capacity.

**Solution:** For \( b = 0, F = 18(0.01) = 0.18 \)
\[ T_p = 1.0 + 0.18(8.0) = 1.0 + 1.44 = 2.44 \text{ min/pc} \]
\[ E_o = 1.0/2.44 = 0.4098 \]

For \( B = \infty, F = 9(0.01) = 0.09 \)
\[ T_p = 1.0 + 0.09(8.0) = 1.0 + 0.72 = 1.72 \text{ min/pc} \]
\[ E_\infty = 1.0/1.72 = 0.5814 \]
\[ D_1' h(b) E_2 = 0.1373 \]
\[ D_1' = 0.72/2.44 = 0.2951 \]
\[ 0.1373 = 0.2951(h(b))(0.5814) \]
\[ h(b) = \frac{0.1373}{(0.2951)(0.5814)} = 0.80 \]

\[ r = \frac{F_1}{F_2} = 1.0, \text{ therefore } h(b) = \frac{B}{B+1} + \frac{L}{T_d} \left( \frac{1}{(B+1)(B+2)} \right) \]

For ease of calculations, ignore the second term. If \( B \) turns out to be an integer, the second term does not apply. If \( B \) is not an integer, a trial and error solution will be required to find \( B \) and \( L \).

\[ h(b) = 0.80 = \frac{B}{B+1} \]
\[ 0.80 B + 0.80 = B \]
\[ B = 4 \rightarrow b = \frac{T_d}{T_c} = 4(8/1) = 32 = \text{ buffer capacity} \]

16.29 In Problem 16.17, suppose that a two-stage line were to be designed, with an equal number of stations in each stage. Work content time will be divided evenly between the two stages. The storage buffer between the stages will have a capacity = \( 3 T_d/T_c \). Assume a constant repair distribution. (a) For this two-stage line, determine the number of workstations that should be included in each stage of the line to maximize production rate. (b) What is the production rate and line efficiency for this line configuration? (c) What is the buffer storage capacity?

**Solution:** (a) Given from Problem 16.17: \( p = 0.005, T_d = 8.0 \text{ min} \) For one stage, \( T_{wc} = 18 \text{ min} \)
\[ T_c = 0.1 + \frac{18}{n} \]
\[ T_p = 0.1 + \frac{18}{n} + 0.005 n(8.0) = 0.1 + \frac{18}{n} + 0.04 n \]
\[ \frac{dT_p}{dn} = -\frac{18}{n^2} + 0.04 = 0 \]
\[ n^2 = 18/0.04 = 450 \]
\[ n = 21.2, \text{ use } n = 21 \text{ stations} \]

(b) \( T_c = 0.1 + 18/21 = 0.9571 \text{ min/pc} \)
\[ T_p = 0.9571 + 0.005(21)(8) = 1.7971 \text{ min/pc} \) for each stage.
\[ E_b = E_o + D_1' h(b) E_2 \]
Transfer Lines-3e-SI  7-10/06, 06/04/07, 09/18/07

\[ E_2 = \frac{0.9571}{1.7971} = 0.5326 \]

\[ D_1' = \frac{0.005(21)(8)}{0.9571 + 0.005(42)(8)} = 0.3185 \]

Given \( b = 3 \frac{T_c}{T_c} \), then \( B = 3 \) and \( L = 0 \)

\[ h(b) = \frac{B}{B+1} = \frac{3}{4} = 0.75 \]

\[ E_0 = \frac{0.9571}{0.9571 + 0.005(42)(8)} = 0.3629 \]

\[ E_b = 0.3629 + 0.3185(0.75)(0.5326) = 0.4901 \]

\[ R_p = \frac{0.4901}{0.9571} = 0.5121 \text{ pc/min} = 30.73 \text{ pc/hr} \]

(c) \( b = 3 \frac{T_c}{T_c} = 3 \left( \frac{8.0}{0.9571} \right) = 25.07 \rightarrow \text{use } b = 25 \text{ buffer capacity} \)

16.30 A 20-station transfer line presently operates with a line efficiency \( E = 0.30 \). The ideal cycle time = 1.0 min. The repair distribution is geometric with an average downtime per occurrence = 8 min, and each station has an equal probability of failure. It is possible to divide the line into two stages with 10 stations each, separating the stages by a storage buffer of capacity \( b \). With the information given, determine the required value of \( b \) that will increase the efficiency from \( E = 0.30 \) to \( E = 0.40 \).

**Solution:** \( E = 0.30 \), \( T_p = T_c/E = 1.0/0.30 = 3.333 \text{ min/pc} \)

\[ T_p = T_c + npT_d = 1.0 + 20p(8.0) = 1.0 + 160p = 3.333 \]

\( 160p = 3.333 - 1.0 = 2.333 \)

\( p = 2.333/160 = 0.01458 \)

Two stage line: \( E_b = E_0 + D'_1 h(b) E_2 \)

Given \( E_0 = 0.30 \)

\[ D_1' = \frac{10(0.01458)(8)}{1.0 + 20(0.01458)(8)} = 0.35 \]

\[ E_2 = \frac{1.0}{1.0 + 10(0.01458)(8)} = 0.4616 \]

Use Eq. (16.26): \( h(b) = \frac{b(1/8)}{2 + (b-1)(1/8)} = \frac{0.125b}{2 + 0.125(b-1)} = \frac{0.125b}{1.875 + 0.125b} = \frac{0.125b}{1.16 + 0.0774b} \)

\[ E_b = 0.30 + 0.35(\frac{0.125b}{1.875 + 0.125b})(0.4616) \]

Target \( E = 0.40 = 0.30 + 0.1616(\frac{0.125b}{1.875 + 0.125b}) \)

\[ 0.40 - 0.30 = 0.10 = 0.1616(\frac{0.125b}{1.875 + 0.125b}) \]

\[ \frac{0.125b}{1.875 + 0.125b} = \frac{0.10}{0.1616} = 0.619 \]

\[ 0.619(1.875 + 0.125b) = 0.125b \]

\[ 1.16 + 0.0774b = 0.125b \]

\[ 0.125b - 0.0774b = 1.16 \]

\[ 0.0476b = 1.16 \]

\[ b = 24.4 \text{ rounded to 25 pc buffer capacity} \]
Chapter 17
AUTOMATED ASSEMBLY SYSTEMS

REVIEW QUESTIONS

17.1 Name three of the four conditions under which automated assembly technology should be considered.

Answer: The four conditions named in the text are (1) high product demand, so that millions of units are produced, (2) stable product design, because design changes require tooling changes in the assembly system, (3) the assembly consists of no more than a limited number of components, say around a dozen or fewer, and (4) the product is designed for automated assembly.

17.2 What are the four automated assembly system configurations listed in the text?

Answer: The four configurations are (a) in-line assembly machine, (b) dial-type assembly machine, (c) carousel assembly system, and (d) single-station assembly machine.

17.3 What are the typical hardware components of a workstation parts delivery system?

Answer: The typical components are (1) hopper, (2) parts feeder, (3) selector and/or orientor, (4) feed track, and (5) escapement and placement device.

17.4 What is a programmable parts feeder?

Answer: As defined in the text, a programmable parts feeder is a feeder that is capable of feeding components of varying geometries with only a few minutes required to make the adjustments (change the program) for the differences.

17.5 Name six typical products that are made by automated assembly.

Answer: The products identified in the text are alarm clocks, audio tape cassettes, ball bearings, ball point pens, cigarette lighters, computer disks, electrical plugs and sockets, fuel injectors, gear boxes, light bulbs, locks, mechanical pens and pencils, printed circuit board assemblies, pumps for household appliances, small electric motors, spark plugs, video tape cassettes, and wrist watches.

17.6 Considering the assembly machine as a game of chance, what are the three possible events that might occur when the feed mechanism attempts to feed the next component to the assembly workhead at a given workstation in a multi-station system?

Answer: The three possible events are (1) the component is defective and causes a station jam, (2) the component is defective but does not cause a station jam, and (3) the component is not defective.

17.7 Name some of the important performance measures for an automated assembly system.

Answer: The performance measures considered in the text include yield (proportion of assemblies produced with no defective components), production rate, proportion uptime (a.k.a. line efficiency), and unit cost per assembly.

17.8 Why is the production rate inherently lower on a single-station assembly system than on a multi-station assembly system?

Answer: Because all of the work elements are performed sequentially at one station in the single station system, whereas the elements are performed simultaneously at multiple workstations in a multi-station system.

17.9 What are two reasons for the existence of partially automated production lines?

Answer: The two reasons given in the text are (1) automation is introduced gradually on an existing manual line and (2) certain manual operations are too difficult or too costly to automate.

17.10 What are the effects of poor quality parts, as represented by the fraction defect rate, on the performance of an automated assembly system?

Answer: The two effects given in the text are (1) jams at stations that stop the entire assembly system to adversely affect production rate, uptime proportion, and cost per unit produced; or (2) assembly of defective parts in the product to adversely affect yield of good assemblies and product cost.
17.11 Why are storage buffers used on partially automated production lines?

**Answer:** Storage buffers are used on partially automated production lines to isolate the manual stations from the breakdowns of the automated stations. Thus, workers do not have to stop working when an automated station breaks down.

**PROBLEMS**

**Parts Feeding**

17.1 A feeder-selector device at one of the stations of an automated assembly machine has a feed rate of 25 parts per minute and provides a throughput of one part in four. The ideal cycle time of the assembly machine is 10 sec. The low level sensor on the feed track is set at 10 parts, and the high level sensor is set at 20 parts. (a) How long will it take for the supply of parts to be depleted from the high level sensor to the low level sensor once the feeder-selector device is turned off? (b) How long will it take for the parts to be resupplied from the low level sensor to the high level sensor, on average, after the feeder-selector device is turned on? (c) What proportion of the time that the assembly machine is operating will the feeder-selector device be turned on? Turned off?

**Solution:**

(a) Time to deplete from \( n_2 \) to \( n_1 \)

Rate of depletion = cycle rate \( R_c = \frac{60}{10} = 6 \text{ parts/min} \)

Time to deplete = \( \frac{20 - 10}{6} = 10/6 = 1.667 \text{ min} \)

(b) Time to resupply from \( n_1 \) to \( n_2 \)

Rate of resupply = \( f \theta - R_c = 25(0.25) - 6 = 0.25 \text{ parts/min} \)

Time to resupply = \( \frac{20 - 10}{0.25} = 10/0.25 = 40 \text{ min} \)

(c) Total cycle of depletion and resupply = 41.667 min

Proportion of time feeder-selector is on = \( \frac{40}{41.667} = 0.96 \)

Proportion of time feeder-selector is off = \( \frac{1.667}{41.667} = 0.04 \)

17.2 Solve Problem 17.1 but use a feed rate of 32 parts per minute. Note the importance of tuning the feeder-selector rate to the cycle rate of the assembly machine.

**Solution:**

(a) Time to deplete = \( \frac{20 - 10}{6} = 1.667 \text{ min} \)

(b) Rate of resupply = \( 32(0.25) - 6 = 8 - 6 = 2 \text{ parts/min} \)

Time to resupply = \( \frac{20 - 10}{2} = 10/2 = 5 \text{ min} \)

(c) Total cycle time = 6.667 min

Proportion of time feeder-selector turned on = \( \frac{5}{6.667} = 0.75 \)

Proportion of time feeder-selector turned off = \( \frac{1.667}{6.667} = 0.25 \)

17.3 A synchronous assembly machine has 8 stations and must produce at an average rate of 480 completed assemblies per hour. Average downtime per jam is 2.5 min. When a breakdown occurs, all subsystems (including the feeder) stop. The frequency of breakdowns of the machine is once every 50 parts. One of the eight stations is an automatic assembly operation that uses a feeder-selector. The components fed into the selector can have any of six possible orientations, each with equal probability, but only one of which is correct for passage into the feed track to the assembly workhead. Parts rejected by the selector are fed back into the hopper. What minimum rate must the feeder deliver components to the selector during system uptime in order to keep up with the assembly machine?

**Solution:**

\[ T_p = 60/480 = 0.125 \text{ min/assembly} \]

\[ T_p = T_c + FTP_d = T_c + \frac{1}{50}(2.5) = T_c + 0.05 \]

\[ T_c = 0.125 - 0.05 = 0.075 \text{ min/assembly} \]

\[ R_c = \frac{1}{T_c} = \frac{1}{0.075} = 13.333 \text{ asbys/minute} \]

\[ \text{Min } f \theta = 0.1667 f = 13.333 \text{ asbys/minute} \]

Feeder rate \( f = \frac{13.333}{0.1667} = 80 \text{ parts/minute} \)
Multi-Station Assembly Systems

17.4 A dial indexing machine has six stations that perform assembly operations on a base part. The operations, element times, $q$ and $m$ values for components added are given in the table below (NA means $q$ and $m$ are not applicable to the operation). The indexing time for the dial table is 2 sec. When a jam occurs, it requires 1.5 min to release the jam and put the machine back in operation. Determine (a) production rate for the assembly machine, (b) yield of good product (final assemblies containing no defective components), and (c) proportion uptime of the system.

<table>
<thead>
<tr>
<th>Station</th>
<th>Operation</th>
<th>Element time</th>
<th>$q$</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Add part A</td>
<td>4 sec</td>
<td>0.015</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>Fasten part A</td>
<td>3 sec</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>3</td>
<td>Assemble part B</td>
<td>5 sec</td>
<td>0.01</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>Add part C</td>
<td>4 sec</td>
<td>0.02</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>Fasten part C</td>
<td>3 sec</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>6</td>
<td>Assemble part D</td>
<td>6 sec</td>
<td>0.01</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Solution: (a) $\Sigma(qm) = 0.6(0.015) + 0.8(0.01) + 1(0.02) + 0.5(0.01) = .042$
$T_p = 0.1333 + 0.042(1.5) = 0.19633$ min/asby
$R_p = 60/0.19633 = 305.6$ asbys/hr

(b) $P_{ap} = (1-0.015+0.6x0.015)(1-0.01+0.8x0.01)(1-0.02+1x0.02)(1-0.01+0.5x0.01)$
$= (0.994)(0.998)(1.0)(0.995) = 0.98705$

(c) $E = 0.1333/0.19633 = 0.679 = 67.9\%$

17.5 An eight-station assembly machine has an ideal cycle time of 6 sec. The fraction defect rate at each of the 8 stations is $q = 0.015$ and a defect always jams the affected station. When a breakdown occurs, it takes 1 minute, on average, for the system to be put back into operation. Determine the production rate for the assembly machine, the yield of good product (final assemblies containing no defective components), and proportion uptime of the system.

Solution: $T_p = 0.1 + 8(1.0)(0.015)(1.0) = 0.22$ min/asby
$R_p = 60/0.22 = 272.7$ asbys/hr

If defects always jam the affected station, then $m = 1.0$
$P_{ap} = (1 - 0.015 + 1x0.015)^8 = 1.0 = yield$
$E = 0.1/0.22 = 0.4545 = 45.45\%$

17.6 Solve Problem 17.5 but assume that defects never jam the workstations. Other data are the same.

Solution: $T_p = 0.1 + 8(0)(0.015)(1.0) = 0.10$ min/asby
$R_p = 60/0.10 = 600$ asbys/hr

If defects never jam, then $m = 0$
$P_{ap} = (1 - 0.015 + 0x0.015)^8 = 0.8861 = yield$
$E = 0.1/0.1 = 100\%$

17.7 Solve Problem 17.5 but assume that $m = 0.6$ for all stations. Other data are the same.

Solution: $T_p = 0.1 + 8(0.6)(0.015)(1.0) = 0.172$ min/asby
$R_p = 60/0.172 = 348.8$ asbys/hr

$P_{ap} = (1 - 0.015 + 0.6x0.015)^8 = 0.953 = yield$
$E = 0.1/0.172 = 0.5814 = 58.14\%$

17.8 A six-station automatic assembly line has an ideal cycle time of 12 sec. Downtime occurs for two reasons. First, mechanical and electrical failures cause line stops that occur with a frequency of once per 50 cycles. Average downtime for these causes is 3 min. Second, defective components also result in downtime. The fraction defect rate of each of the six components added to the base part at the six stations is 2%. The probability that a defective component will cause a station jam is 0.5 for all stations. Downtime per occurrence for defective parts is 2 min. Determine (a) yield of assemblies that are free of defective components, (b) proportion of assemblies that contain at least one defective component, (c) average production rate of good product, and (d) uptime efficiency.
**Solution:** (a) \( P_{ap} = (1 - 0.02 + 0.5 \times 0.02)^6 = (0.99)^6 = 0.9415 \)

(b) \( P_{ap} = 1 - 0.9415 = 0.0585 \)

(c) \( T_p = \frac{12}{60} + 0.02(3) + 6(0.5)(0.02)(2) = 0.38 \text{ min} \)
\( R_p = \frac{60}{0.38} = 157.6 \text{ cycles/hr} \)
\( R_{ap} = (0.9415)(157.9) = 148.66 \text{ good asbys/hr} \)

(d) \( E = 0.2/0.38 = 0.526 = 52.6\% \)

17.9 An eight-station automatic assembly machine has an ideal cycle time of 10 sec. Downtime is caused by defective parts jamming at the individual assembly stations. The average downtime per occurrence is 2.0 min. The fraction defect rate is 1.0% and the probability that a defective part will jam at a given station is 0.6 for all stations. The cost to operate the assembly machine is $90.00 per hour and the cost of components being assembled is $60 per unit assembly. Ignore other costs. Determine (a) yield of good assemblies, (b) average production rate of good assemblies, (c) proportion of assemblies with at least one defective component, and (d) unit cost of the assembled product.

**Solution:** (a) \( P_{ap} = (1 - 0.01 + 0.6 \times 0.01)^8 = (0.996)^8 = 0.9684 \)

(b) \( T_p = 0.1667 + 8(0.6)(0.01)(2) = 0.2627 \text{ min/asby} \)
\( R_p = \frac{60}{0.2627} = 228.4 \text{ asbys/hr} \)
\( R_{ap} = (0.9684)(228.4) = 221.2 \text{ good asbys/hr} \)

(c) \( P_{qp} = 1 - 0.9684 = 0.0316 \)

(d) \( C_{pc} = \frac{0.60+1.50(0.2627)}{0.9684} = \$1.0265/\text{asby} \)

17.10 An automated assembly machine has four workstations. The first station presents the base part, and the other three stations add parts to the base. The ideal cycle time for the machine is 3 sec, and the average downtime when a jam results from a defective part is 1.5 min. The fraction defective rates \( (q) \) and probabilities that a defective part will jam the station \( (m) \) are given in the table below. Quantities of 100,000 for each of the bases, brackets, pins, and retainers are used to stock the assembly line for operation. Determine (a) proportion of good product to total product coming off the line, (b) production rate of good product coming off the line, (c) total number of final assemblies produced, given the starting component quantities. Of the total, how many are good product, and how many are products that contain at least one defective component? (d) Of the number of defective assemblies determined in above part (c), how many will have defective base parts? How many will have defective brackets? How many will have defective pins? How many will have defective retainers?

<table>
<thead>
<tr>
<th>Station</th>
<th>Part identification</th>
<th>( q )</th>
<th>( m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base</td>
<td>0.01</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>Bracket</td>
<td>0.02</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>Pin</td>
<td>0.03</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>Retainer</td>
<td>0.04</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Solution:** (a) \( P_{ap} = (1-0.01+1x0.01)(1-0.02+1x0.02)(1-0.03+1x0.03)(1-0.04+0.5x0.04) = (1.0)(1.0)(1.0)(0.98) = 0.98 \)

(b) \( T_p = 3/60 + (0.01+0.02+0.03+0.04x0.5)(1.5) = 0.17 \text{ min} \)
\( R_p = 0.98(60/0.17) = 345.9 \text{ good asbys/hr} \)

(c) The diagram below shows quantities of components at the four workstations in the assembly machine:

<table>
<thead>
<tr>
<th>base 100,000</th>
<th>bracket 100,000</th>
<th>pin 100,000</th>
<th>retainer 100,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>1000 def</td>
<td>2000 def</td>
<td>3000 def</td>
<td>1940 def</td>
</tr>
<tr>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>95060 good asbys + 1940 with defective retainers</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total number produced = 95,060 + 1,940 = 97,000
Number of units of good product = 95,060
Number of units containing at least one defect = 1,940
(d) Number of products containing defective base parts = 0
Number of products containing defective brackets = 0
Number of products containing defective pins = 0
Number of products containing defective retainers = 1,940

17.11 A six-station automatic assembly machine has an ideal cycle time of 6 sec. At stations 2 through 6, parts feeders deliver components to be assembled to a base part that is added at the first station. Each of stations 2 through 6 is identical and the five components are identical. That is, the completed product consists of the base part plus the five components. The base parts have zero defects, but the other components are defective at a rate \( q \). When an attempt is made to assemble a defective component to the base part, the machine stops (\( m = 1.0 \)). It takes an average of 2.0 min to make repairs and start the machine up after each stoppage. Since all components are identical, they are purchased from a supplier who can control the fraction defect rate very closely. However, the supplier charges a premium for better quality. The cost per component is determined by the following equation:

\[
\text{Cost per component} = 0.1 + \frac{0.0012}{q}
\]

where \( q \) = the fraction defect rate. Cost of the base part is 20 cents. Accordingly, the total cost of the base part and the five components is:

\[
\text{Product material cost} = 0.70 + \frac{0.006}{q}
\]

The cost to operate the automatic assembly machine is $150.00 per hour. The problem facing the production manager is this: As the component quality decreases (\( q \) increases), the downtime increases which drives production costs up. As the quality improves (\( q \) decreases), the material cost increases because of the price formula used by the supplier. To minimize total cost, the optimum value of \( q \) must be determined. Determine by analytical methods (rather than trial-and-error) the value of \( q \) that minimizes the total cost per assembly. Also, determine the associated cost per assembly and production rate. (Ignore other costs).

**Solution:**

Product material cost \( C_m = 0.20 + 5(0.1 + \frac{0.0012}{q}) = 0.70 + \frac{0.006}{q} \)

\( T_p = 0.1 + 5(1)(q)(2.0) = 0.1 + 10q \)

\( C_{pc} = C_m + C_p T_p = 0.70 + \frac{0.006}{q} + 2.50(0.1 + 10q) = 0.70 + \frac{0.006}{q} + 0.25 + 25q = 0.95 + \frac{0.006}{q} + 25q \)

Taking the derivative of the cost equation with respect to \( q \):

\[
\frac{dC_{pc}}{dq} = -\frac{0.006}{q^2} + 25 = 0
\]

\[
\frac{0.006}{q^2} = 25 \quad q^2 = 0.006/25 = 0.00024 \quad q = 0.0155
\]

Using this value in the preceding cost equation,

\( C_{pc} = 0.70 + 0.006/0.0155 + 2.50(0.1 + 10\times0.0155) = $1.725/\text{asby} \)

\( T_p = 0.1 + 5(1)(0.0155)(2.0) = 0.255 \text{ min/asby} \)

\( R_p = 60/0.255 = 235.3 \text{ asbys/hr} \)

17.12 A six-station dial indexing machine is designed to perform four assembly operations at stations 2 through 5 after a base part has been manually loaded at station 1. Station 6 is the unload station. Each assembly operation involves the attachment of a component to the existing base. At each of the four assembly stations, a hopper-feeder is used to deliver components to a selector device that separates components that are improperly oriented and drops them back into the hopper. The system was designed with the operating parameters for stations 2 through 5 as given in the table below. It takes 2 sec to index the dial from one station position to the next. When a component jam occurs, it takes an average of 2 min to release the jam and restart the system. Line stops due to mechanical and electrical failures of the assembly machine are not significant and can be neglected. The foreman says the system was designed to produce at a certain hourly rate, which takes into account the jams resulting from defective components. However, the actual delivery of finished assemblies is far below that designed production rate. Analyze the problem and determine the following: (a) the designed average production rate that the foreman alluded to, (b) the proportion of assemblies coming off the system that contain
one or more defective components, (c) the problem that limits the assembly system from achieving the expected production rate, and (d) the production rate that the system is actually achieving. State any assumptions that you make in determining your answer.

<table>
<thead>
<tr>
<th>Station</th>
<th>Assembly time</th>
<th>Feed rate $f$</th>
<th>Selector $\theta$</th>
<th>$q$</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4 sec</td>
<td>32/min</td>
<td>0.25</td>
<td>0.01</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>7 sec</td>
<td>20/min</td>
<td>0.50</td>
<td>0.005</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>5 sec</td>
<td>20/min</td>
<td>0.25</td>
<td>0.02</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>3 sec</td>
<td>15/min</td>
<td>1.0</td>
<td>0.01</td>
<td>0.7</td>
</tr>
</tbody>
</table>

**Solution:**

- **Solution:** $T_d = 2$ min, $T_c = 7 + 2 = 9$ sec = 0.15 min
  - (a) $\Sigma mq = 1(0.01) + 0.6(0.005) + 1(0.02) + 0.7(0.01) = 0.04$
  - $T_p = 0.15 + 0.04(2) = 0.23$ min
  - $R_p = 60/0.23 = \text{260.9 asbys/hr}$

- (b) $P_{ap} = (1-0.01)(1-0.005)(1-0.02)(1-0.01)(1-0.01) = 0.995$
  - $P_{ap} = 1 - 0.995 = 0.005$
  - $R_{ap} = 260.9(0.995) = 259.6$ good asbys/hr

- (c) Station 2: $f\theta = 32(.25) = 8$ components/min
  - Station 3: $f\theta = 20(0.50) = 10$ components/min
  - Station 4: $f\theta = 20(0.25) = 5$ components/min
  - Station 5: $f\theta = 15(1.0) = 15$ components/min

The problem is that the feeder for station 4 is slower than the machine's cycle rate of 6.667 cycles/min

- (d) If the machine operates at the cycle rate that is consistent with the feed rate of Station 4, then $T_c = 12$ sec = 0.20 min
  - $T_p = 0.20 + 0.04(2) = 0.28$ min
  - $R_p = 60/0.28 = \text{214.3 asbys/hr}$
  - $R_{ap} = 214.3(0.995) = \text{213.2 good asbys/hr}$

**Comment:** Comparing the values with those in Example 17.4, production rate is more than double for the multi-station system, yield is the same, and line efficiency is greatly reduced because of the much faster cycle time.

**Single Station Assembly Systems**

17.14 A single-station assembly machine is to be considered as an alternative to the dial-indexing machine in Problem 17.4. Use the data given in the table for that problem to determine (a) production rate, (b) yield of good product (final assemblies containing no defective components), and (c) proportion uptime of the system. Handling time to load the base part and unload the finished assembly is 7 sec and the downtime averages 1.5 min every time a
component jams. Why is the proportion uptime so much higher than in the case of the dial-indexing machine in Problem 17.4?

**Solution:** (a) \( T_c = 7 + (4 + 3 + 5 + 4 + 3 + 6) = 7 + 25 = 32 \text{ sec} = 0.5333 \text{ min} \)
\[ \Sigma(mq) = 0.6(0.015) + 0.8(0.01) + 1(0.02) + 0.5(0.01) = 0.042 \] (same as for Problem 17.4)
\[ T_p = 0.5333 + 0.042(1.5) = 0.5963 \text{ min} \]
\[ R_p = 60/0.59633 = 100.6 \text{ asbys/hr} \]

(b) \( P_{ap} = (1 - 0.015 + 0.6x0.015)(1 - 0.01 + 0.8x0.01)(1 - 0.02 + 1x0.02)(1 - 0.01 + 0.5x0.01) = 0.98705 \) (same as for Problem 17.4)

(c) \( E = 0.5333 / 0.59633 = 0.8943 = 89.43\% \)

**Comment:** Proportion of uptime \( E \) is so much higher than in Problem 17.4 because the cycle time is much longer for the single-station machine than for the six-station dial-indexing machine (32 sec vs 6 sec). The average downtime per occurrence is the same for both machines, but it is a much lower proportion of the longer cycle time in the single station case.

17.15 A single station robotic assembly system performs a series of five assembly elements, each of which adds a different component to a base part. Each element takes 4.5 sec. In addition, the handling time needed to move the base part into and out of position is 4 sec. For identification, the components, as well as the elements that assemble them, are numbered 1, 2, 3, 4, and 5. The fraction defect rate is 0.005 for all components, and the probability of a jam by a defective component is 0.7. Average downtime per occurrence = 2.0 min. Determine (a) production rate, (b) yield of good product in the output, (c) uptime efficiency, and (d) proportion of the output that contains a defective type 3 component.

**Solution:** (a) \( T_p = T_c + nmqT_d \)
\[ T_c = 4 + 5(4.5) = 26.5 \text{ sec} = 0.44167 \text{ min} \]
\[ T_p = 0.44167 + 5(0.7)(0.005)(2.0) = 0.47667 \text{ min} \]
\[ R_p = 1/0.47667 = 2.098 \text{ asbys/min} = 125.9 \text{ asbys/hr} \]

(b) \( P_{ap} = (1 - 0.005 + 0.7(0.005))^5 = (0.9985)^5 = 0.9925 \)

(c) \( E = 0.44167 / 0.47667 = 0.9266 = 92.66\% \)

(d) Type 3 defect = 1 - (1 - 0.005 + 0.7(0.005)) = 0.005 - 0.7(0.005) = 0.3(0.005) = 0.0015

17.16 A robotic assembly cell uses an industrial robot to perform a series of assembly operations. The base part and parts 2 and 3 are delivered by vibratory bowl feeders that use selectors to insure that only properly oriented parts are delivered to the robot for assembly. The robot cell performs the elements in the table below (also given are feeder rates, selector proportion \( \theta \), element times, fraction defect rate \( q \), and probability of jam \( m \), and, for the last element, the frequency of downtime incidents \( p \)). In addition to the times given in the table, the time required to unload the completed subassembly takes 4 sec. When a linestop occurs, it takes an average of 1.8 min to make repairs and restart the cell. Determine (a) yield of good product, (b) average production rate of good product, and (c) uptime efficiency for the cell? State any assumptions you must make about the operation of the cell in order to solve the problem.

<table>
<thead>
<tr>
<th>Element</th>
<th>Feed rate ( f )</th>
<th>Selector ( \theta )</th>
<th>Element</th>
<th>Time ( T_e )</th>
<th>( q )</th>
<th>( m )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15 pc/min</td>
<td>0.30</td>
<td>Load base part</td>
<td>4 sec</td>
<td>0.01</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>12 pc/min</td>
<td>0.25</td>
<td>Add part 2</td>
<td>3 sec</td>
<td>0.02</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>25 pc/min</td>
<td>0.10</td>
<td>Add part 3</td>
<td>4 sec</td>
<td>0.03</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>Fasten</td>
<td>3 sec</td>
<td></td>
<td>0.02</td>
<td></td>
</tr>
</tbody>
</table>

**Solution:** Assumptions: (1) Feeders continue to operate and deliver parts into the feed track even when a jam occurs during assembly. (2) Low level quantity \( n_{f1} \) is sufficient to eliminate possibility of a stockout.
\[ T_c = T_e + \Sigma T_e = 4 + 4 + 3 + 4 + 3 = 18 \text{ sec} = 0.3 \text{ min} \]
\[ T_p = T_c + (\Sigma mq + p)T_d = 0.3 + (0.01 \times 0.6 + 0.02 \times 0.3 + 0.03 \times 0.8 + 0.02)(1.8) \]
\[ = 0.3 + 0.056(1.8) = 0.4008 \text{ min/asby} \]

Check feed rates:
\[ f_1 \theta_1 = 15(0.3) = 4.5 \text{ pc/min or 0.2222 min/pc} \]
\[ f_2 \theta_2 = 12(0.25) = 3.0 \text{ pc/min or 0.3333 min/pc} \]
$f_3 \theta_3 = 25(0.1) = 2.5 \text{ pc/min or 0.40 min/pc} 
Each of these can be completed within the average cycle time of the robot assembly operation.

(a) $P_{ap} = (1 - 0.01 + 0.6 \times 0.01)(1 - 0.02 + 0.3 \times 0.02)(1 - 0.03 + 0.8 \times 0.03) 
= (0.996)(0.986)(0.994) = 0.976

(b) $R_p = 1/0.4008 = 2.495 \text{ asbys/min} = 149.7 \text{ asbys/hr}$
$R_{ap} = 149.7(0.9762) = 146.1 \text{ good asbys/hr}$

(c) $E = 0.3/0.4008 = 0.7485 = 74.85\%$

Alternative assumption: (1) Feeder stops when jam occurs. Hence, cycle time is limited by feeder #3.
$T_c = 0.4 \text{ min}$ $T_p = 0.4 + (0.056)(1.8) = 0.5008 \text{ min}$

(a) $R_p = 1/0.5008 = 1.9968 \text{ asbys/min} = 119.8 \text{ asbys/hr}$ $P_{ap} = 0.976$ (same as above)

(b) $R_{ap} = 119.8(0.9762) = 116.9 \text{ good asbys/hr}$

(c) $E = 0.400/0.5008 = 0.7987 = 79.87\%$

Partial Automation

17.17 A partially automated production line has a mixture of three mechanized and three manual workstations. There are a total of six stations, and the ideal cycle time of 1.0 min, which includes a transfer time of 6 sec. Data on the six stations are listed in the accompanying table. Cost of the transfer mechanism $C_{at} = $0.10/min, cost to run each automated station $C_{as} = $0.12/min, and labor cost to operate each manual station $C_{w} = $0.17/min. It has been proposed to substitute an automated station in place of station 5. The cost of this station is estimated at $C_{as5} = $0.25/min and its breakdown rate $p_5 = 0.02$, but its process time would be only 30 sec, thus reducing the overall cycle time of the line from 1.0 min to 36 sec. Average downtime per breakdown of the current line, as well as for the proposed configuration, is 3.5 min. Determine the following for the current line and the proposed line: (a) production rate, (b) proportion uptime, and (c) cost per unit. Assume the line operates without storage buffers, so when an automated station stops, the whole line stops, including the manual stations. Also, in computing costs, neglect material and tooling costs.

<table>
<thead>
<tr>
<th>Station</th>
<th>Type</th>
<th>Process time</th>
<th>$p_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Manual</td>
<td>36 sec</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Automatic</td>
<td>15 sec</td>
<td>0.01</td>
</tr>
<tr>
<td>3</td>
<td>Automatic</td>
<td>20 sec</td>
<td>0.02</td>
</tr>
<tr>
<td>4</td>
<td>Automatic</td>
<td>25 sec</td>
<td>0.01</td>
</tr>
<tr>
<td>5</td>
<td>Manual</td>
<td>54 sec</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>Manual</td>
<td>33 sec</td>
<td>0</td>
</tr>
</tbody>
</table>

Solution: For the current line,

(a) $T_c = 1.0 \text{ min}$, $F = 0.01 + 0.02 + 0.01 = 0.04$
$T_p = 1.0 + 0.04(3.5) = 1.0 + 0.14 = 1.14 \text{ min/unit}$, $R_p = 1/1.14 = 0.877 \text{ units/min} = 52.6 \text{ units/hr}$

(b) $E = 1.0/1.14 = 0.877 = 87.7\%$

(c) $C_o = 0.10 + 3(0.12) + 3(0.17) = $0.97/min. $C_{pc} = (0.97)(1.14) = $1.016/unit.$

For the proposed line in which station 5 is automated,

(a) $T_c = 36 \text{ sec} = 0.6 \text{ min}$, $F = 0.01 + 0.02 + 0.01 + 0.02 = 0.06$
$T_p = 0.6 + 0.06(3.5) = 0.6 + 0.21 = 0.81 \text{ min/unit}$, $R_p = 1/0.81 = 1.235 \text{ units/min} = 74.1 \text{ units/hr}$

(b) $E = 0.6/0.81 = 0.7407 = 74.1\%$

(c) $C_o = 0.10 + 3(0.12) + 2(0.17) = $1.05/min. $C_{pc} = (1.05)(0.81) = $0.851/unit.$

17.18 Reconsider Problem 17.17 except that both the current line and the proposed line will have storage buffers before and after the manual stations. The storage buffers will be of sufficient capacity to allow these manual stations to operate independently of the automated portions of the line. Determine (a) production rate, (b) proportion uptime, and (c) cost per unit for the current line and the proposed line.

Solution: For the current line,
17.19 A manual assembly line has six stations. The assembly time at each manual station is 60 sec. Parts are transferred by hand from one station to the next, and the lack of discipline in this method adds 12 sec \((T_i = 12\) sec\) to the cycle time. Hence, the current cycle time is 72 sec. The following two proposals have been made: (1) Install a mechanized transfer system to pace the line; and (2) automate one or more of the manual stations using robots that would perform the same tasks as humans only faster. The second proposal requires the mechanized transfer system of the first proposal and would result in a partially or fully automated assembly line. The transfer system would have a transfer time of 6 sec, thus reducing the cycle time on the manual line to 66 sec. Regarding the second proposal, all six stations are candidates for automation. Each automated station would have an assembly time of 30 sec. Thus if all six stations were automated the cycle time for the line would be 36 sec. There are differences in the quality of parts added at the stations; these data are given in the accompanying table for each station \((q = \text{fraction defect rate}, m = \text{probability that a defect will jam the station})\). Average downtime per station jam at the automated stations is 3.0 min. Assume that the manual stations do not experience line stops due to defective components. Cost data: \(C_{at} = \$0.10/\text{min}\); \(C_{w} = \$0.20/\text{min}\); and \(C_{w} = \$0.15/\text{min}\). Determine if either or both of the proposals should be accepted. If the second proposal is accepted, how many stations should be automated and which ones? Use cost per piece as the criterion of your decision. Assume for all cases considered that the line operates without storage buffers, so when an automated station stops, the whole line stops, including the manual stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>(q_i)</th>
<th>(m_i)</th>
<th>Station</th>
<th>(q_i)</th>
<th>(m_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.005</td>
<td>1.0</td>
<td>4</td>
<td>0.020</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>0.010</td>
<td>1.0</td>
<td>5</td>
<td>0.025</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>0.015</td>
<td>1.0</td>
<td>6</td>
<td>0.030</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Solution:**

**Proposal 1:** Current operation: \(T_i = 1.2\) min \(C_o = 6(0.20) = \$1.20/\text{min}\) \(C_{pc} = 1.20(1.2) = \$1.44/\text{unit}\).

Proposal: \(T_i = 1.1\) min \(C_o = 0.10 + 6(0.20) = 1.30/\text{min}\) \(C_{pc} = 1.30(1.1) = \$1.43/\text{unit}\).

**Conclusion:** Accept Proposal 1.

**Proposal 2:** \(T_i = 36\) sec \(= 0.6\) min if all six stations are automated.

\[F = 0.005(1.0) + 0.01(1.0) + 0.015(1.0) + 0.02(1.0) + 0.025(1.0) + 0.03(1.0) = 0.105\]

\[T_p = 0.6 + 0.105(3.0) = 0.6 + 0.315 = 0.915 \text{ min/unit}\]

\[C_o = 0.10 + 6(0.15) = 1.00/\text{min}\]

\[C_{pc} = 1.00(0.915) = \$0.915/\text{unit}\]

**Conclusion:** Accept Proposal 2.
17.20 Solve preceding Problem 17.19, except that the probability that a defective part will jam the automated station is $m = 0.5$ for all stations.

Solution: Proposal 1: Current operation: $T_c = 1.2$ min

$C_{pc} = 1.20(1.2) = 1.44/\text{unit}$.

Proposal: $T_c = 1.1$ min

$C_{pc} = 1.30(1.1) = 1.43/\text{unit}$.

Conclusion: Accept Proposal 1.

Proposal 2: $T_c = 36$ sec = 0.6 min if all six stations are automated.

$F = 0.005(0.5) + 0.01(0.5) + 0.015(0.5) + 0.02(0.5) + 0.025(0.5) + 0.03(0.5) = 0.0525$

$T_p = 0.6 + 0.0525(3.0) = 0.6 + 0.1575 = 0.7575$ min/unit

$C_o = 0.10 + 6(0.15) = 1.00/\text{min}$

$P_{ap} = (1-0.005)(0.995)(0.9925)(0.990)(0.9875)(0.985) = 0.9486$

$C_{pc} = 1.00(0.7575)/0.9486 = 0.798/\text{unit}$

Conclusion: Accept Proposal 2, assuming the problem of sortation good units from bad can be solved.
Chapter 18
CELLULAR MANUFACTURING

REVIEW QUESTIONS

18.1 What is group technology?
Answer: As defined in the text, group technology is a manufacturing philosophy in which similar parts are identified and grouped together to take advantage of their similarities in design and production.

18.2 What is cellular manufacturing?
Answer: As defined in the text, cellular manufacturing is an application of group technology in which dissimilar machines or processes have been aggregated into cells, each of which is dedicated to the production of a part or product family or a limited group of families.

18.3 What are the production conditions under which group technology and cellular manufacturing are most applicable?
Answer: The conditions identified in the text are (1) the plant currently uses traditional batch production and a process type layout, and this results in much material handling effort, high in-process inventory, and long manufacturing lead times; and (2) the parts can be grouped into part families.

18.4 What are the two major tasks that a company must undertake when it implements group technology?
Answer: The two major tasks are (1) identifying the part families and (2) rearranging production machines into machine cells.

18.5 What is a part family?
Answer: As defined in the text, a part family is a collection of parts that are similar either because of geometric shape and size or because similar processing steps are required in their manufacture.

18.6 What are the three methods for solving the problem of grouping parts into part families?
Answer: The three methods are (1) visual inspection, (2) parts classification and coding, and (3) production flow analysis.

18.7 What is the difference between a hierarchical structure and a chain-type structure in a classification and coding scheme?
Answer: In a hierarchical structure, also known as a monocode, the interpretation of each successive symbol depends on the value of the preceding symbols. In a chain-type structure, also known as a polyc ode, the interpretation of each symbol in the sequence is always the same; it does not depend on the value of preceding symbols.

18.8 What is production flow analysis?
Answer: As defined in the text, production flow analysis is a method for identifying part families and associated machine groupings that uses the information contained on production route sheets rather than part drawings. Workparts with identical or similar routings are grouped into part families.

18.9 What are the typical objectives when implementing cellular manufacturing?
Answer: As enumerated in the text, the objectives are to (1) shorten manufacturing lead times, by reducing setup, workpart handling, waiting times, and batch sizes; (2) reduce work-in-process inventory; (3) improve quality; (4) simplify production scheduling; and (5) reduce setup times.

18.10 What is the composite part concept, as the term is applied in group technology?
Answer: The composite part concept is based on part families. It conceives of a hypothetical part for a given family that includes all of the design and manufacturing attributes of the family. In general, an individual part in the family will have some of the features that characterize the family, but not all of them. The composite part possesses all of the features.

18.11 What are the four common GT cell configurations, as identified in the text?
**Answer:** The four GT cell configurations listed in the text are (1) single machine cell, (2) group machine cell with manual handling, (3) group machine cell with semi-integrated handling, and (4) flexible manufacturing cell or flexible manufacturing system.

18.12 What is the key machine concept in cellular manufacturing?

**Answer:** The key machine concept acknowledges that there is typically a certain machine in a cell that is more expensive to operate than the other machines or that performs certain critical operations. This machine is referred to as the key machine. It is important that the utilization of this key machine be high, even if it means that the other machines in the cell have relatively low utilizations. The other machines are referred to as supporting machines, and they should be organized in the cell to keep the key machine busy.

18.13 What is the difference between a virtual machine cell and a formal machine cell?

**Answer:** Virtual machine cells involve the creation of part families and the dedication of equipment to the manufacture of these part families, but without the physical rearrangement of machines into formal cells. The machines in the virtual cell remain in their original locations in the factory. Formal machine cells represent the conventional GT approach in which a group of dissimilar machines are physically relocated into a cell that is dedicated to the production of one or a limited set of part.

18.14 What is the principal application of group technology in product design?

**Answer:** As indicated in the text, the principal application of GT in design is to implement a design retrieval system that reduces part proliferation.

18.15 What is the application of the rank order clustering?

**Answer:** The application of the rank order clustering in GT is grouping machines into cells based on the part-machine incidence matrix, which in turn is based on route sheets.

### PROBLEMS

#### Parts Classification and Coding

18.1 Develop the form code (first five digits) in the Opitz System for the part illustrated in Figure P18.1.

**Solution:**

$\frac{L}{D} = 0.06/0.80 = 0.075$

- Digit 1 = 0
- External shape = smooth
- Internal shape = smooth, no shape element
- Plane surface machining = none
- Auxiliary holes, etc., = none

Digit 5 = 0

Form code in Opitz system = **00100**

18.2 Develop the form code (first five digits) in the Opitz System for the part illustrated in Figure P18.2.

**Solution:**

$\frac{L}{D} = 2.5/1.5 = 1.667$

- Digit 1 = 1
- External shape = stepped, one hole
- Internal shape = smooth hole
- Plane surface machining = none
- Auxiliary holes, etc., = none

Digit 5 = 0

Form code in Opitz system = **11100**

18.3 Develop the form code (first five digits) in the Opitz System for the part illustrated in Figure P18.3.

**Solution:**

$\frac{L}{D} = 121/36 = 3.361$

- Digit 1 = 2
- External shape = stepped both ends with functional groove
- Internal shape = no hole
- Plane surface machining = none
- Auxiliary holes and gear teeth = spur gear.

Digit 5 = 6

Form code in Opitz = **26006**

#### Rank Order Clustering

18.4 Apply the rank order clustering technique to the part-machine incidence matrix in the following table to identify logical part families and machine groups. Parts are identified by letters, and machines are identified numerically.

<table>
<thead>
<tr>
<th>Parts</th>
<th>Machines</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
</table>

147
Part families and machine groups: I = (A, D) and (3, 1, 5), II = (B, C, E) and (4, 2).

18.5 Apply the rank order clustering technique to the part-machine incidence matrix in the following table to identify logical part families and machine groups. Parts are identified by letters, and machines are identified numerically.

<table>
<thead>
<tr>
<th>Machines</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
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</tr>
</tbody>
</table>

Solution:

Part families and machine groups: I = (A, B, E) and (3, 1, 5), II = (D, C, F) and (4, 2)
Apply the rank order clustering technique to the part-machine incidence matrix in the following table to identify logical part families and machine groups. Parts are identified by letters, and machines are identified numerically.

<table>
<thead>
<tr>
<th>Machines</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
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Solution:

Step 1

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<th>C</th>
<th>D</th>
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Step 2

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Part families and machine groups:  I = (A, D, I) and (7, 1)
II = (G, B, F) and (4, 2, 6)
III = (C, E, H) and (3, 8, 5)

Step 3

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Part families and machine groups:  I = (A, D, I) and (7, 1)
II = (G, B, F) and (4, 2, 6)
III = (C, E, H) and (3, 8, 5)
The following table lists the weekly quantities and routings of ten parts that are being considered for cellular manufacturing in a machine shop. Parts are identified by letters and machines are identified numerically. For the data given, (a) develop the part-machine incidence matrix, and (b) apply the rank order clustering technique to the part-machine incidence matrix to identify logical part families and machine groups.

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<th>Weekly quantity</th>
<th>Machine routing</th>
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<td>40</td>
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</tr>
<tr>
<td>J</td>
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**Solution:** (a) See step 1. (b) See steps 1 through 4.
Machine Cell Organization and Design

Four machines used to produce a family of parts are to be arranged into a GT cell. The from-to data for the parts processed by the machines are shown in the table below. (a) Determine the most logical sequence of machines for this data. (b) Construct the network diagram for the data, showing where and how many parts enter and exit the system. (c) Compute the percentages of in-sequence moves, bypassing moves, and backtracking moves in the solution. (d) Develop a feasible layout plan for the cell.

<table>
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<tr>
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Solution: (a) Hollier method

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Sequence: 3 → 1 → 4 → 2

(b) Network diagram:

(c) % in-sequence moves = (50 + 40 + 50)/170 = 0.824 = 82.4%
% bypassing moves = (20 + 10)/170 = 0.176 = 17.6%
% backtracking moves = 0

(d) Layout plan: In-line sequence of U-shaped layout is appropriate for the given flows with no backtracking.
18.10 In Problem 18.8, two logical machine groups are identified by rank order clustering. For each machine group, (a) determine the most logical sequence of machines for this data. (b) Construct the network diagram for the data. (c) Compute the percentages of in-sequence moves, bypassing moves, and backtracking moves in the solution.

**Solution:**

(a) Hollier method applied to first machine group (machines 2, 3, 4, 7):

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Sequence: 3 → 2 → 4 → 7

(b) Network diagram:

(c) % in-sequence moves = (167 + 145 + 140)/526 = 0.859 = 85.9%

% bypassing moves = 62/526 = 0.118 = 11.8%

% backtracking moves = 12/526 = 0.023 = 2.3%

(a) Hollier method applied to second machine group (machines 1, 5, 6):

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Sequence: 6 → 5 → 1

(b) Network diagram:

(c) % in-sequence moves = (85 + 70)/205 = 0.756 = 75.6%

% bypassing moves = 35/205 = 0.171 = 17.1%

% backtracking moves = 15/205 = 0.073 = 7.3%
18.11 Five machines will constitute a GT cell. The from-to data for the machines are shown in the table below. (a) Determine the most logical sequence of machines for this data, and construct the network diagram, showing where and how many parts enter and exit the system. (b) Compute the percentages of in-sequence moves, bypassing moves, and backtracking moves in the solution. (c) Develop a feasible layout plan for the cell based on the solution.

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Solution: (a) Hollier method:

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Sequence: 5 → 1 → 2 → 4 → 3

(b) % in-sequence moves = (10 + 85 + 20)/360 = 0.319 = 31.9%
% bypassing moves = (75 + 20 + 80)/360 = 0.486 = 48.6%
% backtracking moves = 70/360 = 0.194 = 19.4%

(d) Student exercise. There is no single correct solution for this design problem.

18.12 A GT machine cell contains three machines. Machine 1 feeds machine 2, the key machine in the cell. Machine 2 feeds machine 3. The cell is set up to produce a family of five parts (A, B, C, D, and E). The operation times for each part at each machine are given in the table below. The products are to be produced in the ratios 4:3:2:2:1, respectively. (a) If the machine cell runs for 35 hours per week, how many of each product will be made by the cell, and (b) what is the utilization of each machine in the cell?

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<th>Operation time</th>
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<td>26.0 min.</td>
</tr>
<tr>
<td>D</td>
<td>15.0 min.</td>
</tr>
<tr>
<td>E</td>
<td>8.0 min.</td>
</tr>
</tbody>
</table>

Solution: (a) Compute time to produce units in given ratio:
Machine 1: \( T = 4(4) + 3(15) + 2(26) + 2(15) + 1(8) = 151 \) min.
Machine 2: \( T = 4(15) + 3(18) + 2(20) + 2(20) + 1(16) = 210 \) min.
Machine 3: \( T = 4(10) + 3(7) + 2(15) + 2(10) + 1(10) = 121 \) min.
Machine 2 is the bottleneck machine that determines cell output.

Time available = 35(60) = 2100 min.

Number of cycles to produce the products in the ratio given = \( \frac{2100}{210} = 10 \) cycles
Thus, output = 10(4 + 3 + 2 + 2 + 1) = 10(12) = 120 pc.
Machine 1 utilization
\[ U = \frac{10(151)}{2100} = 0.719 = 71.9\% \]

Machine 2 utilization
\[ U = 100\% \]

Machine 3 utilization
\[ U = \frac{10(121)}{2100} = 0.576 = 57.6\% \]

18.13 A GT cell will machine the components for a family of parts. The parts come in several different sizes and the cell will be designed to quickly change over from one size to the next. This will be accomplished using fast-change fixtures and downloading the part programs from the plant computer to the CNC machines in the cell. The parts are rotational type, and so the cell must be able to perform turning, boring, facing, drilling, and cylindrical grinding operations. Accordingly, there will be several machine tools in the cell, of types and numbers to be specified by the designer. To transfer parts between machines in the cell, the designer may elect to use a belt or similar conveyor system. Any conveyor equipment of this type will be 0.4 m. wide. The arrangement of the various pieces of equipment in the cell is the principal problem to be considered. The raw workparts will be delivered into the machine cell on a belt conveyor. The finished parts must be deposited onto a conveyor that delivers them to the assembly department. The input and output conveyors are 0.4 m wide, and the designer must specify where they enter and exit the cell. The parts are currently machined by conventional methods in a process-type layout. In the current production method, there are seven machines involved but two of the machines are duplicates. "From-to" data have been collected for the jobs that are relevant to this problem.

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<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>325</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>174</td>
<td>16</td>
<td>20</td>
<td>30</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

| Parts in | 25 | 0 | 300 | 0 | 0 | 0 | 0 | 75 |

The from-to data indicate the number of workparts moved between machines during a typical 40 hour week. The data refer to the parts considered in the case. The two categories "parts in" and parts out" indicate parts entering and exiting the seven machine group. A total of 400 parts on average are processed through the seven machines each week. However, as indicated by the data, not all 400 parts are processed by every machine. Machines 4 and 5 are identical and assignment of parts to these machines is arbitrary. Average production rate capacity on each of the machines for the particular distribution of this parts family is given in the table below. Also given are the floor space dimensions of each machine in meters. Assume that all loading and unloading operations take place in the center of the machine.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Operation</th>
<th>Production rate</th>
<th>Machine dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Turn outside diameter</td>
<td>9 pc/hr</td>
<td>3.5 m x 1.5 m</td>
</tr>
<tr>
<td>2</td>
<td>Bore inside diameter</td>
<td>15 pc/hr</td>
<td>3.0 m x 1.6 m</td>
</tr>
<tr>
<td>3</td>
<td>Face ends</td>
<td>10 pc/hr</td>
<td>2.5 m x 1.5 m</td>
</tr>
<tr>
<td>4</td>
<td>Grind outside diameter</td>
<td>12 pc/hr</td>
<td>3.0 m x 1.5 m</td>
</tr>
<tr>
<td>5</td>
<td>Grind outside diameter</td>
<td>12 pc/hr</td>
<td>3.0 m x 1.5 m</td>
</tr>
<tr>
<td>6</td>
<td>Inspect</td>
<td>5 pc/hr</td>
<td>Bench 1.5 m x 1.5 m</td>
</tr>
<tr>
<td>7</td>
<td>Drill</td>
<td>9 pc/hr</td>
<td>1.5 m x 2.5 m</td>
</tr>
</tbody>
</table>

Operation 6 is currently a manual inspection operation. It is anticipated that this manual station will be replaced by a coordinate measuring machine (CMM). This automated inspection machine will triple throughput rate to 15 parts per hour from 5 parts per hour for the manual method. The floor space dimensions of the CMM are 2.0 m x 1.6 m. All other machines currently listed are to be candidates for inclusion in the new machine cell. (a) Analyze the problem and determine the most appropriate sequence of machines in the cell using the data contained in the From-To chart. (b) Construct the network diagram for the cell, showing where and how many
parts enter and exit the cell. (c) Determine the utilization and production capacity of the machines in the cell as you have designed it. (d) Prepare a layout (top view) drawing of the GT cell, showing the machines, the robot(s), and any other pieces of equipment in the cell. (e) Write a one-page (or less) description of the cell, explaining the basis of your design and why the cell is arranged as it is.

Solution: (a) Use Hollier method to analyze sequence.

<table>
<thead>
<tr>
<th>From</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>From sums</th>
<th>To sums</th>
<th>From/To ratio</th>
<th>Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>112</td>
<td>0</td>
<td>61</td>
<td>59</td>
<td>53</td>
<td>0</td>
<td>285</td>
<td>1</td>
<td>285</td>
<td>260</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>226</td>
<td>0</td>
<td>238</td>
<td>2</td>
<td>238</td>
<td>283</td>
</tr>
<tr>
<td>3</td>
<td>74</td>
<td>0</td>
<td>0</td>
<td>35</td>
<td>31</td>
<td>0</td>
<td>180</td>
<td>320</td>
<td>3</td>
<td>320</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>82</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>23</td>
<td>5</td>
<td>110</td>
<td>4</td>
<td>110</td>
<td>126</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>73</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>23</td>
<td>0</td>
<td>96</td>
<td>5</td>
<td>96</td>
<td>110</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>60</td>
<td>6</td>
<td>0</td>
<td>325</td>
</tr>
<tr>
<td>7</td>
<td>174</td>
<td>16</td>
<td>20</td>
<td>30</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>260</td>
<td>7</td>
<td>260</td>
<td>185</td>
</tr>
</tbody>
</table>

Sequence: 3 → 7 → 1 → 4, 5 → 2 → 6

(b) Network diagram: Combine operations 4 and 5 into one operation; call it operation 4.

(c) Utilization and production capacity

<table>
<thead>
<tr>
<th>Op.</th>
<th>Throughput</th>
<th>Production rate</th>
<th>Capacity</th>
<th>Hrs/wk</th>
<th>Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>285 pc/wk</td>
<td>9 pc/hr</td>
<td>369 pc/wk</td>
<td>31.7 hr</td>
<td>0.792</td>
</tr>
<tr>
<td>2</td>
<td>283 pc/wk</td>
<td>15 pc/hr</td>
<td>600 pc/wk</td>
<td>18.9 hr</td>
<td>0.472</td>
</tr>
<tr>
<td>3</td>
<td>320 pc/wk</td>
<td>10 pc/hr</td>
<td>400 pc/wk</td>
<td>32.0 hr</td>
<td>0.800</td>
</tr>
<tr>
<td>4*</td>
<td>236 pc/wk</td>
<td>12 pc/hr</td>
<td>480 pc/wk</td>
<td>19.7 hr</td>
<td>0.492</td>
</tr>
<tr>
<td>6</td>
<td>325 pc/wk</td>
<td>15 pc/hr</td>
<td>600 pc/wk</td>
<td>21.7 hr</td>
<td>0.542</td>
</tr>
<tr>
<td>7</td>
<td>260 pc/wk</td>
<td>9 pc/hr</td>
<td>360 pc/wk</td>
<td>28.9 hr</td>
<td>0.722</td>
</tr>
</tbody>
</table>

* Operations 4 and 5 combined into operation 4.

(d) and (e) Cell design and one page essay: Student exercises. There is no single correct solution to this design problem.
Chapter 19
FLEXIBLE MANUFACTURING SYSTEMS

REVIEW QUESTIONS

19.1 Name three production situations in which FMS technology can be applied?

Answer: The situations are similar to those identified for cellular manufacturing. They are the following: (1) Presently, the plant either produces parts in batches or uses manned GT cells and management wants to automate. (2) It must be possible to group a portion of the parts made in the plant into part families, whose similarities permit them to be processed on the machines in the flexible manufacturing system. (3) The parts or products made by the facility are in the mid-volume, mid-variety production range. The appropriate production volume range is 5000 to 75,000 parts per year.

19.2 What is a flexible manufacturing system?

Answer: The definition provided in the text is the following: A flexible manufacturing system (FMS) is a highly automated GT machine cell, consisting of a group of processing workstations (usually CNC machine tools), interconnected by an automated material handling and storage system, and controlled by a distributed computer system. The reason the FMS is called flexible is that it is capable of processing a variety of different part styles simultaneously at the various workstations, and the mix of part styles and quantities of production can be adjusted in response to changing demand patterns.

19.3 What are the three capabilities that a manufacturing system must possess in order to be flexible?

Answer: The three capabilities that a manufacturing system must possess in order to be flexible are (1) the ability to identify and distinguish among the different incoming part or product styles processed by the system, (2) quick changeover of operating instructions, and (3) quick changeover of physical setup.

19.4 Name the four tests of flexibility that a manufacturing system must satisfy in order to be classified as flexible.

Answer: The four tests of flexibility that a manufacturing system must satisfy in order to be classified as flexible are the following, as identified in the text: (1) Part variety test. Can the system process different part styles in a non-batch mode? (2) Schedule change test. Can the system readily accept changes in production schedule: changes in either part mix or production quantities? (3) Error recovery test. Can the system recover gracefully from equipment malfunctions and breakdowns, so that production is not completely disrupted? (4) New part test. Can new part designs be introduced into the existing product mix with relative ease?

19.5 What is the dividing line between a flexible manufacturing cell and a flexible manufacturing system, in terms of the number of workstations in the system?

Answer: The dividing line is between 3 and 4 workstations. A flexible manufacturing cell has 2 or 3 stations, while a flexible manufacturing system has 4 or more stations.

19.6 What is the difference between a dedicated FMS and a random-order FMS?

Answer: As defined in the text, a dedicated FMS is designed to produce a limited variety of part styles, and the complete universe of parts to be made on the system is known in advance. By comparison, a random-order FMS is more flexible and is more appropriate when the part family is large, there are substantial variations in part configurations, there will be new part designs introduced into the system and engineering changes in parts currently produced, and the production schedule is subject to change from day to day.

19.7 What are the four basic components of a flexible manufacturing system?

Answer: The text lists the following as the four basic components: (1) workstations, (2) material handling and storage system, (3) computer control system, and (4) people who are required to manage and operate the system.

19.8 What are three of the five functions of the material handling and storage system in a flexible manufacturing system?

Answer: The five functions of the material handling and storage system identified in the text are the following: (1) random, independent movement of workparts between stations; (2) handling of a variety of
workpart configurations; (3) temporary storage; (4) convenient access for loading and unloading workparts; and
(5) compatibility with computer control.

19.9 What is the difference between the primary and secondary handling systems that are common in flexible manufacturing systems?

**Answer:** The primary handling system establishes the basic layout of the FMS and is responsible for moving parts between stations in the system, whereas the secondary handling system consists of transfer devices, automatic pallet changers, and similar mechanisms located at the workstations in the FMS. The function of the secondary handling system is to transfer work from the primary system to the workstation and to position parts with sufficient accuracy and repeatability to perform the processing or assembly operation.

19.10 The text lists five categories of layout configurations that are found in a flexible manufacturing system. Name four of the five layout configurations.

**Answer:** The five categories listed in the text are (1) in-line layout, (2) loop layout, (3) ladder layout, (4) open field layout, and (5) robot-centered layout.

19.11 Name four of the seven functions performed by human resources in an FMS.

**Answer:** The seven functions listed in the text are (1) loading raw workparts into the system, (2) unloading finished parts (or assemblies) from the system, (3) changing and setting tools, (4) equipment maintenance and repair, (5) NC part programming, (6) programming and operating the computer system, and (7) overall management of the system.

19.12 What are four benefits that can be expected from a successful FMS installation?

**Answer:** The text lists the following benefits of a successful FMS installation: (1) increased machine utilization, (2) fewer machines required to accomplish the same amount of work, (3) reduction in factory floor space required, (4) greater responsiveness to change, (5) reduced inventory requirements, (6) lower manufacturing lead times, (7) reduced labor requirements and higher labor productivity, and (8) opportunity for unattended operation.

**PROBLEMS**

**Bottleneck Model**

19.1 A flexible manufacturing cell consists of two machining workstations plus a load/unload station. The load/unload station is station 1. Station 2 performs milling operations and consists of one server (one CNC milling machine). Station 3 has one server that performs drilling (one CNC drill press). The three stations are connected by a part handling system that has one work carrier. The mean transport time is 2.5 min. The FMC produces three parts, A, B, and C. The part mix fractions and process routings for the three parts are presented in the table below. The operation frequency \( f_{ijk} = 1.0 \) for all operations. Determine (a) maximum production rate of the FMC, (b) corresponding production rates of each product, (c) utilization of each machine in the system, and (d) number of busy servers at each station.

<table>
<thead>
<tr>
<th>Part</th>
<th>( p_j )</th>
<th>Operation ( k )</th>
<th>Description</th>
<th>Station ( i )</th>
<th>Process time ( t_{ijk} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.2</td>
<td>1</td>
<td>Load</td>
<td>1</td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Mill</td>
<td>2</td>
<td>20 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Drill</td>
<td>3</td>
<td>12 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Unload</td>
<td>1</td>
<td>2 min</td>
</tr>
<tr>
<td>B</td>
<td>0.3</td>
<td>1</td>
<td>Load</td>
<td>1</td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Mill</td>
<td>2</td>
<td>15 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Drill</td>
<td>3</td>
<td>30 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Unload</td>
<td>1</td>
<td>2 min</td>
</tr>
<tr>
<td>C</td>
<td>0.5</td>
<td>1</td>
<td>Load</td>
<td>1</td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Drill</td>
<td>3</td>
<td>14 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Mill</td>
<td>2</td>
<td>22 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Unload</td>
<td>1</td>
<td>2 min</td>
</tr>
</tbody>
</table>

**Solution:** (a) \( WL_1 = (3+2)(0.2)(1.0) + (3+2)(0.3)(1.0) + (3+2)(0.5)(1.0) = 5.0 \) min

\( WL_2 = 20(0.2)(1.0) + 15(0.3)(1.0) + 22(0.5)(1.0) = 19.5 \) min
WL_3 = 12(0.2)(1.0) + 30(0.3)(1.0) + 14(0.5)(1.0) = 18.4 \text{ min} \\
WL_4 = 3(2.5) = 7.5 \text{ min} \\
Bottleneck station has largest \( WL_i/s_i \) ratio:

<table>
<thead>
<tr>
<th>Station</th>
<th>( WL_i/s_i ) ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (load/unload)</td>
<td>5.0/1 = 5.0 min</td>
</tr>
<tr>
<td>2 (mill)</td>
<td>19.5/1 = 19.5 min</td>
</tr>
<tr>
<td>3 (drill)</td>
<td>18.4/1 = 18.4 min</td>
</tr>
<tr>
<td>4 (material handling)</td>
<td>7.5/1 = 7.5 min</td>
</tr>
</tbody>
</table>

Bottleneck is station 2: \( R_p^* = 1/19.5 = 0.05128 \text{ pc/min} = 3.077 \text{ pc/hr} \)

(b) \( R_{pA} = 0.05128(0.2) = 0.01026 \text{ pc/min} = 0.6154 \text{ pc/hr} \) \\
\( R_{pB} = 0.05128(0.3) = 0.01538 \text{ pc/min} = 0.9231 \text{ pc/hr} \) \\
\( R_{pC} = 0.05128(0.5) = 0.02564 \text{ pc/min} = 1.5385 \text{ pc/hr} \)

(c) \( U_1 = (5.0/1)(0.05128) = 0.256 = 25.6\% \) \\
\( U_2 = (19.5/1)(0.05128) = 1.0 = 100\% \) \\
\( U_3 = (18.4/1)(0.05128) = 0.944 = 94.4\% \) \\
\( U_4 = (7.5/1)(0.05128) = 0.385 = 38.5\% \)

(d) \( BS_1 = (5.0)(0.05128) = 0.256 \text{ servers} \) \\
\( BS_2 = (19.5)(0.05128) = 1.0 \text{ servers} \) \\
\( BS_3 = (18.4)(0.05128) = 0.944 \text{ servers} \) \\
\( BS_4 = (7.5)(0.05128) = 0.385 \text{ servers} \)

19.2 Solve Problem 19.1 except the number of servers at station 2 (CNC milling machines) = 3 and the number of servers at station 3 (CNC drill presses) = 2. Note that with the increase in the number of machines from two to five, the FMC is now a FMS according to our definitions in Section 19.1.2.

**Solution:** (a) \( WL_1 = (3+2)(0.2)(1.0) + (3+2)(0.3)(1.0) + (3+2)(0.5)(1.0) = 5.0 \text{ min} \) \\
\( WL_2 = 20(0.2)(1.0) + 15(0.3)(1.0) + 22(0.5)(1.0) = 19.5 \text{ min} \) \\
\( WL_3 = 12(0.2)(1.0) + 30(0.3)(1.0) + 14(0.5)(1.0) = 18.4 \text{ min} \) \\
\( WL_4 = 3(2.5) = 7.5 \text{ min} \) \\
Bottleneck station has largest \( WL_i/s_i \) ratio:

<table>
<thead>
<tr>
<th>Station</th>
<th>( WL_i/s_i ) ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (load/unload)</td>
<td>5.0/1 = 5.0 min</td>
</tr>
<tr>
<td>2 (mill)</td>
<td>19.5/3 = 6.5 min</td>
</tr>
<tr>
<td>3 (drill)</td>
<td>18.4/2 = 9.2 min</td>
</tr>
<tr>
<td>4 (material handling)</td>
<td>7.5/1 = 7.5 min</td>
</tr>
</tbody>
</table>

Bottleneck is station 3: \( R_p^* = 2/18.4 = 0.1087 \text{ pc/min} = 6.522 \text{ pc/hr} \)

(b) \( R_{pA} = 0.1087(0.2) = 0.02174 \text{ pc/min} = 1.3043 \text{ pc/hr} \) \\
\( R_{pB} = 0.1087(0.3) = 0.03261 \text{ pc/min} = 1.9565 \text{ pc/hr} \) \\
\( R_{pC} = 0.1087(0.5) = 0.05435 \text{ pc/min} = 3.261 \text{ pc/hr} \)

(c) \( U_1 = (5.0/1)(0.1087) = 0.544 = 54.4\% \) \\
\( U_2 = (19.5/3)(0.1087) = 0.706 = 70.6\% \) \\
\( U_3 = (18.4/2)(0.1087) = 1.00 = 100\% \) \\
\( U_4 = (7.5/1)(0.1087) = 0.815 = 81.5\% \)

(d) \( BS_1 = (5.0)(0.1087) = 0.544 \text{ servers} \) \\
\( BS_2 = (19.5)(0.1087) = 2.12 \text{ servers} \) \\
\( BS_3 = (18.4)(0.1087) = 2.0 \text{ servers} \) \\
\( BS_4 = (7.5)(0.1087) = 0.815 \text{ servers} \)

19.3 A FMS consists of three stations plus a load/unload station. Station 1 loads and unloads parts using two servers (material handling workers). Station 2 performs horizontal milling operations with two servers (identical CNC
horizontal milling machines). Station 3 performs vertical milling operations with three servers (identical CNC vertical milling machines). Station 4 performs drilling operations with two servers (identical drill presses). The machines are connected by a part handling system that has two work carriers and a mean transport time = 3.5 min. The FMS produces four parts, A, B, C, and D, whose part mix fractions and process routings are presented in the table below. The operation frequency $f_{ijk} = 1.0$ for all operations. Determine (a) maximum production rate of the FMS, (b) utilization of each machine in the system, and (c) average utilization of the system $U$.

<table>
<thead>
<tr>
<th>Part $j$</th>
<th>Part mix $p_j$</th>
<th>Operation $k$</th>
<th>Description</th>
<th>Station $i$</th>
<th>Process time $t_{ijk}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.2</td>
<td>1</td>
<td>Load</td>
<td>1</td>
<td>4 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>H. Mill</td>
<td>2</td>
<td>15 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>V Mill</td>
<td>3</td>
<td>14 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Drill</td>
<td>4</td>
<td>13 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>Unload</td>
<td>1</td>
<td>3 min</td>
</tr>
<tr>
<td>B</td>
<td>0.2</td>
<td>1</td>
<td>Load</td>
<td>1</td>
<td>4 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Drill</td>
<td>4</td>
<td>12 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>H. Mill</td>
<td>2</td>
<td>16 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>V. Mill</td>
<td>3</td>
<td>11 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>Drill</td>
<td>4</td>
<td>17 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>Unload</td>
<td>1</td>
<td>3 min</td>
</tr>
<tr>
<td>C</td>
<td>0.25</td>
<td>1</td>
<td>Load</td>
<td>1</td>
<td>4 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>H. Mill</td>
<td>2</td>
<td>10 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Drill</td>
<td>4</td>
<td>9 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Unload</td>
<td>1</td>
<td>3 min</td>
</tr>
<tr>
<td>D</td>
<td>0.35</td>
<td>1</td>
<td>Load</td>
<td>1</td>
<td>4 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>V. Mill</td>
<td>3</td>
<td>18 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Drill</td>
<td>4</td>
<td>8 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Unload</td>
<td>1</td>
<td>3 min</td>
</tr>
</tbody>
</table>

**Solution:**

\[ WL_1 = (4+3)(0.2)(1.0) + (4+3)(0.2)(1.0) + (4+3)(0.25)(1.0) + (4+3)(0.35)(1.0) = 7.0 \text{ min} \]

\[ WL_2 = 15(0.2)(1.0) + 16(0.2)(1.0) + 10(0.25)(1.0) = 8.7 \text{ min} \]

\[ WL_3 = 14(0.2)(1.0) + 11(0.2)(1.0) + 18(0.35)(1.0) = 11.3 \text{ min} \]

\[ WL_4 = 13(0.2)(1.0) + (12+17)(0.2)(1.0) + 9(0.25)(1.0) + 8(0.35)(1.0) = 13.45 \text{ min} \]

\[ n_i = 4(0.2) + 5(0.2) + 3(0.25) + 3(0.35) = 3.6, \quad WL_5 = 3.6(3.5) = 12.6 \text{ min} \]

<table>
<thead>
<tr>
<th>Station</th>
<th>$WL_i/s$, ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (load/unload)</td>
<td>7.0/2 = 3.5 min</td>
</tr>
<tr>
<td>2 (drill)</td>
<td>8.7/2 = 4.35 min</td>
</tr>
<tr>
<td>3 (H. mill)</td>
<td>11.3/3 = 3.77 min</td>
</tr>
<tr>
<td>4 (V. mill)</td>
<td>13.45/2 = 6.725 min</td>
</tr>
<tr>
<td>5 (material handling)</td>
<td>12.6/2 = 6.3 min ← Bottleneck</td>
</tr>
</tbody>
</table>

Bottleneck is station 4 (vertical mill): $R^*_p = 2/13.45 = 0.1487 \text{ pc/min} = 8.92 \text{ pc/hr}$

(b) $U_1 = (7.0/2)(0.1487) = 0.555 = 55.5\%$

$U_2 = (8.7/2)(0.1487) = 0.690 = 69.0\%$

$U_3 = (11.3/3)(0.1487) = 0.598 = 59.8\%$

$U_4 = (13.45/2)(0.1487) = 0.893 = 89.3\%$

$U_5 = (12.6/2)(0.1487) = 1.0 = 100\%$

(c) $\bar{U}_s = \frac{2(0.555) + 2(0.69) + 3(0.598) + 2(0.893)}{9} = 0.674 = 67.4\%$

19.4 Solve Problem 19.3 except the number of carriers in the part handling system = 3.

**Solution:**

\[ WL_1 = (4+3)(0.2)(1.0) + (4+3)(0.2)(1.0) + (4+3)(0.25)(1.0) + (4+3)(0.35)(1.0) = 7.0 \text{ min} \]

\[ WL_2 = 15(0.2)(1.0) + 16(0.2)(1.0) + 10(0.25)(1.0) = 8.7 \text{ min} \]

\[ WL_3 = 14(0.2)(1.0) + 11(0.2)(1.0) + 18(0.35)(1.0) = 11.3 \text{ min} \]

\[ WL_4 = 13(0.2)(1.0) + (12+17)(0.2)(1.0) + 9(0.25)(1.0) + 8(0.35)(1.0) = 13.45 \text{ min} \]
\[ n_t = 4(0.2) + 5(0.2) + 3(0.25) + 3(0.35) = 3.6, \quad WL_5 = 3.6(3.5) = 12.6 \text{ min} \]

<table>
<thead>
<tr>
<th>Station</th>
<th>WL/s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (load/unload)</td>
<td>7.0/2 = 3.5 min</td>
</tr>
<tr>
<td>2 (drill)</td>
<td>8.7/2 = 4.35 min</td>
</tr>
<tr>
<td>3 (H. mill)</td>
<td>11.3/3 = 3.77 min</td>
</tr>
<tr>
<td>4 (V. mill)</td>
<td>13.45/2 = 6.725 min ← Bottleneck</td>
</tr>
<tr>
<td>5 (material handling)</td>
<td>12.6/3 = 4.2 min</td>
</tr>
</tbody>
</table>

Bottleneck is station 4: \( R_p^* = 2/13.45 = 0.1487 \text{ pc/min} = 8.92 \text{ pc/hr} \)

(b) \( U_1 = (7.0/2)(0.1487) = 0.520 = 52.0\% \)
\( U_2 = (8.7/2)(0.1487) = 0.647 = 64.7\% \)
\( U_3 = (10.5/3)(0.1487) = 0.560 = 52.0\% \)
\( U_4 = (11.25/2)(0.1487) = 1.00 = 100\% \)
\( U_5 = (12.6/2)(0.1487) = 0.624 = 62.4\% \)

(c) \( \bar{U} = \frac{2(0.520) + 2(0.647) + 3(0.560) + 2(1.0)}{9} = 0.668 = 66.8\% \)

19.5 Suppose it is decided to increase the utilization of the two non-bottleneck machining stations in the FMS of Problem 19.4 by introducing a new part, part E, into the part mix. If the new product will be produced at a rate of 2 units per hour, what would be the ideal process routing (sequence and processing times) for part E that would increase the utilization of the two non-bottleneck machining stations to 100% each. The respective production rates of parts A, B, C, and D will remain the same as they are in Problem 19.4. Disregard the utilizations of the load/unload station and the part handling system.

**Solution:** Ideal process routing would be \( 1 \rightarrow 2 \rightarrow 3 \rightarrow 1 \)

Consider station 2: let \( U_2 = 100\% \); that is, \( U_2 = \frac{WL_2}{2}(0.1487) = 1.0 \)

At \( U_2 = 1.0, \ WL_2 = 1.0(2)/0.1487 = 13.45 \text{ min} \)

Current \( WL_2 = 8.7 \text{ min} \)

\( \Delta WL_2(E) = 13.45 - 8.7 = 4.75 \text{ min} \)

\( R_pE = 2 \text{ pc/hr}, \text{ so total } R_p^* = 8.92 + 2 = 10.92 \text{ pc/hr} \)

\( p_E = 2/10.92 = 0.1832 \)

\( \Delta WL_2(E) = 4.75 \text{ min} = t_{3E2} (1.0)(0.1832) \)

Ideal process time \( t_{3E2} = 4.75/0.1832 = 25.93 \text{ min} \)

Consider station 3: let \( U_3 = 100\% \); that is, \( U_3 = \frac{WL_3}{3}(0.1487) = 1.0 \)

At \( U_3 = 1.0, \ WL_3 = 1.0(3)/0.1487 = 20.175 \text{ min} \)

Current \( WL_3 = 11.3 \text{ min} \)

\( \Delta WL_3(E) = 20.175 - 11.3 = 8.875 \text{ min} \)

From the computation above, \( p_E = 0.1832 \)

8.875 min = \( t_{3E3} (1.0)(0.1832) \)

Ideal process time \( t_{3E3} = 8.875/0.1832 = 48.44 \text{ min} \)

New part mix fractions:

\( p_A = (8.92/10.92)(0.2) = 0.1634 \)
\( p_B = (8.92/10.92)(0.2) = 0.1634 \)
\( p_C = (8.92/10.92)(0.25) = 0.2042 \)
\( p_D = (8.92/10.92)(0.35) = 0.2859 \)
\( p_E = 0.1832 \text{ as calculated above.} \)

19.6 A semi-automated flexible manufacturing cell is used to produce three products. The products are made by two automated processing stations followed by an assembly station. There is also a load/unload station. Material handling between stations in the FMC is accomplished by mechanized carts that move tote bins containing the particular components to be processed and then assembled into a given product. The carts transfer tote bins
between stations. In this way the carts are kept busy while the tote bins are queued in front of the workstations. Each tote bin remains with the product throughout processing and assembly. The details of the FMC can be summarized as follows:

<table>
<thead>
<tr>
<th>Station</th>
<th>Description</th>
<th>Number of servers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Load and unload</td>
<td>1 human worker</td>
</tr>
<tr>
<td>2</td>
<td>Process X</td>
<td>1 automated server</td>
</tr>
<tr>
<td>3</td>
<td>Process Y</td>
<td>1 automated server</td>
</tr>
<tr>
<td>4</td>
<td>Assembly</td>
<td>2 human workers</td>
</tr>
<tr>
<td>5</td>
<td>Transport</td>
<td>Number of carriers to be determined.</td>
</tr>
</tbody>
</table>

The product mix fractions and station processing times for the parts are presented in the table below. The same station sequence is followed by all products: 1 → 2 → 3 → 4 → 1.

<table>
<thead>
<tr>
<th>Product</th>
<th>Product mix $p_j$</th>
<th>Station 1</th>
<th>Station 2</th>
<th>Station 3</th>
<th>Station 4</th>
<th>Station 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.35</td>
<td>3 min</td>
<td>9 min</td>
<td>7 min</td>
<td>5 min</td>
<td>2 min</td>
</tr>
<tr>
<td>B</td>
<td>0.25</td>
<td>3 min</td>
<td>5 min</td>
<td>8 min</td>
<td>5 min</td>
<td>2 min</td>
</tr>
<tr>
<td>C</td>
<td>0.40</td>
<td>3 min</td>
<td>4 min</td>
<td>6 min</td>
<td>8 min</td>
<td>2 min</td>
</tr>
</tbody>
</table>

The average cart transfer time between stations is 4 minutes. (a) What is the bottleneck station in the FMC, assuming that the material handling system is not the bottleneck? (b) At full capacity, what is the overall production rate of the system and the rate for each product? (c) What is the minimum number of carts in the material handling system required to keep up with the production workstations? (d) Compute the overall utilization of the FMC. (e) What recommendation would you make to improve the efficiency and/or reduce the cost of operating the FMC?

**Solution:**

- $WL_1 = (3+2)(0.35 + 0.25 + 0.4) = 5.0$ min
- $WL_2 = 9(0.35)(1.0) + 5(0.25)(1.0) + 4(0.4)(1.0) = 6.0$ min
- $WL_3 = 7(0.35)(1.0) + 8(0.25)(1.0) + 6(0.4)(1.0) = 6.85$ min
- $WL_4 = 5(0.35)(1.0) + 5(0.25)(1.0) + 8(0.4)(1.0) = 6.2$ min
- $nt = 4$ for all parts, $WL_5 = 4(4) = 16.0$ min

<table>
<thead>
<tr>
<th>Station</th>
<th>$WL/s_i$ ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (load/unload)</td>
<td>5.0/1 = 5.0 min</td>
</tr>
<tr>
<td>2 (process X)</td>
<td>6.0/1 = 6.0 min</td>
</tr>
<tr>
<td>3 (process Y)</td>
<td>6.85/1 = 6.85 min</td>
</tr>
<tr>
<td>4 (assembly)</td>
<td>6.2/2 = 3.1 min</td>
</tr>
<tr>
<td>5 (transport)</td>
<td>16.0/nc</td>
</tr>
</tbody>
</table>

(b) Bottleneck is station 3: $R_p^* = 1/6.85 = 0.146$ pc/min = 8.76 pc/hr

- $R_{pA} = 0.35(8.76) = 3.07$ pc/hr
- $R_{pB} = 0.25(8.76) = 2.19$ pc/hr
- $R_{pC} = 0.4(8.76) = 3.50$ pc/hr

(c) Minimum number of carts required in system: 16.0/nc = 6.85
Rearranging, $nc = 16/6.85 = 2.34$ → Use 3 carts

(d) $U_1 = (5.0/1)(0.146) = 0.73 = 73.0\%$
$U_2 = (6.0/1)(0.146) = 0.876 = 87.6\%$
$U_3 = (6.85/1)(0.146) = 1.0 = 100\%$
$U_4 = (6.2/2)(0.146) = 0.453 = 45.3\%$
$U_5 = (16.0/3)(0.146) = 0.779 = 77.9\%$

$$U_s = \frac{1(0.73) + 1(0.876) + 1(1.0) + 2(0.453)}{5} = 0.7024 = 70.24\%$$

(e) Recommendation: reduce number of servers at station 4 to 1 server.
**Extended Bottleneck Model**

19.7 Use the extended bottleneck model to solve problem 19.1 with the following number of parts in the system: (a) \( N = 2 \) parts and (b) \( N = 4 \) parts. Also determine the manufacturing lead time for the two cases of \( N \) in (a) and (b).

**Solution:** See solution to Problem 19.1.

\[ MLT_1 = 5.0 + 19.5 + 18.4 + 7.5 = 50.4 \text{ min} \]

\( R_{p*} = 0.05128 \text{ pc/min} \) from solution to Problem 19.1.

\( N^* = 0.05128(50.4) = 2.58 \)

(a) For \( N = 2 < N^* = 2.58 \), apply case 1 (Table 19.5)

\[ MLT_1 = 50.4 \text{ min}, \text{ and } T_w = 0 \]

\( R_p = 2/50.4 = 0.0397 \text{ pc/min} = 2.38 \text{ pc/hr} \)

\( R_{pA} = 0.0397(0.2) = 0.00794 \text{ pc/min} = 0.476 \text{ pc/hr} \)

\( R_{pB} = 0.0397(0.3) = 0.01191 \text{ pc/min} = 0.714 \text{ pc/hr} \)

\( R_{pC} = 0.0397(0.5) = 0.01985 \text{ pc/min} = 1.191 \text{ pc/hr} \)

\( U_1 = (5.0/1)(0.0397) = 0.198 = 19.8\% \)

\( U_2 = (19.5/1)(0.0397) = 0.774 = 77.4\% \)

\( U_3 = (18.4/1)(0.0397) = 0.730 = 73.0\% \)

\( U_4 = (7.5/1)(0.0397) = 0.298 = 29.8\% \)

\( BS_1 = (5.0)(0.0397) = 0.198 \text{ servers} \)

\( BS_2 = (19.5)(0.0397) = 0.774 \text{ servers} \)

\( BS_3 = (18.4)(0.0397) = 0.730 \text{ servers} \)

\( BS_4 = (7.5)(0.0397) = 0.298 \text{ servers} \)

(b) \( N = 4 > N^* = 2.58 \), apply case 2 (Table 19.5)

\( R_{p*} = 0.05128 \text{ pc/min} = 3.077 \text{ pc/hr} \)

\[ MLT_2 = 4/0.05128 = 78.0 \text{ min}, \text{ and } T_w = 78.0 - 50.4 = 27.6 \text{ min} \]

\( R_{pA} = 0.05128(0.2) = 0.01026 \text{ pc/min} = 0.6154 \text{ pc/hr} \)

\( R_{pB} = 0.05128(0.3) = 0.01538 \text{ pc/min} = 0.9231 \text{ pc/hr} \)

\( R_{pC} = 0.05128(0.5) = 0.02564 \text{ pc/min} = 1.5385 \text{ pc/hr} \)

\( U_1 = (5.0/1)(0.05128) = 0.256 = 25.6\% \)

\( U_2 = (19.5/1)(0.05128) = 1.0 = 100\% \)

\( U_3 = (18.4/1)(0.05128) = 0.944 = 94.4\% \)

\( U_4 = (7.5/1)(0.05128) = 0.385 = 38.5\% \)

\( BS_1 = (5.0)(0.05128) = 0.256 \text{ servers} \)

\( BS_2 = (19.5)(0.05128) = 1.0 \text{ servers} \)

\( BS_3 = (18.4)(0.05128) = 0.944 \text{ servers} \)

\( BS_4 = (7.5)(0.05128) = 0.385 \text{ servers} \)

* These answers are the same as in Problem 19.1

19.8 Use the extended bottleneck model to solve problem 19.2 with the following number of parts in the system: (a) \( N = 3 \) parts and (b) \( N = 6 \) parts. Also determine the manufacturing lead time for the two cases of \( N \) in (a) and (b).

**Solution:** See solution to Problem 19.2.

\[ MLT_1 = 5.0 + 19.5 + 18.4 + 7.5 = 50.4 \text{ min} \]

\( R_{p*} = 0.1087 \text{ pc/min} \) from solution to Problem 19.2.

\( N^* = 0.1087(50.4) = 5.48 \)

(a) For \( N = 3 < N^* = 5.48 \), apply case 1 (Table 19.5)

\[ MLT_1 = 50.4 \text{ min}, \text{ and } T_w = 0 \]

\( R_p = 3/50.4 = 0.0595 \text{ pc/min} = 3.57 \text{ pc/hr} \)

\( R_{pA} = 0.0595(0.2) = 0.0119 \text{ pc/min} = 0.714 \text{ pc/hr} \)

\( R_{pB} = 0.0595(0.3) = 0.0178 \text{ pc/min} = 1.071 \text{ pc/hr} \)

\( R_{pC} = 0.0595(0.5) = 0.02975 \text{ pc/min} = 1.785 \text{ pc/hr} \)

\( U_1 = (5.0/1)(0.0595) = 0.297 = 29.7\% \)
164

(b) \( N = 6 > N^* = 5.48 \), apply case 2 (Table 19.5)

\[ R_p^* = 0.1087 \text{ pc/min} = 6.52 \text{ pc/hr} \]

\[ MLT_1 = 6/0.1087 = 55.2 \text{ min}, \text{ and } T_w = 55.2 - 50.4 = 4.8 \text{ min} \]

\[ R_pA = 0.1087(0.2) = 0.02174 \text{ pc/min} = 1.3043 \text{ pc/hr}^* \]

\[ R_pB = 0.1087(0.3) = 0.03261 \text{ pc/min} = 1.9565 \text{ pc/hr}^* \]

\[ R_pC = 0.1087(0.5) = 0.05435 \text{ pc/min} = 3.261 \text{ pc/hr}^* \]

\( U_1 = (5.0/1)(0.1087) = 0.544 = 54.4\%^* \)

\( U_2 = (19.5/3)(0.1087) = 0.706 = 70.6\%^* \)

\( U_3 = (18.4/2)(0.1087) = 1.00 = 100\%^* \)

\( U_4 = (7.5/1)(0.1087) = 0.815 = 81.5\%^* \)

\( BS_1 = (5.0)(0.1087) = 0.544 \text{ servers}^* \)

\( BS_2 = (19.5)(0.1087) = 2.12 \text{ servers}^* \)

\( BS_3 = (18.4)(0.1087) = 2.0 \text{ servers}^* \)

\( BS_4 = (7.5)(0.1087) = 0.815 \text{ servers}^* \)

* These answers are the same as in Problem 19.2.

19.9 Use the extended bottleneck model to solve problem 19.3 with the following number of parts in the system: (a) \( N = 6 \) parts, (b) \( N = 8 \) parts, and (c) \( N = 10 \) parts. Also determine the manufacturing lead time for the three cases of \( N \) in (a), (b), and (c).

**Solution:** See solution to Problem 19.3.

\[ MLT_1 = 7.0 + 8.7 + 10.5 + 11.25 + 12.6 = 50.05 \text{ min} \]

\[ R_p^* = 0.1587 \text{ pc/min from solution to Problem 19.3.} \]

\( N^* = 0.1587(50.05) = 7.94 \)

(a) For \( N = 6 < N^* = 7.94 \), apply case 1 (Table 19.5)

\[ MLT_1 = 50.05 \text{ min}, \text{ and } T_w = 0 \]

\[ R_p = 6/50.05 = 0.1199 \text{ pc/min} = 7.19 \text{ pc/hr} \]

\[ U_1 = (7.0/2)(0.1199) = 0.42 = 42\% \]

\( U_2 = (8.7/2)(0.1199) = 0.522 = 52.2\% \)

\( U_3 = (10.5/3)(0.1199) = 0.42 = 42\% \)

\( U_4 = (11.25/2)(0.1199) = 0.674 = 67.4\% \)

\( U_5 = (12.6/2)(0.1199) = 0.755 = 75.5\% \)

\[ \bar{U}_s = \frac{2(0.42) + 2(0.522) + 3(0.42) + 2(0.674)}{9} = 0.499 = 49.9\% \]

(b) \( N = 8 > N^* = 7.94 \), apply case 2 (Table 19.5)

\[ R_p^* = 0.1587 \text{ pc/min} = 9.52 \text{ pc/hr} \]

\[ MLT_2 = 8/0.1587 = 50.4 \text{ min}, \text{ and } T_w = 50.4 - 50.05 = 0.35 \text{ min} \]

\[ U_1 = (7.0/2)(0.1587) = 0.555 = 55.5\%^* \]

\( U_2 = (8.7/2)(0.1587) = 0.690 = 69.0\%^* \)

\( U_3 = (10.5/3)(0.1587) = 0.555 = 55.5\%^* \)

\( U_4 = (11.25/2)(0.1587) = 0.893 = 89.3\%^* \)

\( U_5 = (12.6/2)(0.1587) = 1.0 = 100\%^* \)

\[ \bar{U}_s = \frac{2(0.555) + 2(0.60) + 3(0.555) + 2(0.893)}{9} = 0.660 = 66.0\%^* \]
(c) \( N = 10 > \lambda^* = 7.94 \), apply case 2 (Table 19.5)
\[ R_p^* = 0.1587 \text{ pc/min} = 9.52 \text{ pc/hr} \]
\[ MLT_2 = 12/0.1587 = 67.5 \text{ min}, \text{ and } T_w = 67.5 - 50.05 = 17.45 \text{ min} \]
\[ U_1 = (7.0/2)(0.1778) = 0.622 = 62.2\%* \]
\[ U_2 = (8.7/2)(0.1778) = 0.773 = 77.3\%* \]
\[ U_3 = (10.5/3)(0.1778) = 0.622 = 62.2\%* \]
\[ U_4 = (11.25/2)(0.1778) = 1.0 = 100\%* \]
\[ U_5 = (12.6/3)(0.1778) = 0.747 = 74.7\%* \]
\[ \bar{U}_s = \frac{2(0.622) + 2(0.773) + 3(0.622) + 2(1.0)}{9} = 0.739 = 73.9\%* \]

* These answers are the same as in Problem 19.3.

19.10

Use the extended bottleneck model to solve Problem 19.4 with the following number of parts in the system: (a) \( N = 5 \) parts, (b) \( N = 8 \) parts, and (c) \( N = 12 \) parts. Also determine the manufacturing lead time for the three cases of \( N \) in (a), (b), and (c).

**Solution:** See solution to Problem 19.4.
\[ MLT_1 = 7.0 + 8.7 + 10.5 + 11.25 + 12.6 = 50.05 \text{ min} \]
\[ R_p^* = 0.1778 \text{ pc/min from solution to Problem 19.4} \]
\[ N^* = 0.1778(50.05) = 8.9 \]

(a) For \( N = 5 < N^* = 8.9 \), apply case 1 (Table 19.5)
\[ MLT_1 = 50.05 \text{ min}, \text{ and } T_w = 0. \]
\[ R_p = 5/50.05 = 0.0999 \text{ pc/min} = 5.99 \text{ pc/hr} \]
\[ U_1 = (7.0/2)(0.0999) = 0.350 = 35.0\% \]
\[ U_2 = (8.7/2)(0.0999) = 0.435 = 43.5\% \]
\[ U_3 = (10.5/3)(0.0999) = 0.350 = 35.0\% \]
\[ U_4 = (11.25/2)(0.0999) = 0.562 = 56.2\% \]
\[ U_5 = (12.6/3)(0.0999) = 0.420 = 42.0\% \]
\[ \bar{U}_s = \frac{2(0.350) + 2(0.435) + 3(0.350) + 2(0.562)}{9} = 0.416 = 41.6\% \]

(b) \( N = 8 < N^* = 8.9 \), apply case 1 (Table 19.5)
\[ R_p = 8/50.05 = 0.1598 \text{ pc/min} = 9.59 \text{ pc/hr} \]
\[ MLT_1 = 50.05 \text{ min}, \text{ and } T_w = 0. \]
\[ U_1 = (7.0/2)(0.1598) = 0.559 = 55.9\% \]
\[ U_2 = (8.7/2)(0.1598) = 0.695 = 69.5\% \]
\[ U_3 = (10.5/3)(0.1598) = 0.559 = 55.9\% \]
\[ U_4 = (11.25/2)(0.1598) = 0.899 = 89.9\% \]
\[ U_5 = (12.6/3)(0.1598) = 0.671 = 67.1\% \]
\[ \bar{U}_s = \frac{2(0.559) + 2(0.695) + 3(0.559) + 2(0.899)}{9} = 0.665 = 66.5\% \]

(c) \( N = 12 > N^* = 8.9 \), apply case 2 (Table 19.5)
\[ R_p^* = 0.1778 \text{ pc/min} = 10.67 \text{ pc/hr} \]
\[ MLT_2 = 12/0.1778 = 67.5 \text{ min}, \text{ and } T_w = 67.5 - 50.05 = 17.45 \text{ min} \]
\[ U_1 = (7.0/2)(0.1778) = 0.622 = 62.2\%* \]
\[ U_2 = (8.7/2)(0.1778) = 0.773 = 77.3\%* \]
\[ U_3 = (10.5/3)(0.1778) = 0.622 = 62.2\%* \]
\[ U_4 = (11.25/2)(0.1778) = 1.0 = 100\%* \]
\[ U_5 = (12.6/3)(0.1778) = 0.747 = 74.7\%* \]
\[ \bar{U}_s = \frac{2(0.622) + 2(0.773) + 3(0.622) + 2(1.0)}{9} = 0.739 = 73.9\%* \]
19.11 For the data given in Problem 19.6, use the extended bottleneck model to develop the relationships for production rate \( R_p \) and manufacturing lead time \( MLT \) each as a function of the number of parts in the system \( N \). Plot the relationships as in Figure 19.12.

**Solution:** See solution for Problem 19.6.

\[
MLT_1 = 5.0 + 6.0 + 6.85 + 6.2 + 16.0 = 40.05 \text{ min}
\]

\[
R_p^* = 0.146 \text{ pc/min} = 8.76 \text{ pc/hr} \text{ from Problem 19.6 solution.}
\]

\[
N^* = 0.146(40.05) = 5.85
\]

Establish point at \( N = 10 > 5.85 \) (case 2 in Table 19.5): \( MLT_2 = 10/0.146 = 68.5 \text{ min} \)

Plot of \( R_p \) vs \( N \):

\[
N^* = 5.85
\]

Plot of \( MLT \) vs \( N \):

\[
N^* = 5.85
\]

19.12 A flexible manufacturing system is used to produce three products. The FMS consists of a load/unload station, two automated processing stations, an inspection station, and an automated conveyor system with an individual cart for each product. The conveyor carts remain with the parts during their time in the system, and therefore the mean transport time includes not only the move time, but also the average total processing time per part. The number of servers at each station is given in the following table:

<table>
<thead>
<tr>
<th>Station</th>
<th>Load and unload</th>
<th>2 workers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station 2</td>
<td>Process X</td>
<td>3 servers</td>
</tr>
<tr>
<td>Station 3</td>
<td>Process Y</td>
<td>4 servers</td>
</tr>
<tr>
<td>Station 4</td>
<td>Inspection</td>
<td>1 server</td>
</tr>
<tr>
<td>Transport system</td>
<td>Conveyor</td>
<td>8 carriers</td>
</tr>
</tbody>
</table>

All parts follow either of two routings, which are \( 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 1 \) or \( 1 \rightarrow 2 \rightarrow 3 \rightarrow 1 \), the difference being that inspections at station 4 are performed on only one part in four for each product (\( f_{4k} = 0.25 \)). The product mix and process times for the parts are presented in the table below:

<table>
<thead>
<tr>
<th>Product ( j )</th>
<th>Part mix ( p_j )</th>
<th>Station 1</th>
<th>Station 2</th>
<th>Station 3</th>
<th>Station 4</th>
<th>Station 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.2</td>
<td>5 min</td>
<td>15 min</td>
<td>25 min</td>
<td>20 min</td>
<td>4 min</td>
</tr>
<tr>
<td>B</td>
<td>0.3</td>
<td>5 min</td>
<td>10 min</td>
<td>30 min</td>
<td>20 min</td>
<td>4 min</td>
</tr>
<tr>
<td>C</td>
<td>0.5</td>
<td>5 min</td>
<td>20 min</td>
<td>10 min</td>
<td>20 min</td>
<td>4 min</td>
</tr>
</tbody>
</table>

The move time between stations is 4 min. (a) Using the bottleneck model, show that the conveyor system is the bottleneck in the present FMS configuration, and determine the overall production rate of the system. (b) Determine how many carts are required to eliminate the conveyor system as the bottleneck. (c) With the number of carts determined in (b), use the extended bottleneck model to determine the production rate for the case when
\(N = 8\); that is, only eight parts are allowed in the system even though the conveyor system has a sufficient number of carriers to handle more than eight. (d) How close are your answers in (a) and (c)? Why?

**Solution:**

(a) \(WL_1 = (5+4)(0.2 + 0.3 + 0.5) = 9.0\) min
\[WL_2 = 15(0.2)(1.0) + 10(0.3)(1.0) = 16.0\] min
\[WL_3 = 25(0.2)(1.0) + 30(0.3)(1.0) = 19.0\] min
\[WL_4 = 20(0.2)(1.0) + 20(0.3)(1.0) + 20(0.5)(1.0) = 5.0\] min
\(n_1 = 1 + 1 + 0.25 + 1 = 3.25,\) \(WL_5 = 3.25(4) = 12.5\) min

<table>
<thead>
<tr>
<th>Station</th>
<th>WL/s, ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (load/unload)</td>
<td>9.0/2 = 4.5 min</td>
</tr>
<tr>
<td>2 (process X)</td>
<td>16.0/3 = 5.333 min</td>
</tr>
<tr>
<td>3 (process Y)</td>
<td>19.0/4 = 4.75 min</td>
</tr>
<tr>
<td>4 (inspection)</td>
<td>5.0/1 = 5.0 min</td>
</tr>
<tr>
<td>5 (transport)</td>
<td>62.0/8 = 7.75 min ← Bottleneck</td>
</tr>
</tbody>
</table>

Bottleneck is station 5 (transport): \(R_p^* = 8/62 = 0.129\) pc/min = 7.74 pc/hr

(b) Next bottleneck station after transport system = station 2. Find the minimum number of carriers to eliminate the transport system as the bottleneck.
\[62.0/n_c = 5.33,\] \(n_c = 62/5.333 = 11.63\) \(\rightarrow\) Use \(n_c = 12\) carriers.

With station 2 as bottleneck, \(R_p^* = 3/16 = 0.1875\) pc/min = 11.25 pc/hr

(c) \(N^* = 0.1875(62.0) = 11.625\)

Given \(N = 8\), case 1 applies since \(8 < N^* = 11.625\)
\(MLT_1 = 62.0\) min
\(R_p = 8/62 = 0.129\) pc/min = 7.74 pc/hr

(d) Answers in (a) and (c) are identical. The reason is that the same bottleneck is in effect, which is the number of parts allowed in the system, whether that is determined by the available number of carriers in the FMS or by the number of parts launched into the system.

19.13 A group technology cell is organized to produce a particular family of products. The cell consists of three processing stations, each with one server; an assembly station with 3 servers; and a load/unload station with 2 servers. A mechanized transfer system moves the products between stations. The transfer system has a total of 6 transfer carts. Each cart includes a workholder that holds the products during their processing and assembly, and therefore, each cart must remain with the product throughout processing and assembly. The cell resources can be summarized as follows:

<table>
<thead>
<tr>
<th>Station</th>
<th>Description</th>
<th>Number of servers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Load and unload</td>
<td>2 workers</td>
</tr>
<tr>
<td>2</td>
<td>Process X</td>
<td>1 server</td>
</tr>
<tr>
<td>3</td>
<td>Process Y</td>
<td>1 server</td>
</tr>
<tr>
<td>4</td>
<td>Process Z</td>
<td>1 server</td>
</tr>
<tr>
<td>5</td>
<td>Assembly</td>
<td>3 workers</td>
</tr>
<tr>
<td>6</td>
<td>Transport system</td>
<td>6 carriers</td>
</tr>
</tbody>
</table>

The GT cell is currently used to produce four products. All products follow the same routing, which is \(1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 1\). The product mix and station times for the parts are presented in the table below:

<table>
<thead>
<tr>
<th>Product</th>
<th>Product mix (p_j)</th>
<th>Station 1</th>
<th>Station 2</th>
<th>Station 3</th>
<th>Station 4</th>
<th>Station 5</th>
<th>Station 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.35</td>
<td>4 min</td>
<td>8 min</td>
<td>5 min</td>
<td>7 min</td>
<td>9 min</td>
<td>6 min</td>
</tr>
<tr>
<td>B</td>
<td>0.25</td>
<td>4 min</td>
<td>4 min</td>
<td>8 min</td>
<td>6 min</td>
<td>14 min</td>
<td>2.5 min</td>
</tr>
<tr>
<td>C</td>
<td>0.10</td>
<td>4 min</td>
<td>2 min</td>
<td>6 min</td>
<td>5 min</td>
<td>11 min</td>
<td>2.5 min</td>
</tr>
<tr>
<td>D</td>
<td>0.30</td>
<td>4 min</td>
<td>6 min</td>
<td>7 min</td>
<td>10 min</td>
<td>12 min</td>
<td>2.5 min</td>
</tr>
</tbody>
</table>

The average transfer between stations takes 2 minutes in addition to the time spent at the workstation. (a) Determine the bottleneck station in the GT cell and the critical value of \(N\). Compute the overall production rate and manufacturing lead time of the cell, given that the number of parts in the system = \(N^*\). If \(N^*\) is not an integer,
use the integer that is closest to \( N \).

(b) Compute the overall production rate and manufacturing lead time of the cell, given that the number of parts in the system = \( N + 10 \). If \( N \) is not an integer, use the integer that is closest to \( N + 10 \).

(c) Compute the utilizations of the six stations.

Solution: (a) 

\[
WL_1 = (4+2.5)(0.35+0.25+0.1+0.3) = 6.5 \text{ min}
\]

\[
WL_2 = 8(0.35)(1.0) + 4(0.25)(1.0) + 2(0.1)(1.0) + 6(0.30)(1.0) = 5.8 \text{ min}
\]

\[
WL_3 = 5(0.35)(1.0) + 8(0.25)(1.0) + 6(0.1)(1.0) + 7(0.30)(1.0) = 6.45 \text{ min}
\]

\[
WL_4 = 7(0.35)(1.0) + 6(0.25)(1.0) + 5(0.1)(1.0) + 10(0.30)(1.0) = 7.45 \text{ min}
\]

\[
WL_5 = 18(0.35)(1.0) + 14(0.25)(1.0) + 11(0.1)(1.0) + 12(0.30)(1.0) = 14.5 \text{ min}
\]

\[
n_t = 5, \quad WL_6 = 5(2) + 6.5 + 5.8 + 6.45 + 7.45 + 14.5 = 50.7 \text{ min}
\]

<table>
<thead>
<tr>
<th>Station</th>
<th>WL/s, ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (load/unload)</td>
<td>6.5/2 = 3.25 min</td>
</tr>
<tr>
<td>2 (process X)</td>
<td>5.8/1 = 5.8 min</td>
</tr>
<tr>
<td>3 (process Y)</td>
<td>6.45/1 = 6.45 min</td>
</tr>
<tr>
<td>4 (process Z)</td>
<td>7.45/1 = 7.45 min</td>
</tr>
<tr>
<td>5 (assembly)</td>
<td>14.5/3 = 4.833 min</td>
</tr>
<tr>
<td>6 (transport)</td>
<td>50.7/6 = 8.45 min</td>
</tr>
</tbody>
</table>

Bottleneck is station 6 (transport): \( R_p^* = 6/50.7 = 0.1183 \text{ pc/min} = 7.1 \text{ pc/hr} \)

\( MLT_1 = 50.7 \text{ min} \)

\( N^* = 0.1183(50.7) = 6.0 \)

(b) \( N = N^* + 10 = 6 + 10 = 16 \). For \( N = 16 \), 16 carriers are needed. This removes the transport system as the bottleneck. Now the bottleneck is station 4 (process Z), and the new production rate is:

\( R_p^* = 1/7.45 = 0.13423 \text{ pc/min} = 8.05 \text{ pc/hr} \)

and the new \( N^* = 0.13423(50.7) = 6.805 \). Apply case 2 (Table 19.5): \( R_p^* = 0.13423 \text{ pc/min} = 8.05 \text{ pc/hr} \)

\( MLT_2 = 16/0.13423 = 119.2 \text{ min} \)

(c) \( U_1 = (6.5/2)(0.13423) = 0.436 \)

\( U_2 = (5.8/1)(0.13423) = 0.778 \)

\( U_3 = (6.45/1)(0.13423) = 0.866 \)

\( U_4 = (7.45/1)(0.13423) = 1.0 \)

\( U_5 = (14.5/3)(0.13423) = 0.649 \)

\( U_6 = (50.7/16)(0.13423) = 0.425 \) (Note that all 16 carriers are in use full time because the 16 parts in the system are fixtured to them while waiting in their respective queues at servers, so in that sense the utilization = 1.00; thus, the calculated utilization of 0.425 refers to how many carriers are at stations rather than waiting).

19.14 In Problem 19.13, compute the average manufacturing lead times for each product for the two cases: (a) \( N = N^* \), and (b) \( N = N^* + 10 \). If \( N^* \) is not an integer, use the integers that are closest to \( N^* \) and \( N^* + 10 \), respectively.

Solution: \( MLT \) for \( N = N^* = 6: \) \( MLT_1 = 50.7 \text{ min} \) from the solution to Problem 19.14.

\( MLT \) for \( N = N^* + 10 = 16: \) \( MLT_2 = 119.2 \text{ min} \) from the solution to Problem 19.14.

(a) For \( N = N^* = 6: \)

Product A: \( MLT_{1A} = 4 + 8 + 5 + 7 + 18 + 2.5 + 5(2) = 54.5 \text{ min} \)

Product B: \( MLT_{1B} = 4 + 4 + 8 + 6 + 14 + 2.5 + 5(2) = 48.5 \text{ min} \)

Product C: \( MLT_{1C} = 4 + 2 + 6 + 5 + 11 + 2.5 + 5(2) = 40.5 \text{ min} \)

Product D: \( MLT_{1D} = 4 + 6 + 7 + 10 + 12 + 2.5 + 5(2) = 51.5 \text{ min} \)

Check: \( \text{mean } MLT_1 = 0.35(54.5) + 0.25(48.5) + 0.1(40.5) + 0.3(51.5) = 50.7 \text{ min} \), which agrees with the solution to Problem 19.14(a).

(b) For \( N = N^* + 10 = 16: \)

From Problem 19.14, \( T_w = 119.2 - 50.7 = 68.5 \text{ min} \)

Product A: \( MLT_{1A} = 54.5 + 68.5 = 123.0 \text{ min} \)

Product B: \( MLT_{1B} = 48.5 + 68.5 = 117.0 \text{ min} \)

Product C: \( MLT_{1C} = 40.5 + 68.5 = 109.0 \text{ min} \)

Product D: \( MLT_{1D} = 51.5 + 68.5 = 120.0 \text{ min} \)
Check: mean $MLT_1 = 0.35(123) + 0.25(117) + 0.1(109) + 0.3(120) = 119.2$ min, which agrees with the solution to Problem 19.14(b).

19.15 In Problem 19.13, what could be done to (a) increase the production rate and/or (b) reduce the operating costs of the cell in light of your analysis? Support your answers with calculations.

**Solution:** (a) To increase $R_p$, increase the number of carts in the transport system since it is the bottleneck in the system. The utilization at station 6 (transport system) $U_6 = 100\%$. The next highest utilization is at station 4 with a workload $WL_4 = 7.45$ min. If the workload per server (per carrier) in the transport system were reduced to 7.45 min or less, $R_p$ could be increased to the capacity of station 4.

$$\frac{50/7}{s_6} = 7.45, \quad s_6 = 50.7/7.45 = 6.8 \rightarrow \text{Use } s_6 = 7 \text{ carriers.}$$

$$R_p^* = 1/7.45 = 0.1342 \text{ pc/min} = 8.05 \text{ pc/hr. This is a 13\% increase in production rate.}$$

(b) To reduce cost, reduce the number of servers (workers) at station 1 to one worker, since the utilization at that station is only 0.385 (38.5\%) with two workers. With one worker, $U_1 = 6.5(0.1183) = 0.769$ (76.9\%).

19.16 A flexible manufacturing cell consists of a manual load/unload station, three CNC machines, and an automated guided vehicle system (AGVS) with two vehicles. The vehicles deliver parts to the individual machines, drop off the parts, then go perform other work. The workstations are listed in the table below, where the AGVS is listed as station 5.

<table>
<thead>
<tr>
<th>Station</th>
<th>Description</th>
<th>Servers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Load and unload</td>
<td>1 worker</td>
</tr>
<tr>
<td>2</td>
<td>Milling</td>
<td>1 CNC milling machine</td>
</tr>
<tr>
<td>3</td>
<td>Drilling</td>
<td>1 CNC drill press</td>
</tr>
<tr>
<td>4</td>
<td>Grinding</td>
<td>1 CNC grinding machine</td>
</tr>
<tr>
<td>5</td>
<td>AGVS</td>
<td>2 vehicles</td>
</tr>
</tbody>
</table>

The FMC is used to machine four workparts. The product mix, routings, and processing times for the parts are presented in the table below:

<table>
<thead>
<tr>
<th>Part $j$</th>
<th>Part mix $p_j$</th>
<th>Station routing</th>
<th>Station 1</th>
<th>Station 2</th>
<th>Station 3</th>
<th>Station 4</th>
<th>Station 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.25</td>
<td>1→2→3→4→1</td>
<td>4 min</td>
<td>8 min</td>
<td>7 min</td>
<td>18 min</td>
<td>2 min</td>
</tr>
<tr>
<td>B</td>
<td>0.33</td>
<td>1→3→2→1</td>
<td>4 min</td>
<td>9 min</td>
<td>10 min</td>
<td>0</td>
<td>2 min</td>
</tr>
<tr>
<td>C</td>
<td>0.12</td>
<td>1→2→4→1</td>
<td>4 min</td>
<td>10 min</td>
<td>0</td>
<td>14 min</td>
<td>2 min</td>
</tr>
<tr>
<td>D</td>
<td>0.30</td>
<td>1→2→4→3→1</td>
<td>4 min</td>
<td>6 min</td>
<td>12 min</td>
<td>16 min</td>
<td>2 min</td>
</tr>
</tbody>
</table>

The mean travel time of the AGVS between any two stations in the FMC is 3 min which includes the time required to transfer loads to and from the stations. Given that the loading on the system is maintained at 10 parts (10 workparts in the system at all times), use the extended bottleneck model to determine (a) the bottleneck station, (b) the production rate of the system and the average time to complete a unit of production, and (c) the overall utilization of the system, not including the AGVS.

**Solution:** (a) $WL_1 = (4+2)(0.25 + 0.33 + 0.12 + 0.30) = 6.0$ min

$WL_2 = 8(0.25)(1.0) + 9(0.33)(1.0) + 10(0.12)(1.0) + 6(0.30)(1.0) = 7.97$ min

$WL_3 = 7(0.25)(1.0) + 10(0.33)(1.0) + 0(0.12)(1.0) + 12(0.30)(1.0) = 8.65$ min

$WL_4 = 18(0.25)(1.0) + 0(0.33)(1.0) + 14(0.12)(1.0) + 16(0.30)(1.0) = 10.98$ min

$n_i = 4(0.25) + 3(0.33) + 3(0.12) + 4(0.30) = 3.55, \quad WL_5 = 3.55(3) = 10.65$ min

<table>
<thead>
<tr>
<th>Station</th>
<th>$WL/s$, ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (load/unload)</td>
<td>6.0/1 = 6.0 min</td>
</tr>
<tr>
<td>2 (milling)</td>
<td>7.97/1 = 7.97 min</td>
</tr>
<tr>
<td>3 (drilling)</td>
<td>8.65/1 = 8.65 min</td>
</tr>
<tr>
<td>4 (grinding)</td>
<td>10.98/1 = 10.98 min</td>
</tr>
<tr>
<td>5 (AGVS)</td>
<td>10.65/2 = 5.325 min</td>
</tr>
</tbody>
</table>

Bottleneck = station 4 (grinding).

(b) $R_p^* = 1/10.98 = 0.09107$ pc/min

$MLT_1 = 6 + 7.97 + 8.65 + 10.98 + 10.65 = 44.25$ min
Since $N = 10 > N^* = 4.03$, case 2 (Table 19.5) applies: $R_{p^*} = 0.09107 \text{ pc/min} = 5.46 \text{ pc/hr}$.

$MLT_2 = 10/0.09107 = 109.8 \text{ min}$

(c) $U_1 = (6.0/1)(0.09107) = 0.546 = 54.6\%$

$U_2 = (7.97/1)(0.09107) = 0.726 = 72.6\%$

$U_3 = (8.65/1)(0.09107) = 0.788 = 78.8\%$

$U_4 = (10.98)(0.09107) = 1.0 = 100\%$

$U_s = \frac{0.546 + 0.726 + 0.788 + 1.0}{4} = 0.765 = 76.5\%$

Sizing the FMS

A flexible manufacturing system is used to produce four parts. The FMS consists of one load/unload station and two automated processing stations (processes X and Y). The number of servers for each station type is to be determined. The FMS also includes an automated conveyor system with individual carts to transport parts between servers. The carts move the parts from one server to the next, drop them off, and proceed to the next delivery task. Average time required per transfer is 3.5 minutes. The following table summarizes the FMS:

<table>
<thead>
<tr>
<th>Station 1</th>
<th>Load and unload</th>
<th>Number of human servers (workers) to be determined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station 2</td>
<td>Process X</td>
<td>Number of automated servers to be determined</td>
</tr>
<tr>
<td>Station 3</td>
<td>Process Y</td>
<td>Number of automated servers to be determined</td>
</tr>
<tr>
<td>Station 4</td>
<td>Transport system</td>
<td>Number of carts to be determined</td>
</tr>
</tbody>
</table>

All parts follow the same routing, which is $1 \rightarrow 2 \rightarrow 3 \rightarrow 1$. The product mix and processing times at each station are presented in the table below:

<table>
<thead>
<tr>
<th>Product $j$</th>
<th>Product mix $p_j$</th>
<th>Station 1</th>
<th>Station 2</th>
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Required production is 10 parts per hour, distributed according to the product mix indicated. Use the bottleneck model to determine (a) the minimum number of servers at each station and the minimum number of carts in the transport system that are required to satisfy production demand and (b) the utilization of each station for the answers above.

Solution: (a) $WL_1 = (3+2)(0.1 + 0.3 + 0.4 + 0.2)(1.0) = 5.0 \text{ min}$

$WL_2 = 15(0.1)(1.0) + 40(0.3)(1.0) + 20(0.4)(1.0) + 30(0.2)(1.0) = 27.5 \text{ min}$

$WL_3 = 25(0.1)(1.0) + 20(0.3)(1.0) + 10(0.4)(1.0) + 5(0.2)(1.0) = 13.5 \text{ min}$

$n_1 = 3$, $WL_4 = 3(3.5) = 10.5 \text{ min}$

The preceding workloads are for one unit/hr. For $R_p = 10 \text{ pc/hr}$, the above workloads would be 10 times the above values. The time available in one hour for each server = 60 min. Therefore, the number of servers at each station and the number of carriers in the transport system are determined as follows:

Station 1: $n_1 = 10(5.0)/60 = 50/60 = 0.833 \rightarrow use 1 \text{ server}$

Station 1: $n_2 = 10(27.5)/60 = 275/60 = 4.583 \rightarrow use 5 \text{ servers}$

Station 1: $n_3 = 10(13.5)/60 = 135/60 = 2.25 \rightarrow use 3 \text{ servers}$

Station 1: $n_4 = 10(10.5)/60 = 105/60 = 1.75 \rightarrow use 2 \text{ carriers}$

(b) $U_1 = 0.833/1 = 0.833 = 83.3\%$

$U_2 = 4.583/5 = 0.917 = 91.7\%$

$U_3 = 2.25/3 = 0.75 = 75.0\%$

$U_4 = 1.75/2 = 0.875 = 87.5\%$

19.18 A flexible machining system is being planned that will consist of four workstations plus a part handling system. Station 1 will be a load/unload station. Station 2 will consist of horizontal machining centers. Station 3 will consist of vertical machining centers. Station 4 will be an inspection station. For the part mix that will be processed by the FMS, the workloads at the four stations are as follows: $WL_1 = 7.5 \text{ min}$, $WL_2 = 22.0 \text{ min}$, $WL_3 = 18.0 \text{ min}$, and $WL_4 = 10.2 \text{ min}$. The workload of the part handling system $WL_5 = 8.0 \text{ min}$. The FMS will be
operated 16 hours per day, 250 days per year. Maintenance will be performed during nonproduction hours, so uptime proportion (availability) is expected to be 97%. Annual production of the system will be 65,000 parts. Determine the number of machines (servers) of each type (station) required to satisfy production requirements.

**Solution:** \[ R_p = \frac{65{,}000}{4000 \times (0.97)} = 16.75 \text{ pc/hr} = 0.2792 \text{ pc/min} \]

- \( s_1 = \text{Minimum Integer } \geq (0.2792 \times 7.5) = 2.09 \) = **3 servers** (load/unload workers)
- \( s_2 = \text{Minimum Integer } \geq (0.2792 \times 22.0) = 6.14 \) = **7 servers** (horizontal machining centers)
- \( s_3 = \text{Minimum Integer } \geq (0.2792 \times 18.0) = 5.03 \) = **6 servers** (vertical machining centers)
- \( s_4 = \text{Minimum Integer } \geq (0.2792 \times 10.2) = 2.85 \) = **3 servers** (inspection stations)
- \( s_5 = \text{Minimum Integer } \geq (0.2792 \times 7.5) = 2.09 \) = **3 servers** (work carriers)

In Problem 19.18, determine (a) the utilizations of each station in the system for the specified production requirements, and (b) what is the maximum possible production rate of the system if the bottleneck station were to operate at 100% utilization.

**Solution:**
- (a) \[ U_1 = \frac{2.09}{3} = 0.697 = 69.7\% \]
- \[ U_2 = \frac{6.14}{7} = 0.877 = 87.7\% \]
- \[ U_3 = \frac{5.03}{6} = 0.838 = 83.8\% \]
- \[ U_4 = \frac{2.85}{3} = 0.95 = 95\% \]
- \[ U_5 = \frac{2.09}{3} = 0.697 = 69.7\% \]

- (b) Maximum value of utilization is at station 4. If station 4 were to operate at 100% utilization, \( R_p^* = \frac{16.75}{100} = 17.63 \text{ pc/hr} \)

Given the part mix, process routings, and processing times for the three parts in Problem 19.1. The FMS planned for this part family will operate 250 days per year and the anticipated availability of the system is 90%. Determine how many servers at each station will be required to achieve an annual production rate of 40,000 parts per year if (a) the FMS operates 8 hours per day, (b) 16 hours per day, and (c) 24 hours per day. (d) Which system configuration is preferred, and why?

**Solution:**
- (a) Annual hours of operation = \( (8 \text{ hr/day})(250 \text{ days/yr}) = 2000 \text{ hr/yr} \).
  \[ R_p = \frac{40{,}000 \text{ pc/yr}}{2000 \text{ hr/yr} \times (0.90)} = 22.22 \text{ pc/hr} = 0.3704 \text{ pc/min} \]
  From Problem 19.1, \( WL_1 = 5.0 \text{ min}, WL_2 = 19.5 \text{ min}, WL_3 = 18.4 \text{ min}, \) and \( WL_4 = 7.5 \text{ min} \)
  - \( s_1 = \text{Minimum Integer } \geq (0.3704 \times 5.0) = 1.85 \) = **2 servers** (load/unload workers)
  - \( s_2 = \text{Minimum Integer } \geq (0.3704 \times 19.5) = 7.22 \) = **8 servers** (milling machines)
  - \( s_3 = \text{Minimum Integer } \geq (0.3704 \times 18.4) = 6.82 \) = **7 servers** (drill presses)
  - \( s_4 = \text{Minimum Integer } \geq (0.3704 \times 7.5) = 2.78 \) = **3 servers** (transport carriers)

- (b) Annual hours of operation = \( (16 \text{ hr/day})(250 \text{ days/yr}) = 4000 \text{ hr/yr} \).
  \[ R_p = \frac{40{,}000 \text{ pc/yr}}{4000 \text{ hr/yr} \times (0.90)} = 11.11 \text{ pc/hr} = 0.1852 \text{ pc/min} \]
  - \( s_1 = \text{Minimum Integer } \geq (0.1852 \times 5.0) = 0.926 \) = **1 server** (load/unload worker)
  - \( s_2 = \text{Minimum Integer } \geq (0.1852 \times 19.5) = 3.611 \) = **4 servers** (milling machines)
  - \( s_3 = \text{Minimum Integer } \geq (0.1852 \times 18.4) = 3.407 \) = **4 servers** (drill presses)
  - \( s_4 = \text{Minimum Integer } \geq (0.1852 \times 7.5) = 1.389 \) = **2 servers** (transport carriers)

- (c) Annual hours of operation = \( (24 \text{ hr/day})(250 \text{ days/yr}) = 6000 \text{ hr/yr} \).
  \[ R_p = \frac{40{,}000 \text{ pc/yr}}{6000 \text{ hr/yr} \times (0.90)} = 7.407 \text{ pc/hr} = 0.1234 \text{ pc/min} \]
  - \( s_1 = \text{Minimum Integer } \geq (0.1234 \times 5.0) = 0.617 \) = **1 server** (load/unload worker)
  - \( s_2 = \text{Minimum Integer } \geq (0.1234 \times 19.5) = 2.407 \) = **3 servers** (milling machines)
  - \( s_3 = \text{Minimum Integer } \geq (0.1234 \times 18.4) = 2.272 \) = **3 servers** (drill presses)
  - \( s_4 = \text{Minimum Integer } \geq (0.1234 \times 7.5) = 0.926 \) = **1 server** (transport carrier)
(d) Configuration (c) is preferable because it requires the minimum capital investment and involves the minimum complexity. Labor cost to operate 24 hr/day would probably be higher even though there are fewer machines that must be managed.

19.21 Given the part mix, process routings, and processing times for the four parts in Problem 19.3. The FMS proposed to machine these parts will operate 20 hours per day, 250 days per year. Assume system availability = 95%. Determine (a) how many servers at each station will be required to achieve an annual production rate of 95,000 parts per year, and (b) the utilization of each workstation. (c) What is the maximum possible annual production rate of the system if the bottleneck station were to operate at 100% utilization?

**Solution:**

(a) \[ H = \frac{20 \text{ hr/day}}{(250 \text{ days/yr})} = 5000 \text{ hr/yr} \]

\[ R_p = \frac{95,000}{(5000)(0.95)} = 20 \text{ pc/hr} = 0.333 \text{ pc/min} \]

From Problem 19.3, \( W_{L1} = 7.0 \text{ min}, \ W_{L2} = 8.7 \text{ min}, \ W_{L3} = 11.3 \text{ min}, \ W_{L4} = 13.45 \text{ min}, \) and \( W_{L5} = 12.6 \text{ min} \)

- \( s_1 = \text{Minimum Integer} \geq (0.333(7.0) = 2.33) = 3 \text{ servers} \) (load/unload workers)
- \( s_2 = \text{Minimum Integer} \geq (0.333(8.7) = 2.90) = 3 \text{ servers} \) (horizontal mills)
- \( s_3 = \text{Minimum Integer} \geq (0.333(11.3) = 3.76) = 4 \text{ servers} \) (vertical mills)
- \( s_4 = \text{Minimum Integer} \geq (0.333(13.45) = 4.48) = 5 \text{ servers} \) (drill presses)
- \( s_5 = \text{Minimum Integer} \geq (0.333(12.6) = 4.20) = 5 \text{ servers} \) (work carriers)

(b) \( U_1 = \frac{2.33}{3} = 0.777 = 77.7\% \)
\( U_2 = \frac{2.90}{3} = 0.967 = 96.7\% \)
\( U_3 = \frac{3.76}{4} = 0.94 = 94\% \)
\( U_4 = \frac{4.48}{5} = 0.896 = 89.6\% \)
\( U_5 = \frac{4.2}{5} = 0.84 = 84\% \)

(c) Maximum utilization is at station 2. If station 2 were to operate at 100% utilization, \( R_p^* = \frac{20}{0.967} = 20.68 \text{ pc/hr} \)

Annual production = \( 20.68(20)(250)(0.95) = 98,242 \text{ pc/yr} \)
Chapter 20
QUALITY PROGRAMS FOR MANUFACTURING

REVIEW QUESTIONS

20.1 What are the two aspects of quality in a manufactured product? List some of the product characteristics in each category.

**Answer:** The two aspects of quality identified in the text are (1) product features and (2) freedom from deficiencies. Product features include design configuration, size of product, function and performance, aesthetic appeal, ease of use, reliability, and serviceability. Freedom from deficiencies includes absence of defects, conformance to specifications, components within tolerance, and no missing parts.

20.2 Discuss the differences between the traditional view of quality control and the modern view.

**Answer:** As discussed in the text, traditional QC focused on inspection. In many factories, the only department responsible for quality control was the inspection department. Much attention was given to sampling and statistical methods. The modern view of quality control emphasizes management involvement in quality, focus on customer satisfaction, continuous improvement, and encouraging the involvement of all employees.

20.3 What are the three main objectives of Total Quality Management?

**Answer:** As identified in the text, the three main objectives of Total Quality Management are (1) achieving customer satisfaction, and (2) encouraging involvement of the entire work force, and (3) continuous improvement.

20.4 What do the terms external customer and internal customer mean?

**Answer:** External customers are those who buy the final product or service. Internal customers are those within the same organization; for example, the assembly department is the customer of the parts production department within the same company.

20.5 Manufacturing process variations can be divided into two types: (1) random and (2) assignable. Distinguish between these two types.

**Answer:** Random variations result from intrinsic variability in the process. All processes are characterized by these kinds of variations. Random variations cannot be avoided; they are caused by factors such as inherent human variability and minor variations in raw materials. Random variations typically form a normal statistical distribution. This kind of variability continues so long as the process is operating normally. Assignable variations indicate an exception from normal operating conditions. Something has occurred in the process that is not accounted for by random variations. Reasons for assignable variations include operator mistakes, defective raw materials, tool failures, and equipment malfunctions.

20.6 What is meant by the term **process capability**?

**Answer:** Process capability equals $\pm 3$ standard deviations about the mean output value (a total range of $6$ standard deviations), under the assumptions that (1) the output is normally distributed, and (2) steady state operation has been achieved and the process is in statistical control.

20.7 What is a control chart?

**Answer:** According to the text, a control chart is a graphical technique in which statistics computed from measured values of a certain process characteristic are plotted over time to determine if the process remains in statistical control. The chart consists of three horizontal lines that remain constant over time: a center, a lower control limit ($LCL$), and an upper control limit ($UCL$). The center is usually set at the nominal design value, and the upper and lower control limits are generally set at $\pm 3$ standard deviations of the sample means.

20.8 What are the two basic types of control charts?

**Answer:** The two basic types of control charts are (1) control charts for variables, and (2) control charts for attributes. Control charts for variables require measurements of the quality characteristic of interest. Control charts for attributes simply require a determination of either the fraction of defects in the sample or the number of defects in the sample.
20.9 What is a histogram?

**Answer:** A histogram is a statistical graph consisting of bars representing different values or ranges of values, in which the length of each bar is proportional to the frequency or relative frequency of the value or range.

20.10 What is a Pareto chart?

**Answer:** A Pareto chart is a special form of histogram, in which attribute data are arranged according to some criteria such as cost or value. It provides a graphical display of the tendency for a small proportion of a given population to be more valuable than the much larger majority.

20.11 What is a defect concentration diagram?

**Answer:** The defect concentration diagram is a drawing of the product (or other item of interest), with all relevant views displayed, onto which are sketched the various types of defects or other problems of interest at the locations where they each occurred.

20.12 What is a scatter diagram?

**Answer:** A scatter diagram is an x-y plot of the data taken of two variables of interest.

20.13 What is a cause and effect diagram?

**Answer:** The cause and effect diagram, also known as a fishbone diagram, is a graphical-tabular chart used to list and analyze the potential causes of a given problem. The diagram consists of a central stem leading to the effect (the problem), with multiple branches coming off the stem listing the various groups of possible causes of the problem.

20.14 What is Six Sigma?

**Answer:** As defined in the text, Six Sigma is a quality-focused program that utilizes worker teams to accomplish projects aimed at improving an organization's operational performance. The name Six Sigma is derived from the Normal statistical distribution, in which the Greek letter sigma (σ) is the standard deviation or measure of dispersion in a normal population. Six sigma implies near perfection in a process, and that is the goal of a Six Sigma program. There is a strong emphasis on the customer and customer satisfaction in Six Sigma.

20.15 What are the general goals of Six Sigma?

**Answer:** As listed in the text, the general goals of Six Sigma are (1) better customer satisfaction, (2) high quality products and services, (3) reduced defects, (4) improved process capability through reduction in process variations, (5) continuous improvement, and (6) cost reduction through more effective and efficient processes.

20.16 Why does $6\sigma$ in Six Sigma really mean $4.5\sigma$?

**Answer:** When the Motorola engineers devised the six sigma standard, they considered processes that operate over the long run. And over the long run processes tend to shift from the original process mean to the right or left. To compensate for these likely shifts, Motorola selected to use $1.5\sigma$ as the magnitude of the shift, while leaving the original $\pm 6\sigma$ limits in place for the process. Thus, when $6\sigma$ is used in Six Sigma, it really refers to $4.5\sigma$ in the normal probability tables.

20.17 What does DMAIC stand for?

**Answer:** DMAIC stands for define, measure, analyze, improve, and control.

20.18 What is the define step in DMAIC? What is accomplished during the define step?

**Answer:** The define step in DMAIC defines the project goals and customer requirements. It includes (1) organizing the project team, (2) providing it with a charter (the problem to solve), (3) identifying the customers served by the process, and (4) developing a high-level process map.

20.19 What are master black belts in the Six Sigma hierarchy?

**Answer:** Master black belts provide technical resources and serve as consultants and mentors for the black belts, who are the team leaders and project managers for a Six Sigma project. Master black belts are full-time positions, and they are selected for their teaching aptitudes, quantitative skills, and experience in Six Sigma.
20.20 What is a CTQ characteristic?

**Answer:** CTQ stands for critical to quality. CTQ characteristics are the features or elements of the process and its output that directly impact the customer’s perception of quality. Typical CTQ characteristics include the reliability of a product or the timeliness of a service.

20.21 What is the measure step in DMAIC?

**Answer:** The measure step in DMAIC measures the process to assess its current performance. The measure step consists of (1) creating a data collection plan, (2) collecting the data, and (3) assessing the sigma level of the current process.

20.22 Why is defects per million (DPM) not necessarily the same as defects per million opportunities (DPMO)?

**Answer:** Defects per million (DPM) refers to the total number of defects per million parts, thus allowing that a given defective part may contain more than one type of defect. Defects per million opportunities (DPMO) also acknowledges this fact that there may be more than one type of defect that occurs in each unit and takes into account the complexity of the product or service so that entirely different types of products and services can be compared on the same sigma scale.

20.23 What is the analyze step in DMAIC?

**Answer:** The analyze step stands for analyzing the process and determining root causes for variations and defects. The analyze step consists of the following phases: (1) basic data analysis, (2) process analysis, and (3) root cause analysis.

20.24 What is root cause analysis?

**Answer:** Root cause analysis attempts to identify the significant factors that affect process performance. The situation can be depicted using the equation $y = f(x_1, x_2, \ldots, x_i, \ldots x_n)$, where $y$ is some output variable of interest (e.g., some quality feature); and $x_1, x_2, \ldots, x_i, \ldots x_n$ are the independent variables in the process that may affect the output variable. The value of $y$ is a function of the $x_i$ values. In root cause analysis, an attempt is made to determine which $x_i$ variables are most important and how they influence $y$. In all likelihood, there are more than one $y$ variables of interest. For each $y$, there is likely to be a different set of $x_i$ variables.

20.25 What is the improve step in DMAIC?

**Answer:** Improve the process by reducing variations and defects. The improve step consists of (1) generating alternative improvements, (2) analyzing and prioritizing alternative improvements, and (3) implementing the improvements.

20.26 What is the control step in DMAIC?

**Answer:** The control step refers to controlling the future process performance by institutionalizing the improvements. Control consists of the following actions: (1) develop a control plan, (2) transfer responsibility back to original owner, and (3) disband the Six Sigma team.

20.27 What is a robust design in Taguchi’s quality engineering?

**Answer:** A robust design is one in which the function and performance of the product or process are relatively insensitive to variations that are difficult or impossible to control. In product design, robustness means that the product can maintain consistent performance with minimal disturbance due to variations in its operating environment. In process design, robustness means that the process continues to produce good product in spite of uncontrollable variations in its operating environment.

20.28 What is ISO 9000?

**Answer:** ISO 9000 is a set of international standards on quality developed by the International Organization for Standardization (ISO). It is not a standard for the products or services. Instead, ISO 9000 establishes standards for the systems and procedures used by a facility that affect the quality of the products and services produced by the facility. ISO 9000 includes a glossary of quality terms, guidelines for selecting and using the various standards, models for quality systems, and guidelines for auditing quality systems.
PROBLEMS

Process Capability

(Note: Problems 20.2 and 20.5 require the use of standard normal distribution tables not included in this book.)

20.1 A turning process is in statistical control and the output is normally distributed, producing parts with a mean diameter = 30.020 mm and a standard deviation = 0.040 mm. Determine the process capability.

Solution: Process capability \( PC = \mu \pm 3\sigma = 30.020 \pm 3(0.040) = 30.020 \pm 0.120 \text{ mm} \).

The upper and lower limits of the process capability range are: 29.900 to 30.140 mm.

20.2 In previous problem 20.1, the design specification on the part is that the diameter = 30.000 \( \pm \) 0.150 mm. (a) What proportion of parts fall outside the tolerance limits? (b) If the process is adjusted so that its mean diameter = 30.000 mm and the standard deviation remains the same, what proportion of parts fall outside the tolerance limits?

Solution: (a) Given process mean \( \mu = 30.020 \text{ mm} \), \( \sigma = 0.040 \text{ mm} \), tolerance limits = 29.850 to 30.150. On the lower side of the tolerance limit, using the standard normal distribution, \( z = (29.850 - 30.020)/0.040 = -4.25 \).

Conclusion: there are virtually no defects on the lower side of the tolerance. On the upper side of the tolerance limit, \( z = (30.150 - 30.020)/0.040 = +3.25 \)

Using tables of the standard normal distribution, \( Pr(z > 3.25) = 0.0006 \)

The proportion of defects with the current process mean = 0.0006 = 0.06%.

(b) Resetting process mean to \( \mu = 30.000 \text{ mm} \) and \( \sigma = 0.040 \text{ mm} \) and with tolerance limits remaining at 29.850 to 30.150. On the lower side of the tolerance limit, \( z = (29.850 - 30.000)/0.040 = -3.75 \). Using tables of the standard normal distribution, \( Pr(z < -3.75) = 0.0001 \).

On the upper side of the tolerance limit, \( z = (30.150 - 30.000)/0.040 = +3.75 \)

Using tables of the standard normal distribution, \( Pr(z > 3.75) = 0.0001 \)

The proportion of defects with the current process mean = 0.0001 + 0.0001 = 0.0002 = 0.02%.

20.3 An automated tube bending operation produces parts with an included angle = 91.2°. The process is in statistical control and the values of included angle are normally distributed with a standard deviation = 0.45°. The design specification on the angle = 90.0° \( \pm \) 2.0°. (a) Determine the process capability. (b) If the process could be adjusted so that its mean = 90.0°, determine the value of the process capability index.

Solution: (a) \( PC = 91.2 \pm 3(0.45) = 91.2° \pm 1.35° \).

The upper and lower limits of the process capability range are 89.85° to 92.55°.

(b) If \( \mu = 90° \)

\( UTL - LTL = 92° - 88° = 4° \)

\( PCI = 4°/(6 \times 0.45°) = 1.481 \)

20.4 A plastic extrusion process is in statistical control and the output is normally distributed. Extrudate is produced with a critical cross-sectional dimension = 28.6 mm and standard deviation = 0.53 mm. Determine the process capability.

Solution: Process capability \( PC = \mu \pm 3\sigma = 28.6 \pm 3(0.53) = 28.6 \pm 1.59 \text{ mm} \)

The upper and lower limits of the process capability range are 27.01 to 30.19 mm.

20.5 In previous problem 20.4, the design specification on the part is that the critical cross-sectional dimension = 28.0 \( \pm \) 2.0 mm. (a) What proportion of parts fall outside the tolerance limits? (b) If the process were adjusted so that its mean diameter = 28.0 mm and the standard deviation remained the same, what proportion of parts would fall outside the tolerance limits? (c) With the adjusted mean at 28.0 mm, determine the value of the process capability index.

Solution: (a) Given process mean \( \mu = 28.6 \text{ mm} \) and \( \sigma = 0.53 \text{ mm} \) and tolerance limits = 26.0 to 30.0 mm. On the lower side of the limit, using the standard normal distribution, \( z = (26.0 - 28.6)/0.53 = -4.01 \). Conclusion: there are virtually no defects on the lower side of the tolerance. On the upper side of the tolerance limit, \( z = (30.0 - 28.6)/0.53 = +2.64 \)

Using tables of the standard normal distribution, \( Pr(z > 2.64) = 0.0041 \)

The proportion of defects with the current process mean = 0.0041 = 0.41%.
(b) Given process mean $\mu = 28.0$ mm and $\sigma = 0.53$ mm and tolerance limits 26.0 to 30.0 mm. On the lower side of the tolerance limit, $z = (26.0 - 28.0)/0.53 = -3.77$.
Using tables of the standard normal distribution, $Pr(z < -3.77) = \text{approx. 0.0001}$
On the upper side of the tolerance limit, $z = (30.0 - 28.0)/0.53 = +3.77$
Using tables of the standard normal distribution, $Pr(z > 3.77) = \text{approx. 0.0001}$
The proportion of defects with the current process mean = $0.0001 + 0.0001 = 0.0002 = 0.02\%$.

(c) Process capability index $PCI = 4.0/(6 \times 0.53) = 1.258$

Control Charts

20.6 Seven samples of six parts each have been collected from an extrusion process which is in statistical control, and the diameter of the extrudate has been measured for each part. (a) Determine the values of the center, $LCL$, and $UCL$ for $\bar{x}$ and $R$ charts. The calculated values of $\bar{x}$ and $R$ for each sample are given below (measured values are in inches). (b) Construct the control charts and plot the sample data on the charts.

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$\bar{x}$ chart: $CL = \bar{x} = 1.000$ in
$LCL = \bar{x} - A_2 \bar{R} = 1.000 - 0.483(0.0133) = 0.9936$ in
$UCL = \bar{x} + A_2 \bar{R} = 1.000 + 0.483(0.0133) = 1.0064$ in

$R$ chart: $CL = R = 0.0133$ in
$LCL = D_3 \bar{R} = 0$
$UCL = D_4 \bar{R} = 2.004(0.0133) = 0.0267$ in

(b) Student exercise.

20.7 Ten samples of size $n = 8$ have been collected from a process in statistical control, and the dimension of interest has been measured for each part. (a) Determine the values of the center, $LCL$, and $UCL$ for the $\bar{x}$ and $R$ charts. The calculated values of $\bar{x}$ and $R$ for each sample are given below (measured values are in mm). (b) Construct the control charts and plot the sample data on the charts.

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<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>0.24</td>
<td>0.17</td>
<td>0.30</td>
<td>0.26</td>
<td>0.27</td>
<td>0.21</td>
<td>0.21</td>
<td>0.32</td>
<td>0.21</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Solution: $\bar{x} = \frac{\Sigma \bar{x}}{m} = (9.22 + 9.15 + 9.20 + 9.28 + 9.19 + 9.12 + 9.20 + 9.24 + 9.17 + 9.23)/10 = 9.20$
$\bar{R} = \Sigma R/7 = (0.24 + 0.17 + 0.30 + 0.26 + 0.27 + 0.21 + 0.21 + 0.32 + 0.21 + 0.23)/10 = 0.24$

(a) $\bar{x}$ chart: $CL = \bar{x} = 9.20$ mm
$LCL = \bar{x} - A_2 \bar{R} = 9.20 - 0.373(0.24) = 9.1105$ mm
$UCL = \bar{x} + A_2 \bar{R} = 9.20 + 0.373(0.24) = 9.2895$ mm

$R$ chart: $CL = R = 0.24$ mm
$LCL = D_3 \bar{R} = 0.136(0.24) = 0.0326$ mm
$UCL = D_4 \bar{R} = 1.864(0.24) = 0.4474$ mm

(b) Student exercise.
20.8 In 12 samples of size $n = 7$, the average value of the sample means is $\bar{x} = 6.860$ inch for the dimension of interest, and the mean of the ranges of the samples is $R = 0.027$ inch. Determine (a) lower and upper control limits for the $\bar{x}$ chart and (b) lower and upper control limits for the $R$ chart.

**Solution:**
(a) $\bar{x}$ chart: $CL = \bar{x} = 6.860$ in

$LCL = \bar{x} - A_2R = 6.860 - 0.419(0.027) = 6.8487$ in

$UCL = \bar{x} + A_2R = 6.860 + 0.419(0.027) = 6.8713$ in

(b) $R$ chart: $CL = R = 0.027$

$LCL = D_3R = 0.076(0.027) = 0.0205$ in

$UCL = D_4R = 1.924(0.027) = 0.0519$ in

20.9 In nine samples each of size $n = 10$, the grand mean of the samples is $\bar{x} = 97$ for the characteristic of interest, and the mean of the ranges of the samples is $\bar{R} = 8.5$. Determine (a) lower and upper control limits for the $\bar{x}$ chart and (b) lower and upper control limits for the $R$ chart.

**Solution:**
(a) $\bar{x}$ chart: $CL = \bar{x} = 100$

$LCL = \bar{x} - A_2R = 97 - 0.308(8.5) = 94.382$ in

$UCL = \bar{x} + A_2R = 97 + 0.308(8.5) = 99.618$ in

(b) $R$ chart: $CL = R = 8.5$

$LCL = D_3R = 0.223(8.5) = 1.8955$ in

$UCL = D_4R = 1.777(8.5) = 15.1045$ in

20.10 A $p$ chart is to be constructed. Six samples of 25 parts each have been collected, and the average number of defects per sample = 2.75. Determine the center, $LCL$ and $UCL$ for the $p$ chart.

**Solution:**
$CL = \bar{p} = 2.75/25 = 0.11$

$LCL = \bar{p} - 3 \sqrt{p(1-p)/n} = 0.11 - 3 \sqrt{0.11(0.89)/25} = 0.11 - 3(0.0626) = \text{not possible}$

$UCL = \bar{p} + 3 \sqrt{p(1-p)/n} = 0.11 + 3 \sqrt{0.11(0.89)/25} = 0.11 + 3(0.0626) = 0.298$

20.11 Ten samples of equal size are taken to prepare a $p$ chart. The total number of parts in these ten samples was 900 and the total number of defects counted was 117. Determine the center, $LCL$ and $UCL$ for the $p$ chart.

**Solution:**
$CL = \bar{p} = 117/900 = 0.13$

$LCL = \bar{p} - 3 \sqrt{p(1-p)/n} = 0.13 - 3 \sqrt{0.13(0.87)/90} = 0.13 - 3(0.03545) = 0.024$

$UCL = \bar{p} + 3 \sqrt{p(1-p)/n} = 0.11 + 3 \sqrt{0.13(0.87)/90} = 0.11 + 3(0.03545) = 0.236$

20.12 The yield of good chips during a certain step in silicon processing of integrated circuits averages 93%. The number of chips per wafer is 200. Determine the center, $LCL$, and $UCL$ for the $p$ chart that might be used for this process.

**Solution:**
$CL = p = 0.93 \times 0.07 = 0.07$

$LCL = \bar{p} - 3 \sqrt{p(1-p)/n} = 0.07 - 3 \sqrt{0.07(0.93)/200} = 0.07 - 3(0.0018) = 0.0159$

$UCL = \bar{p} + 3 \sqrt{p(1-p)/n} = 0.07 + 3 \sqrt{0.07(0.93)/200} = 0.07 + 3(0.0018) = 0.1241$

20.13 The upper and lower control limits for a $p$ chart are: $LCL = 0.10$ and $UCL = 0.24$. Determine the sample size $n$ that is used with this control chart.

**Solution:**
$p = 0.5(UCL - LCL) = 0.5(0.24 - 0.10) = 0.17$

$LCL = 0.24 - 0.10 = 0.14 = 6 \sqrt{p(1-p)/n} = 6 \sqrt{0.17(0.83)/n}$

$(0.14)^2 = 6^2 (0.17 \times 0.83/n)$

$0.0196 = 36(0.17)(0.83)/n = 5.0796/n$

$n = 5.0796/0.0196 = 259.2 \rightarrow 259$
20.14 The upper and lower control limits for a \( p \) chart are: \( LCL = 0 \) and \( UCL = 0.20 \). The center line of the \( p \) chart is at 0.10. Determine the sample size \( n \) that is compatible with this control chart.

Solution:
\[
p = 0.5(UCL + LCL) = 0.5(0.20 + 0) = 0.10
\]
\[
LCL = p - 3\sqrt{p(1-p)/n} = 0
\]
Therefore,
\[
p = 3\sqrt{p(1-p)/n}
\]
\[
0.10 = 3\sqrt{0.10(0.90)/n}
\]
\[
(0.10)^2 = 0.01 = 3^2 (0.1)(0.9)/n = 0.81/n, \quad n = 0.81/0.01 = 81
\]

20.15 Twelve cars were inspected after final assembly. The number of defects found ranged between 87 and 139 defects per car with an average of 120. Determine the center and upper and lower control limits for the \( c \) chart that might be used in this situation.

Solution:
\[
CL = 120
\]
\[
LCL = c - 3\sqrt{c} = 120 - 3\sqrt{120} = 87.1 \rightarrow 87
\]
\[
UCL = c + 3\sqrt{c} = 120 + 3\sqrt{120} = 152.9 \rightarrow 153
\]

20.16 For each of the three control charts in Figure P20.16, identify whether or not there is evidence that the process depicted is out of control.

Solution:
(a) With reference to indicators in Section 20.4.1, samples 6 through 13 are all above the center.

(b) With reference to indicators in Section 20.4.1, samples 11 and 13 are beyond \(+2\sigma\).

(c) With reference to indicators in Section 20.4.1, each of samples 6 through 11 is lower than its predecessor.

Determining Sigma Level in Six Sigma

20.17 A garment manufacturer produces 22 different coat styles, and every year new coat styles are introduced and old styles are discarded. Whatever the style, the final inspection department checks each coat before it leaves the factory for nine features that are considered critical-to-quality (CTQ) characteristics for customer satisfaction. The inspection report for last month indicated that a total of 366 deficiencies of the nine features were found among 8,240 coats produced. Determine (a) defects per million opportunities and (b) sigma level for the manufacturer’s production performance.

Solution:
(a) Given \( N_d = 366 \), \( N_o = 8,240 \), and \( N_o = 9 \)
\[
DPMO = 1,000,000(366)/(8,240)(9) = 4,935 \text{ defects/million}
\]
(b) From Table 20.5, this corresponds to around the 4.1 sigma level.

20.18 A producer of cell phones checks each phone prior to packaging, using six critical-to-quality (CTQ) characteristics that are deemed important to customers. Last year, out of 220,438 phones produced by the company, a total of 578 phones had at least one defect, and the total number of defects among these 578 phones was 1692. Determine (a) the number of defects per million opportunities and corresponding sigma level, (b) the number of defects per million and corresponding sigma level, and (c) the number of defective units per million and corresponding sigma level.

Solution:
(a) Given \( N_o = 6 \) CTQ features, \( N_d = 1692 \) defects among all units, \( N_d = 578 \) defective phones, \( N_o = 205,438 \).
\[
DPMO = 1,000,000(1,692)/(220,438)(6) = 1,279 \text{ defects/million opportunities}
\]
From Table 20.5, this corresponds to the 4.5 sigma level.

(b) \( DPM = 1,000,000(1,692)/(220,438) = 7,676 \text{ defects/million}
\]
From Table 20.5, this corresponds to around the 3.9 sigma level.

(c) \( DUPM = 1,000,000(578)/(220,438) = 2,622 \text{ defective units/million}
\]
From Table 20.5, this corresponds to around the 4.3 sigma level.

20.19 The inspection department in an automobile final assembly plant checks cars coming off the line against 85 features that are considered critical-to-quality characteristics for customer satisfaction. During a one-month period, a total of 16,578 cars were produced. For those cars, a total of 1,989 defects of various types were found, and the total number of cars that had one or more defects was 512. Determine (a) the number of
defects per million opportunities and corresponding sigma level, (b) the number of defects per million and corresponding sigma level, and (c) the number of defective units per million and corresponding sigma level.

**Solution:**

(a) Given $N_d = 1989$ defects among all units, $N_{du} = 512$ defective cars, $N_u = 16,578$, and $N_o = 85$

(a) $DPMO = \frac{1,000,000(1,989)}{(16,578)(85)} = 1,412$ defects/million opportunities

From Table 20.5, this corresponds to the 4.5 sigma level.

(b) $DPM = \frac{1,000,000(1,989)}{(16,578)} = 119,978$ defects/million

From Table 20.5, this corresponds to around the 2.7 sigma level.

(c) $DUPM = \frac{1,000,000(578)}{(16,578)} = 34,865$ defective units/million

From Table 20.5, this corresponds to around the 3.3 sigma level.

20.20 A digital camera maker produces three different models: (1) base model, (2) zoom model, and (3) zoom model with extra memory. Data for the three models are shown in the table below. The three models have been on the market for one year, and the first year’s sales are given in the table. Also given are critical-to-quality (CTQ) characteristics and total defects that have been tabulated for the products sold. Higher model numbers have more CTQ characteristics (opportunities for defects) because they are more complex. The category of total defects refers to the total number of defects of all CTQ characteristics for each model. For each of the three models, determine (a) the number of defects per million opportunities and corresponding sigma level, (b) the number of defects per million and corresponding sigma level, and (c) the number of defective units per million and corresponding sigma level. (d) Does any one model seem to be produced at a higher quality level than the others? (e) Determine aggregate values for $DPMO$, $DPM$, and $DUPM$ and their corresponding sigma levels for all models made by the camera maker.

<table>
<thead>
<tr>
<th>Model</th>
<th>Annual sales</th>
<th>CTQ characteristics</th>
<th>Number of defective cameras</th>
<th>Total number of defects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>62,347</td>
<td>16</td>
<td>127</td>
<td>282</td>
</tr>
<tr>
<td>2</td>
<td>31,593</td>
<td>23</td>
<td>109</td>
<td>429</td>
</tr>
<tr>
<td>3</td>
<td>18,662</td>
<td>29</td>
<td>84</td>
<td>551</td>
</tr>
</tbody>
</table>

**Solution:**

Summarizing the data, for Model 1, $N_u = 62,347$, $N_o = 16$, $N_{du} = 127$, and $N_d = 282$. For Model 2, $N_u = 31,593$, $N_o = 23$, $N_{du} = 109$, and $N_d = 429$. For Model 3, $N_u = 18,662$, $N_o = 2$, $N_{du} = 84$, and $N_d = 551$.

(a) Model 1: $DPMO = \frac{1,000,000(282)}{(62,347)(16)} = 283$ defects/million opportunities

From Table 20.5, this corresponds to the 4.9 sigma level.

Model 2: $DPMO = \frac{1,000,000(429)}{(31,593)(23)} = 590$ defects/million opportunities

From Table 20.5, this corresponds to the 4.7 sigma level.

Model 3: $DPMO = \frac{1,000,000(551)}{(18,662)(29)} = 1018$ defects/million opportunities

From Table 20.5, this corresponds to the 4.6 sigma level.

(b) Model 1: $DPM = \frac{1,000,000(282)}{(62,347)} = 4,523$ defects/million opportunities

From Table 20.5, this corresponds to the 4.1 sigma level.

Model 2: $DPM = \frac{1,000,000(429)}{(31,593)} = 13,579$ defects/million opportunities

From Table 20.5, this corresponds to the 3.7 sigma level.

Model 3: $DPM = \frac{1,000,000(551)}{(18,662)} = 29,525$ defects/million opportunities

From Table 20.5, this corresponds to the 3.4 sigma level.

(c) Model 1: $DUPM = \frac{1,000,000(127)}{(62,347)} = 2037$ defects/million opportunities

From Table 20.5, this corresponds to the 4.4 sigma level.

Model 2: $DUPM = \frac{1,000,000(109)}{(31,593)} = 3,450$ defects/million opportunities

From Table 20.5, this corresponds to the 4.2 sigma level.

Model 3: $DUPM = \frac{1,000,000(84)}{(18,662)} = 4,501$ defects/million opportunities

From Table 20.5, this corresponds to the 4.6 sigma level.

(d) No model stands out, but model 1 has the highest quality level
(e) Summarizing the data for all models, \(N_v = 62,347 + 31,593 + 18,662 = 112,602\) units, \(N_{dv} = 127 + 109 + 84 = 320\) defective units, \(N_d = 282 + 429 + 551 = 1,262\) defects, and \(N_o = \sum N_vN_o = 62,347(16) + 31,593(23) + 18,662(29) = 2,265,389\) opportunities.

\[DPMO = \frac{1,000,000(1,262)}{2,265,389} = 557 \text{ defects/million opportunities}\]

From Table 20.5, this corresponds to the 4.7 sigma level.

\[DPM = \frac{1,000,000(1,262)}{112,602} = 11,208 \text{ defects/million}\]

From Table 20.5, this corresponds to the 3.8 sigma level.

\[DUPM = \frac{1,000,000(320)}{112,602} = 2,842 \text{ defective units/million}\]

From Table 20.5, this corresponds to the 4.3 sigma level.

**Taguchi Loss Function**

20.21 A certain part dimension on a power garden tool is specified as \(25.50 \pm 0.30\) mm. Company repair records indicate that if the \(\pm 0.30\) mm tolerance is exceeded, there is a 75% chance that the product will be returned for replacement. The cost associated with replacing the product, which includes not only the product cost itself but also the additional paperwork and handling associated with replacement, is estimated to be $200. Determine the constant \(k\) in the Taguchi loss function for this data.

**Solution:**

\[E\{L(x)\} = 0.75(200) + 0.25(0) = $150.00\]

\[150 = k(0.30)^2 \quad k = 1666.67\]

20.22 The design specification on the resistance setting for an electronic component is \(0.50 \pm 0.02\) ohm. If the component is scrapped, the company suffers a $200 cost. (a) What is the implied value of the constant \(k\) in the Taguchi quadratic loss function? (b) If the output of the process that sets the resistance is centered on 0.50 ohm, with a standard deviation of 0.01 ohm, what is the expected loss per unit?

**Solution:**

(a) \[200 = k(0.02)^2 = 0.0004k \quad k = 500,000\]

(b) \[E\{L(x)\} = k\sigma^2 = 500,000(0.01)^2 = 500,000(0.0001) = $50/\text{unit}\]

20.23 The Taguchi quadratic loss function for a particular component in a piece of earth moving equipment is \(L(x) = 3500(x - N)^2\), where \(x\) is the actual value of a critical dimension and \(N\) is the nominal value. If \(N = 150.00\) mm, determine the value of the loss function for tolerances of (a) \(\pm 0.20\) mm and (b) \(\pm 0.10\) mm.

**Solution:**

(a) \[L(x) = 3500(0.20)^2 = $140.00\]

(b) \[L(x) = 3500(0.10)^2 = $35.00\]

20.24 The Taguchi loss function for a certain component is given by \(L(x) = 8000(x - N)^2\), where \(x\) is the actual value of a dimension of critical importance and \(N\) is its nominal value. Company management has decided that the maximum loss that can be accepted is $12.00. (a) If the nominal dimension is 30.00 mm, at what value should the tolerance on this dimension be set? (b) Does the value of the nominal dimension have any effect on the tolerance that should be specified?

**Solution:**

(a) \[12 = 8000(x - N)^2\]

\[(x - N)^2 = 12/8000 = 0.0015 \quad (x - N) = 0.0387 \text{ mm}\]

(b) \(N\) has no effect. It is \((x - N)\) that affects \(L(x)\).

20.25 Two alternative manufacturing processes, A and B, can be used to produce a certain dimension on one of the parts in an assembled product. Both processes can produce parts with an average dimension at the desired nominal value. The tolerance on the dimension is \(\pm 0.15\) mm. The output of each process follows a normal distribution. However, the standard deviations are different. For process A, \(\sigma = 0.12\) mm; and for process B, \(\sigma = 0.07\) mm. Production costs per piece for A and B are $7.00 and $12.00, respectively. If inspection and sortation is required, the cost is $0.50 per piece. If a part is found to be defective, it must be scrapped at a cost = its production cost. The Taguchi loss function for this component is given by \(L(x) = 2500(x - N)^2\), where \(x\) is the actual value of the dimension and \(N\) is its nominal value. Determine the average cost per piece for the two processes.

**Solution:**

Process A: \[E\{L(x)\} = k\sigma^2 = 2500(0.12)^2 = $36.00\]

% scrap: \(z = 0.15/0.12 = 1.25, \quad q = 2(0.5 - 0.3944) = 0.2112\)

\[C_{pc} = 7.00 + 0.50 + 0.2112(7.00) + 36.00 = $44.98\]
20.26 Solve previous problem 20.25, except that the tolerance on the dimension is ± 0.30 mm rather than ± 0.15 mm.

**Solution:** Process A: 
\[ E(L(x)) = k\sigma^2 = 2500(0.12)^2 = $36.00 \]
% scrap: \( z = 0.30/0.12 = 2.5 \), \( q = 2(0.5 - 0.3944) = 0.2112 \)
\[ C_{pc} = 5.00 + 0.50 + 0.2112(5.00) + 36.00 = $44.98 \]
Process B: 
\[ E(L(x)) = k\sigma^2 = 2500(0.07)^2 = $12.25 \]
% scrap: \( z = 0.30/0.07 = 4.29 \), \( q = 0 \)
% inspection not necessary: \( C_{pc} = 12.00 + 12.25 = $24.25 \)

20.27 Solve previous problem 20.25, assuming the average value of the dimension produced by process B is 0.10 mm greater than the nominal value specified. The average value of the dimension produced by process A remains at the nominal value \( N \).

**Solution:** Process A: 
\[ E(L(x)) = k\sigma^2 = 2500(0.12)^2 = $36.00 \]
% scrap: \( z = 0.15/0.12 = 1.25 \), \( q = 2(0.5 - 0.3944) = 0.2112 \)
\[ C_{pc} = 5.00 + 0.50 + 0.2112(5.00) + 36.00 = $44.98 \]
Process B: 
\[ E(L(x)) = k(\mu - N)^2 + \sigma^2 = 2500[0.10^2 + 0.07^2] = 2500[0.01 + 0.0049] = $37.25 \]
Scrap: \( z_1 = (0.15 + 0.10)/0.07 = 3.57 \), \( q_1 = 0.5 - 0.4998 = 0.0002 \)
\( z_2 = (0.15 - 0.10)/0.07 = 0.71 \), \( q_2 = 0.5 - 0.2612 = 0.2388 \)
\( q = q_1 + q_2 = 0.0002 + 0.2388 = 0.2390 \)
\[ C_{pc} = 12.00 + 0.50 + 0.239(12.00) + 37.25 = $52.62 \]

20.28 Two different manufacturing processes, A and B, can be used to produce a certain component. The specification on the dimension of interest is 100.00 mm ± 0.20 mm. The output of process A follows the normal distribution, with \( \mu = 100.00 \) mm and \( \sigma = 0.10 \) mm. The output of process B is a uniform distribution defined by \( f(x) = 2.0 \) for 99.75 ≤ \( x \) ≤ 100.25 mm. Production costs per piece for processes A and B are each $5.00. Inspection and sortation cost is $0.50 per piece. If a part is found to be defective, it must be scrapped at a cost = twice its production cost. The Taguchi loss function for this component is given by \( L(x) = 2500(x - N)^2 \), where \( x \) = value of the dimension and \( N \) is its nominal value. Determine the average cost per piece for the two processes.

**Solution:** Process A: 
\[ E(L(x)) = 2500(0.10)^2 = $25.00 \]
Scrap: \( z = 0.20/0.10 = 2.0 \), \( q = 2(0.5 - 0.4773) = 0.0454 \)
\[ C_{pc} = 5.00 + 0.50 + 0.0454(10.00) + 25.00 = $30.95 \]
Process B: For uniform distribution, \( \sigma^2 = \frac{(100.25 - 99.75)^2}{12} = 0.020833 \)
\[ E(L(x)) = 2500(0.020833) = $52.08 \]
Scrap: \( q = 0.05/0.25 = 0.20 \)
\[ C_{pc} = 5.00 + 0.50 + 0.20(10.00) + 52.08 = $59.58 \]
Chapter 21
INSPECTION PRINCIPLES AND PRACTICES

REVIEW QUESTIONS

21.1 What is inspection?

Answer: As defined in the text, inspection is the activity of examining the product, its components, subassemblies, or materials out of which it is made, to determine whether they conform to design specifications.

21.2 Briefly define the two basic types of inspection.

Answer: The two basic types of inspection are (1) inspection for variables, in which one or more quality characteristics of interest are measured using an appropriate measuring instrument or sensor; and (2) inspection for attributes, in which the part or product is inspected to determine whether it conforms to the accepted quality standard. Inspection by attributes can also involve counting the number of defects in a product.

21.3 What are the four steps in a typical inspection procedure?

Answer: As defined in the text, the four steps are (1) presentation of the item for examination; (2) examination of the item for nonconforming feature(s); (3) deciding whether the item satisfies the defined quality standards; and (4) action, such as accepting or rejecting the item, or sorting the item into the most appropriate quality grade.

21.4 What are the Type I and Type II errors that can occur in inspection?

Answer: A Type I error is when an item of good quality is incorrectly classified as being defective. It is a “false alarm.” A Type II error is when an item of poor quality is erroneously classified as being good. It is a “miss.”

21.5 What is quality control testing as distinguished from inspection?

Answer: Whereas inspection is used to assess the quality of the product relative to design specifications, testing refers to the assessment of the functional aspects of the product: Does the product operate the way it is supposed to operate? Thus, QC testing is a procedure in which the item being tested (product, subassembly, part, or material) is observed during actual operation or under conditions that might be present during operation.

21.6 What are the Type I and Type II statistical errors that can occur in acceptance sampling?

Answer: A Type I error occurs when a batch of product is rejected when in fact it is equal to or better than the acceptable quality level (AQL). The associate probability of a Type I error is called the producer’s risk. A Type II error occurs when a batch of product is accepted when in fact its quality is worse than the lot tolerance percent defective (LTPD). The probability of this error is called the consumer’s risk.

21.7 Describe what an operating characteristic curve is in acceptance sampling.

Answer: An operating characteristic curve for a given sampling plan gives the probability of accepting a batch as a function of the possible fraction defect rates that might exist in the batch.

21.8 What are the two problems associated with 100% manual inspection?

Answer: The first problem is the expense involved. Instead of dividing the time of inspecting the sample over the number of parts in the production run, the inspection time per piece is applied to every part. The inspection cost sometimes exceeds the cost of making the part. The second problem with 100% manual inspection is the problem of inspection accuracy. There are almost always errors associated with 100% inspection (Type I and II errors), especially when human inspectors perform the inspection procedure.

21.9 What are the three ways in which an inspection procedure can be automated?

Answer: As identified in the text, the three ways to implement automated inspection are (1) automated presentation of parts by an automatic handling system with a human operator still performing the examination and decision steps; (2) automated examination and decision by an automatic inspection
machine, with manual loading (presentation) of parts into the machine; and (3) completely automated inspection system in which parts presentation, examination, and decision are all performed automatically.

21.10 What is the difference between off-line inspection and on-line inspection?

**Answer:** Off-line inspection is performed away from the manufacturing process, and there is generally a time delay between processing and inspection. It is often accomplished using statistical sampling methods. On-line inspection is when the inspection procedure is performed when the parts are made, either as an integral step in the processing or assembly operation, or immediately afterward.

21.11 Under what circumstances is process monitoring a suitable alternative to actual inspection of the quality characteristic of the part or product?

**Answer:** The use of process monitoring as an alternative to product inspection relies on the assumption of a deterministic cause-and-effect relationship between the process parameters that can be measured and the quality characteristics that must be maintained within tolerance. Accordingly, by controlling the process parameters, indirect control of product quality is achieved.

21.12 What is the difference between distributed inspection and final inspection in quality control?

**Answer:** Distributed inspection is when inspection stations are located along the line of flow of the part or product. In the most extreme case, there is an inspection station following every operation. Final inspection is when one comprehensive inspection is performed on the part or product after all operations have been completed.

**PROBLEMS**

**Inspection Accuracy**

21.1 An inspector reported a total of 18 defects out of a total batch size of 250 parts. On closer examination, it was determined that 5 of these reported defects were in fact good pieces, while a total of 9 defective units were undetected by the inspector. What is the inspector’s accuracy in this instance? Specifically, what are the values of $p_1$ and $p_2$. (b) What was the true fraction defect rate $q$?

**Solution:** (a) Actual quantity of defects = (18 - 5) + 9 = 22 defects
Actual quantity of good units = 250 - 22 = 228 good units
Inspector correctly found 250 - 18 - 9 = 223 good units $p_1 = 223/228 = 0.9781$
Inspector found 18 - 5 = 13 defects $p_2 = 13/22 = 0.5909$

(b) True defect rate $q = 22/250 = 0.088$

21.2 For the preceding problem, develop a table of outcomes similar in format to Table 21.3 in the text. The entries in the table should represent the probabilities of the various possible outcomes in the inspection operation.

**Solution:** From Problem 21.1, $p_1 = 0.9781$, $p_2 = 0.5909$, and $q = 0.088$

<table>
<thead>
<tr>
<th>Conforming</th>
<th>Nonconforming</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accept item</td>
<td>0.892</td>
<td>0.036</td>
</tr>
<tr>
<td>Reject item</td>
<td>0.020</td>
<td>0.052</td>
</tr>
<tr>
<td>Totals</td>
<td>0.912</td>
<td>0.088</td>
</tr>
</tbody>
</table>

21.3 For Example 21.1 in the text, develop a table of outcomes similar in format to Table 21.3 in the text. The entries will be the probabilities of the various possible outcomes in the inspection operation.

**Solution:** From Example 21.1, $p_1 = 0.9535$, $p_2 = 0.5714$, and actual $q = 14/100 = 0.14$

Conforming items:
Pr(accept) = $p_1 (1 - q) = 0.9535(1 - 0.14) = 0.820$
Pr(reject) = (1 - \( p_1 \))(1 - q) = (1 - 0.9535)(1 - 0.14) = 0.040
Nonconforming items:
Pr(accept) = (1 - \( p_2 \))q = (1 - 0.5714)(0.14) = 0.060
Pr(reject) = \( p_2 \)q = (0.5714)(0.14) = 0.080
Summary table:

<table>
<thead>
<tr>
<th></th>
<th>Conforming</th>
<th>Nonconforming</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accept item</td>
<td>0.820</td>
<td>0.060</td>
<td>0.880</td>
</tr>
<tr>
<td>Reject item</td>
<td>0.040</td>
<td>0.140</td>
<td>0.120</td>
</tr>
<tr>
<td>Totals</td>
<td>0.860</td>
<td>0.140</td>
<td>1.000</td>
</tr>
</tbody>
</table>

21.4 An inspector's accuracy has been assessed as follows: \( p_1 = 0.94 \) and \( p_2 = 0.80 \). The inspector is given the task of inspecting a batch of 200 parts and sorting out the defects from good units. If the actual defect rate in the batch is \( q = 0.04 \), determine (a) the expected number of Type I and (b) Type II errors the inspector will make. (c) Also, what is the expected fraction defect rate that the inspector will report at the end of the inspection task?

Solution: (a) E(Type I error). Probability according to Table 21.3 in text is (1 - \( p_1 \))(1 - q)\((1 - p_2)q\)
(1 - \( p_1 \))(1 - q)\((1 - p_2)q\) = (1 - 0.94)(1 - 0.04)(0.96)(0.04) = 0.0576
In 200 pc, E(number of Type I errors) = 0.0576(200) = 11.52 pc

(b) E(Type II error). Probability according to Table 21.3 in text is (1 - \( p_2 \))q
(1 - \( p_2 \))q = (1 - 0.80)(0.04) = 0.2(0.04) = 0.008
In 200 pc, E(number of Type II errors) = 0.008(200) = 1.6 pc

(c) E(number of defects reported).
Probability of rejection in Table 21.3 is 1 - \( p_1 \) - q(1 - \( p_1 \) - \( p_2 \))
1 - \( p_1 \) - q(1 - \( p_1 \) - \( p_2 \)) = 1 - 0.94 - 0.04(1 - 0.94 - 0.80) = 0.06 - 0.04(0.74) = 0.0896
In 200 pc, E(number of defects reported) = 0.0896(200) = 17.92 pc
Fraction defect rate reported = 17.92/200 = 0.0896

21.5 An inspector must 100% inspect a production batch of 500 parts using a gaging method. If the actual fraction defect rate in the batch is \( q = 0.02 \), and the inspector’s accuracy is given by \( p_1 = 0.96 \) and \( p_2 = 0.84 \), determine (a) the number of defects the inspector can be expected to report and (b) the expected number of Type I and Type II errors the inspector will make.

Solution: (a) Probability of rejection in Table 21.3 = 1 - \( p_1 \) - q(1 - \( p_1 \) - \( p_2 \))
Qf = Qo \((1 - p_1 - q(1 - p_1 - p_2))\) = (1 - 0.96 - 0.02(1 - 0.96 - 0.84))(500)
Qf = (0.04 - 0.02(-0.8))(500) = 0.056(500) = 28 pc

(b) Probability of Type I errors according to Table 21.3 in text is (1 - \( p_1 \))(1 - q)
E(Type I errors) = (1 - \( p_1 \))(1 - q)\(Q \) = (1 - 0.96)(1 - 0.02)(500) = 0.04(0.98)(500) = 19.6 pc

Probability of Type II errors according to Table 21.3 in text is (1 - \( p_2 \))q
E(Type II errors) = (1 - \( p_2 \))q \(Q \) = (1 - 0.84)(0.02)(500) = 1.6 pc

Effect of Fraction Defect Rate

21.6 A batch of 12,000 raw work units is processed through 15 operations, each of which has a fraction defect rate of 0.03. How many defect-free units and how many defects are in the final batch?

Solution: \( Q_f = Q_o (1 - q)^n = Q_o (1 - 0.03)^{15} = 12,000(0.97)^{15} = 12,000(0.63325) = 7599 \) defect-free units
\( D = 12,000 - 7599 = 4401 \) defects

21.7 A silicon wafer has a total of 400 integrated circuits (ICs) at the beginning of its fabrication sequence. A total of 80 operations are used to complete the integrated circuits, each of which inflicts damages on 1.5% of the ICs. The damages compound, meaning that an IC that is already damaged has the same probability of being damaged by a subsequent process as a previously undamaged IC. How many defect-free ICs remain at the end of the fabrication sequence?

Solution: \( Q_f = Q_o (1 - q)^n = Q_o (1 - 0.015)^{80} = 400(0.985)^{80} = 400(0.2985) = 119 \) defect-free ICs
21.8 A batch of workparts is processed through a sequence of nine processing operations, which have fraction defect rates of 0.03, 0.05, 0.02, 0.04, 0.06, 0.01, 0.03, 0.04, and 0.07, respectively. A total of 10,000 completed parts are produced by the sequence. What was the starting batch quantity?

Solution: \[ Q_f = Q_o (1 - q_1)(1 - q_2)...(1 - q_9) \]
\[ 10,000 = Q_o (0.97)(0.95)(0.98)(0.96)(0.94)(0.99)(0.97)(0.96)(0.93) = Q_o (0.6987) \]
\[ Q_o = \frac{10,000}{0.6987} = 14,312 \text{ pc} \]

21.9 A production line consists of six workstations, as shown in the accompanying figure. The six stations are as follows: (1) first manufacturing process, scrap rate is \( q_1 = 0.10 \); (2) inspection for first process, separates all defects from first process; (3) second manufacturing process, scrap rate is \( q_3 = 0.20 \); (4) inspection for second process, separates all defects from second process; (5) rework, repairs defects from second process, recovering 70% of the defects from the preceding operation and leaving 30% of the defects as still defective; (6) third manufacturing process, scrap rate \( q_6 = 0 \). If the output from the production line is to be 100,000 defect-free units, what quantity of raw material units must be launched onto the front of the line?

Solution: \[ Q_f = Q_o (1 - q_1)(1 - q_3 + q_3(1 - q_5))(1 - q_6) \]
\[ 100,000 = Q_o (1 - 0.10)(1 - 0.20 + 0.20 \times 0.70)(1 - 0) = Q_o (0.90)(0.80 + 0.14)(1.0) = 0.846 Q_o \]
\[ Q_o = \frac{100,000}{0.846} = 118,203 \text{ pc} \]

21.10 A certain industrial process can be depicted by the diagram below. Operation 1 is a disassembly process in which each unit of raw material is separated into one unit each of parts A and B. These parts are then processed separately in operations 2 and 3, respectively, which have scrap rates of \( q_2 = 0.05 \) and \( q_3 = 0.10 \). Inspection stations 4 and 5 sort good units from bad for the two parts. Then the parts are assembled back together in operation 6, which has a fraction defect rate \( q_6 = 0.15 \). Final inspection station 7 sorts good units from bad. The desired final output quantity is 100,000 units. (a) What is the required starting quantity (into operation 1) to achieve this output? (b) Will there be any leftover units of parts A or B, and if so, how many?

Solution: (a) Let \( Q_i \) = output quantity of process \( i \), and let \( Q_{i+1} \) = input quantity to process \( i \).
Critical path through diagram = 1 - 3 - 5 - 6 - 7 (path B) since fraction defect rate \( q_3 \) (process 3) is greater than \( q_2 \).
\[ Q_1 = Q_o = 100,000 \text{ pc} \]
\[ Q_2 = Q_o (1 - 0.10) \]
\[ Q_3 = Q_o (1 - 0.15) \]
\[ Q_4 = Q_o (1 - 0.10)(1 - 0.05)(1 - 0.15) = 0.765Q_o \]
\[ Q_o = \frac{100,000}{0.765} = 130,719 \text{ pc} \]

If alternative path 1 - 2 - 4 - 6 - 7 (path A) had been taken, then the calculations are as follows:
\[ Q_o = \frac{100,000}{0.8075} = 123,839 \text{ pc} \]
which would not be enough units to supply path B.

(b) Leftover units of A = 130,719 - 123,839 = 6880 pc

21.11 A certain component is produced in three sequential operations. Operation 1 produces defects at a rate \( q_1 = 4\% \), Operation 2 produces defects at a rate \( q_2 = 5\% \). Operation 3 produces defects at a rate \( q_3 = 6\% \). Operations 2 and 3 can be performed on units that are already defective. If 100,000 starting parts are processed through the sequence, (a) how many units are expected to be defect-free, (b) how many units are expected to have exactly one defect, and (c) how many units are expected to have all three defects?

Solution: (a) Quantity of defect-free pieces \( Q_f = Q_o(1 - q_1)(1 - q_2)(1 - q_3) \)
\[ Q_f = 100,000(1 - 0.04)(1 - 0.05)(1 - 0.06) = 100,000(0.96)(0.95)(0.94) = 85,728 \text{ pc} \]

(b) Quantity of pieces with exactly one defect:
\[ D_1 = 100,000(0.04)(0.95)(0.94) = 3572 \text{ pc} \]
\[ D_2 = 100,000(0.96)(0.05)(0.94) = 4512 \text{ pc} \]
\[ D_3 = 100,000(0.96)(0.95)(0.06) = 5472 \text{ pc} \]
Total pieces with exactly one defect = 3572 + 4512 + 5472 = 13,556 pc

(c) Quantity of pieces with all three defects $D_{1,2,3} = 100,000(0.04)(0.05)(0.06) = 12$ pc

21.12

An industrial process can be depicted as in the diagram below. Two components are made, respectively, by operations 1 and 2, and then assembled together in operation 3. Scrap rates are as follows: $q_1 = 0.20$, $q_2 = 0.10$, and $q_3 = 0$. Input quantities of raw components at operations 1 and 2 are 25,000 and 20,000, respectively. One of each component is required in the assembly operation. Trouble is that defective components can be assembled just as easily as good components, so inspection and sortation is required in operation 4. Determine (a) how many defect-free assemblies will be produced and (b) how many assemblies will be made with one or more defective components. (c) Will there be any leftover units of either component, and if so, how many?

Solution: (a) Determine the limiting operation, 1 or 2.

Let $Q_i = \text{output quantity of good units from operation } i$.

$Q_1 = 25,000(1 - q_1) = 25,000(0.80) = 20,000$ pc

$Q_2 = 20,000(1 - q_2) = 20,000(0.90) = 18,000$ pc

Conclusion: operation 2 is the limiting operation.

Quantity of defect-free pieces $= Q_f = 20,000(1 - q_1)(1 - q_2)(1 - q_3) = 20,000(0.8)(0.9)(1.0) = 20,000(0.72) = 14,400$ pc

(b) Quantity of pieces with one or more defects

$D_f = Q_o - Q_f = 20,000 - 14,400 = 5,600$ pc

Check: $D_f = 20,000(0.8x0.1 + 0.2x0.9) + 0.2x0.1) = 1600 + 3600 + 400 = 5,600$ pc.

(c) Leftover units from operation 1 = 25,000 - 20,000 = 5000 pc

Inspection Costs

21.13

Two inspection alternatives are to be compared for a processing sequence consisting of 20 operations performed on a batch of 100 starting parts: (1) one final inspection and sortation operation following the last processing operation, and (2) distributed inspection with an inspection and sortation operation after each processing operation. The cost of each processing operation $C_{pr} = $1.00 per unit processed. The fraction defect rate at each operation $q = 0.03$. The cost of the single final inspection and sortation operation in alternative (1) is $C_{sf} = $2.00 per unit. The cost of each inspection and sortation operation in alternative (2) is $C_s = $0.10 per unit. Compare total processing and inspection costs per batch for the two cases.

Solution: Alternative (1): Final inspection:

$C_b = Q_o(nC_{pr} + C_{sf}) = 100(20 x 1.00 + 2.00) = 100(22.00) = $2,200.00

Alternative (2): Distributed inspection:

$C_b = Q_o(1 + (1 - q)^5 + (1 - q)^10 + (1 - q)^15 + (1 - q)^20)(C_{pr} + C_s) = 100(1 + (0.97)^5 + (0.97)^10 + (0.97)^15 + (0.97)^20)(1.00 + 0.10) = 100(15.2068)(1.10) = $1,672.75

21.14

In the preceding problem, instead of inspecting and sorting after every operation, the 20 operations will be divided into groups of five, with inspections after operations 5, 10, 15, and 20. Following the logic of Eq. (21.11), the cost of each inspection will be five times the cost of inspecting for one defect feature; that is, $C_{s5} = C_{s10} = C_{s15} = C_{s20} = 5($0.10) = $0.50 per unit inspected. Processing cost per unit for each operation remains the same as before at $C_{pr} = $1.00, and $Q_o = 100$ parts. What is the total processing and inspection cost per batch for this partially distributed inspection system?

Solution:

$C_b = Q_o(5C_{pr} + C_{s5}) + Q_o(1-q)^5(5C_{pr} + C_{s10}) + Q_o(1-q)^10(5C_{pr} + C_{s15}) + Q_o(1-q)^15(5C_{pr} + C_{s20}) = 100(5.00 +0.50) + 100(1-0.03)^5(5.00+0.50) + 100(1-0.03)^10(5.00+0.50) + 100(1-0.03)^15(5.00+0.50) = 100(5.50)(1 + (0.97)^5 + (0.97)^10 + (0.97)^15) = 550(1 + 0.8587 + 0.7374 + 0.6333) = 550(3.2294) = $1776.17

21.15

A processing sequence consists of 10 operations, each of which is followed by an inspection and sortation operation to detect and remove defects generated in the processing operation. Defects in each process occur at a rate of $q = 0.04$. Each processing operation costs $1.25 per unit processed, and the inspection/sortation operation costs $0.25 per unit. (a) Determine the total processing and inspection costs for this distributed inspection system. (b) A proposal is being considered to combine all of the inspections into one final inspection and
sortation station following the last processing operation. Determine the cost per unit of this final inspection and sortation station that would make the total cost of this system equal to that of the distributed inspection system.

**Solution:** (a) Distributed inspection Eq. (21.10): Let \( Q_o = 1 \), thus \( C_b = \text{cost/unit} \).

\[
C_b = Q_o \left[ 1 + (1 - q) + (1 - q)^2 + \ldots + (1 - q)^9 \right] (C_{pr} + C_s) \\
= (1 + 0.96 + 0.9216 + \ldots + 0.6925) (1.25 + 0.25) = 8.3791(1.50) = \$12.5685/pc
\]

(b) Final inspection Eq. (21.8): Again, let \( Q_o = 1 \), thus \( C_b = \text{cost/unit} \).

\[
C_b = Q_o \left( nC_{pr} + C_{sf} \right) = 10 \times 1.25 + C_{sf} = 12.50 + C_{sf}
\]

Set \( C_b \) for distributed inspection \( = C_b \) for final inspection:

\[ 12.5685 = 12.50 + C_{sf} \]

\[ C_{sf} = \$0.0685/pc \]

21.16 This problem is intended to show the merits of a partially distributed inspection systems in which inspections are placed after processing steps that generate a high fraction defect rate. The processing sequence consists of eight operations with fraction defect rates for each operation as follows:

<table>
<thead>
<tr>
<th>Operation</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect rate ( q )</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.11</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Three alternatives are to be compared: (1) fully distributed inspection, with an inspection after every operation; (2) partially distributed inspection, with inspections following operations 4 and 8 only; and (3) one final inspection station after operation 8. All inspections include sortations. In alternative (2), the inspection procedures are each designed to detect all of the defects for the preceding four operations. The cost of processing is \( C_{pr} = \$1.00 \) for each of operations 1 through 8. Inspection/sortation costs for each alternative are given in the table below. Compare total processing and inspection costs for the three cases.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Inspection and sortation cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) C_b = $0.10 per unit for each of the eight inspection stations</td>
<td></td>
</tr>
<tr>
<td>(2) C_b = $0.40 per unit for each of the two inspection stations</td>
<td></td>
</tr>
<tr>
<td>(3) C_b = $0.80 per unit for the one final inspection station</td>
<td></td>
</tr>
</tbody>
</table>

**Solution:** Alternative (1): Fully distributed inspection Eq. (21.10): \( Q_o = 1 \), thus \( C_b = \text{cost/unit} \).

\[
C_b = 1.10 + 0.99(1.10) + (0.99)^2(1.10) + (0.99)^3(1.10) + (0.99)^4(0.89)(1.10) + (0.99)^5(0.89)(0.99)(1.10) \\
+ (0.99)^6(0.89)(0.99)(1.10) + (0.99)^7(0.89)(0.99)(1.10) = 1.10(1 + 0.99 + 0.9801 + 0.9703 + 0.8636 + 0.8549 + 0.8464 + 0.8379) \\
= 1.10(7.3432) = \$8.078/pc
\]

Alternative (2): Partially distributed inspection Eq. (21.14) adapted: Again, \( Q_o = 1 \), thus \( C_b = \text{cost/unit} \).

\[
C_b = (4C_{pr} + C_{sf}) + (1 - q_4)(1 - q_2)(1 - q_4)(1 - q_4)(4C_{pr} + C_{sf}) \\
= (4.40) + (0.99)^4(0.89)(4.40) = 4.40(1 + 0.8636) = \$8.20/pc
\]

Alternative (3): One final inspection Eq. (21.8): again, \( Q_o = 1 \), thus \( C_b = \text{cost/unit} \).

\[
C_b = 8C_{pr} + C_{sf} = 8.00 + 0.80 = \$8.80/pc
\]

**Conclusion:** The partially distributed inspection achieves 83% of the savings of a fully distributed inspection system with only 25% of the inspection stations.

### Inspection or No Inspection

21.17 A batch of 1000 parts has been produced and a decision is needed whether to 100% inspect the batch or not. Past history with this part suggests that the fraction defect rate is around 0.02. Inspection cost per part is \$0.20. If the batch is passed on for subsequent processing, the damage cost for each defective unit in the batch is \$8.00. Determine (a) batch cost for 100% inspection and (b) batch cost if no inspection is performed. (c) What is the critical fraction defect value for deciding whether to inspect.

**Solution:** a) \( C_b \) for 100% inspection \( = QC_s = 1000(0.20) = \$200 \)

(b) \( C_b \) for no inspection \( = QqC_d = 1000(0.02)(8.00) = \$160 \)

(c) \( q_c = \frac{C_s}{C_d} = \frac{0.20}{8.00} = 0.025 \)

188
Since the average $q$ is less than 0.025, the decision should be no inspection.

21.18 Given the data from the preceding problem, sampling inspection is being considered as an alternative to 100% inspection. The sampling plan calls for a sample of 100 parts to be drawn at random from the batch. Based on the operating characteristic curve for this sampling plan, the probability of accepting the batch is 95% at the given defect rate of $q = 0.02$. Determine the batch cost for sampling inspection.

**Solution:**

\[
C_b = C_s Q_s + (Q - Q_s) q C_d P_a + (Q - Q_s) C_c (1 - P_a)
\]

\[
= 0.20(100) + (1000 - 100)(0.02)(8.00)(0.95) + (1000 - 100)(0.20)(0.05)
\]

\[
= 20.00 + 136.80 + 9.00 = $165.80
\]
Chapter 22
INSPECTION TECHNOLOGIES

REVIEW QUESTIONS

22.1 Define the term measurement.

Answer: Measurement is a procedure in which an unknown quantity is compared to a known standard, using an accepted and consistent system of units.

22.2 What is metrology?

Answer: Metrology is the science of measurement.

22.3 What are the seven basic quantities used in metrology upon which all other variables are derived?

Answer: The seven basic quantities are length, mass, time, electric current, temperature, luminous intensity, and matter.

22.4 What is the difference between accuracy and precision in measurement? Define these two terms.

Answer: Measurement accuracy is the degree to which the measured value agrees with the true value of the quantity of interest. A measurement procedure is accurate when it is absent of systematic errors, which are positive or negative deviations from the true value that are consistent from one measurement to the next. Precision is a measure of repeatability in a measurement process. Good precision means that random errors in the measurement procedure are minimized.

22.5 With respect to measuring instruments, what is calibration?

Answer: Calibration is a procedure in which the measuring instrument is checked against a known standard.

22.6 What is meant by the term contact inspection?

Answer: Contact inspection involves the use of a mechanical probe or other device that makes contact with the object being inspected. The purpose of the probe is to measure or gage the object in some way.

22.7 What are some of the advantages of noncontact inspection?

Answer: The text lists four advantages of noncontact inspection: (1) They avoid damage to the surface that might result from contact inspection. (2) Inspection cycle times are inherently faster. (3) Noncontact methods can often be accomplished on the production line without the need for any additional handling of the parts, whereas special handling and positioning of the parts are usually required in contact inspection. (4) There is increased opportunity for 100% automated inspection.

22.8 What is meant by the term coordinate metrology?

Answer: Coordinate metrology is the science concerned with the measurement of the actual shape and dimensions of an object and comparing these with the desired shape and dimensions, as might be specified on a part drawing. It consists of the evaluation of the location, orientation, dimensions, and geometry of the part or object.

22.9 What are the two basic components of a coordinate measuring machine?

Answer: The two basic components of a CMM are (1) the probe head and probe that contacts the surface of an object and (2) the mechanical structure that provides motion of the probe in three-dimensional Cartesian axes.

22.10 Name the four categories into which the methods of operating and controlling a CMM can be classified.

Answer: The four categories are (1) manual drive, (2) manual drive with computer–assisted data processing, (3) motor drive with computer–assisted data processing, and (4) direct computer control with computer–assisted data processing.

22.11 What does the term reverse engineering mean in the context of coordinate measuring machines?

Answer: Reverse engineering means taking an existing physical part and constructing a computer model of the part geometry based on a large number of measurements of its surface by a CMM.
The text lists seven characteristics of potential applications for which CMMs are most appropriate. Name four of the seven characteristics.

**Answer:** The seven characteristics listed in the text are (1) Many inspectors are currently performing repetitive manual inspection operations. (2) The application involves post-process inspection. (3) Measurement of geometric features requires multiple contact points. (4) Multiple inspection setups are required if parts are manually inspected. (5) The part geometry is complex. (6) There is a high variety of parts to be inspected. (7) Repeat orders are common.

What are some of the arguments and objections to the use of inspection probes mounted in toolholders on machine tools?

**Answer:** The two main arguments and objections are the following: (1) Errors that are inherent in the cutting operation will also be manifested in the measuring operation. For example, if there is misalignment between the machine tool axes, thus producing out-of-square parts, this condition will not be identified by the machine-mounted probe because the movement of the probe is affected by the same axis misalignment. (2) Machine–mounted inspection probes take time above and beyond the regular machining cycle. Time is required to program the inspection routines, and time is lost during the cutting sequence for the probe to perform its measurement function.

What is the most common method used to measure surfaces of a part?

**Answer:** The most common surface measuring instruments are stylus–type instruments which are electronic devices that utilize a cone–shaped diamond stylus with very small point radius to traverse across the test surface at a constant slow speed. The stylus moves vertically to trace the deviations from the nominal flat surface of the part.

What is machine vision?

**Answer:** Machine vision can be defined as the acquisition of image data, followed by the processing and interpretation of these data by computer for some useful application.

The operation of a machine vision system can be divided into three functions. Name and briefly describe them.

**Answer:** The three functions are the following: (1) Image acquisition and digitization, which involves the use of a video camera and a digitizing system to store the image data. The image is obtained by dividing the viewing area into a matrix of pixels, in which each pixel has a value proportional to the light intensity of that portion of the scene. An analog-to-digital converter (ADC) converts the intensity value of each pixel into its equivalent digital value. (2) Image processing and analysis, which is designed to separate regions of interest in the image (using techniques such as edge detection) and to characterize the object in the image by means of its features (such as length and area). (3) Interpretation, which is concerned with recognizing the object, usually by comparing it with predefined models or standard values.

What is the largest application of machine vision in industry?

**Answer:** The largest application of machine vision in industry is quality control inspection.

What is an optical comparator?

**Answer:** An optical comparator is an optical device that projects the shadow of an object (e.g., a workpart) against a large screen in front of an operator. The object can be moved in the \( x-y \) axes, permitting the operator to obtain dimensional data using cross hairs on the screen.

The word *laser* is an acronym for what?

**Answer:** The word *laser* stands for light amplification by stimulated emission of radiation).
PROBLEMS

Coordinate Metrology

(For ease of computation, numerical values in the following problems are given at a lower level of precision than most CMMs would be capable of.)

22.1 Two point locations corresponding to a certain length dimension have been measured by a coordinate measuring machine in the x-y plane. The coordinates of the first end are (12.511, 2.273), and the coordinates of the opposite end are (4.172, 1.985), where the units are in inches. The coordinates have been corrected for probe radius. Determine the length dimension that would be computed by the CMM software.

Solution: \[ L = \sqrt{(12.511 - 4.172)^2 + (2.273 - 1.985)^2} = \sqrt{8.339^2 + 0.288^2} = \sqrt{69.622} = 8.344 \text{ in} \]

22.2 The coordinates at the two ends of a certain length dimension have been measured by a CMM. The coordinates of the first end are (120.5, 50.2, 20.2), and the coordinates of the opposite end are (23.1, 11.9, 20.3), where the units are in mm. The given coordinates have been corrected for probe radius. Determine the length dimension that would be computed by the CMM software.

Solution: \[ L = \sqrt{(120.5 - 23.1)^2 + (50.2 - 11.9)^2 + (20.2 - 20.3)^2} \]
\[ L = \sqrt{97.4^2 + 39.3^2 + 0.1^2} = \sqrt{9486.76 + 1466.89 + 0.01} = \sqrt{10953.66} = 104.66 \text{ mm} \]

22.3 Three point locations on the surface of a drilled hole have been measured by a CMM in the x-y axes. The three coordinates are: (16.42, 17.17), (20.20, 11.85), and (24.08, 16.54), where the units are mm. These coordinates have been corrected for probe radius. Determine (a) the coordinates of the hole center and (b) the hole diameter, as they would be computed by the CMM software.

Solution: Use the following equation: \((x-a)^2 + (y-b)^2 = R^2\)

\[
(16.42 - a)^2 + (17.17 - b)^2 = R^2 \quad \text{or} \quad 269.616 - 32.84a + a^2 + 294.809 - 34.34b + b^2 = R^2 \quad (1) \\
(20.20 - a)^2 + (11.85 - b)^2 = R^2 \quad \text{or} \quad 408.040 - 40.40a + a^2 + 140.423 - 23.70b + b^2 = R^2 \quad (2) \\
(24.08 - a)^2 + (16.54 - b)^2 = R^2 \quad \text{or} \quad 579.846 - 48.16a + a^2 + 273.572 - 33.08b + b^2 = R^2 \quad (3)
\]

\[
(1) = (2): \quad 269.616 - 32.84a + 294.809 - 34.34b = 408.040 - 40.40a + 140.423 - 23.70b \\
564.425 - 32.84a + 34.34b = 548.463 - 40.40a + 23.7b \\
564.425 - 548.463 + (40.40 - 32.84)a = (34.34 - 23.70)b \\
15.962 + 7.56a = 10.64b \\
b = 1.500 + 0.7105a \quad (4)
\]

\[
(2) = (3): \quad 408.040 - 40.40a + 140.423 - 23.70b = 579.846 - 48.16a + 273.572 - 33.08b \\
548.463 - 40.40a + 23.7b = 853.418 - 48.16a - 33.08b \\
(48.16 - 40.40)a = (853.418 - 548.463) - (33.08 - 23.7) b \\
7.76a = 304.955 - 9.38b \\
a = 39.298 - 1.2088b \quad (5)
\]

\[
(4) \to (5): \quad a = 39.298 - 1.2088(1.500 + 0.7105a) \\
a = 39.298 - 1.813 - 0.859a \\
1.859a = 37.485 \quad a = 20.16 \text{ mm}
\]

\[
(4) b = 1.500 + 0.7105(20.16) \quad b = 15.83 \text{ mm}
\]

Radius using (1): \[ R^2 = (16.42 - 20.16)^2 + (17.17 - 15.83)^2 = 14.018 + 1.804 = 15.822 \quad R = 3.978 \text{ mm} \]

Diameter = \(2R = 7.96 \text{ mm}\)

22.4 Three point locations on the surface of a cylinder have been measured by a coordinate measuring machine. The cylinder is positioned so that its axis is perpendicular to the x-y plane. The three coordinates in the x-y axes are: (5.242, 0.124), (0.325, 4.811), and (-4.073, -0.544), where the units are inches. The coordinates have been corrected for probe radius. Determine (a) the coordinates of the cylinder axis and (b) the cylinder diameter, as they would be computed by the CMM software.

Solution: Use the following equation: \((x-a)^2 + (y-b)^2 = R^2\)
(5.242 - a)² + (0.124 - b)² = R² or 27.479 - 10.484 a + a² + 0.015 - 0.248 b + b² = R² (1)

(0.325 - a)² + (4.811 - b)² = R² or 0.106 - 0.650 a + a² + 23.146 - 9.622 b + b² = R² (2)

(-4.073 - a)² + (-0.544 - b)² = R² or 16.589 + 8.146 a + a² + 0.296 + 1.088 b + b² = R² (3)

(1) = (2): 27.479 - 10.484 a + 0.015 - 0.248 b = 0.106 - 0.650 a + 23.146 - 9.622 b

27.494 - 10.484 a - 0.248 b = 23.252 - 0.650 a - 9.622 b

(27.494 - 23.252) + (9.622 - 0.248) b = (10.484 - 0.650) a

4.242 + 9.374 b = 10.489 a

a = 0.4314 + 0.9532 b

(4) → (5): b = 0.5973 - 0.8213(0.4314 + 0.9532 b)

b = 0.5873 - 0.3543 - 0.783 b

b = 0.136 in

(4)

a = 0.561 in

Radius using (1) R² = (5.242 - 0.561)² + (0.124 - 0.136)² = 21.9118 + 0.0001 = 21.9119

R = 4.681 in

Diameter = 2 R = 9.362 in

22.5 Two points on a line have been measured by a CMM in the x-y plane. The point locations have the following coordinates: (12.257, 2.550) and (3.341, -10.294), where the units are inches and the coordinates have been corrected for probe radius. Find the equation for the line in the form of Eq. (23.7).

Solution: Use the following equation: x + A y + B = 0

12.257 + 2.550 A + B = 0 or B = -12.257 - 2.550 A

(1)

3.341 - 10.294 A + B = 0 or B = -3.341 + 10.294 A

(2)

(1) = (2): 100.24 + 20.57 A = -3.341 + 10.294 A

A = -0.694

(1) B = -12.257 - 2.550(-0.694)

B = -10.487

Equation: x -0.694 y - 10.487 = 0

22.6 Two points on a line are measured by a CMM in the x-y plane. The points have the following coordinates: (100.24, 20.57) and (50.44, 60.46), where the units are mm. The given coordinates have been corrected for probe radius. Determine the equation for the line in the form of Eq. (23.7).

Solution: Use the following equation: x + A y + B = 0

100.24 + 20.57 A = B

50.44 + 60.46 A = -B

(1)

(2)

(1) = (2): 100.24 + 20.57 A = 50.44 + 60.46 A

(100.24 - 50.44) = (60.46 - 20.57) A

A = 1.248

(1) B = -100.24 - 20.57(1.248)

B = -125.92

Equation: x + 1.248 y - 125.92 = 0

22.7 The coordinates of the intersection of two lines are to be determined using a CMM to define the equations for the two lines. The two lines are the edges of a machined part, and the intersection represents the corner where the two edges meet. Both lines lie in the x-y plane. Measurements are in inches. Two points are measured on the first line to have coordinates of (5.254, 10.430) and (10.223, 6.052). Two points are measured on the second line to have coordinates of (6.101, 0.657) and (8.970, 3.824). The coordinate values have been corrected for
prove probe radius. (a) Determine the equations for the two lines in the form of Eq. (23.7). (b) What are the coordinates of the intersection of the two lines? (c) The edges represented by the two lines are specified to be perpendicular to each other. Find the angle between the two lines to determine if the edges are perpendicular?

**Solution:** (a) First line:
\[ 5.254 + 10.430 A = -B \]  
\[ 10.223 + 6.052 A = -B \]  
(1) = (2):  
\[ 5.254 + 10.430 A = 10.223 + 6.052 A \]  
(10.430 - 6.052) \( A = 1.135 \)  
\[ B = 5.254 + 10.430(1.135) \]  
\[ B = 17.092 \]  
Equation: \[ x + 1.135 y - 17.092 = 0 \]  
(3)

Second line:
\[ 6.101 + 0.657 A = -B \]  
\[ 8.970 + 3.824 A = -B \]  
(4) = (5):  
\[ 6.101 + 0.657 A = 8.970 + 3.824 A \]  
(6.101 - 8.970) \( A = -0.906 \)  
\[ B = -6.101 - 0.657(-0.906) \]  
\[ B = -5.506 \]  
Equation: \[ x - 0.906 y - 5.506 = 0 \]  
(6)

(b) Solve two equations for \( x \) and \( y \) to find intersection point.

\( (3) \ x + 1.135 y - 17.092, \) Rearranging, \( x = 17.092 - 1.135 y \)  
\( (6) \ x - 0.906 y - 5.506, \) Rearranging, \( x = 5.506 + 0.906 y \)  
(3) = (6):  
\[ 17.092 - 1.135 y = 5.506 + 0.906 y \]  
\[ (17.092 - 5.506) = (0.906 + 1.135) y \]  
\[ 11.586 = 2.041 y \]  
\[ y = 5.677 \text{ in} \]  
\( (3) \ x = 17.092 - 1.135(5.677) \)  
\[ x = 10.649 \text{ in} \]  

(c) The angle between the two lines, measured on the positive \( x \) side of the intersection point, is the difference between the angle made with the \( x \)-axis and the first line, and the angle made with the \( x \)-axis and the second line. Converting equations (3) and (6) to the conventional form of Eq. (23.8):
\[ y = m x + b \]

\[ y = -0.881 x + 15.059 \]  
\[ y = 1.1038 x - 6.077 \]  
(6a)

Let the angle made between the \( x \)-axis and the first line = \( \alpha \)
\[ \alpha = \tan^{-1}(-0.881) = -41.38^\circ \]
Let the angle made with the \( x \)-axis and the second line = \( \beta \)
\[ \beta = \tan^{-1}(1.1038) = 47.82^\circ \]
The total angle = \( \beta - \alpha = 47.82^\circ - (-41.38^\circ) = 89.20^\circ \)
The edges are out of perpendicular by 0.80°

22.8 Two of the edges of a rectangular part are represented by two lines in the \( x-y \) plane on a CMM worktable, as illustrated in Figure P22.8. It is desired to mathematically redefine the coordinate system so that the two edges are used as the \( x \)- and \( y \)-axes, rather than the regular \( x-y \) axes of the CMM. To define the new coordinate system, two parameters must be determined: (a) the origin of the new coordinate system must be located in the existing CMM axis system; and (b) the angle of the \( x \)-axis of the new coordinate system must be determined relative to the CMM \( x \)-axis. Two points on the first edge (line 1) have been measured by the CMM and the coordinates are (46.21, 22.98) and (90.25, 32.50), where the units are mm. Also, two points on the second edge (line 2) have been measured by the CMM and the coordinates are (26.53, 40.75) and (15.64, 91.12). The coordinates have been corrected for the radius of the probe. Find (a) the coordinates of the new origin relative to the CMM origin and (b) degrees of rotation of the new \( x \)-axis relative to the CMM \( x \)-axis. (c) Are the two lines (part edges) perpendicular?

**Solution:** First line (line 1):
\[ 46.21 + 22.98 A = -B \]  
\[ 90.25 + 32.50 A = -B \]  
(1) = (2):  
\[ 46.21 + 22.98 A = 90.25 + 32.50 A \]  
\[ (22.98 - 32.50) A = (90.25 - 46.21) \]
Three point locations on the flat surface of a part have been measured by a CMM. The three point locations are
(225.21, 150.23, 40.17), (14.24, 140.92, 38.29), and (12.56, 22.75, 38.02), where the units are mm. The
cordinates have been corrected for probe radius. (a) Determine the equation for the plane in the form of Eq.
(23.10). (b) To assess flatness of the surface, a fourth point is measured by the CMM. If its coordinates are
(120.22, 75.34, 39.26), what is the vertical deviation of this point from the perfectly flat plane determined in (a)?

**Solution:** Use the following equation form: \( x + A y + B z + C = 0 \)

\[
\begin{align*}
225.21 + 150.23 A + 40.17 B &= - C \\
14.24 + 140.92 A + 38.29 B &= - C \\
12.56 + 22.75 A + 38.02 B &= - C
\end{align*}
\]

(1) \( = \) (2) \( = \) (3)

\[
\begin{align*}
(1) &= (2): 225.21 + 150.23 A + 40.17 B = 14.24 + 140.92 A + 38.29 B \\
(225.21 - 14.24) + (150.23 - 140.92) A + (40.17 - 38.29) B &= 0 \\
210.97 + 9.31 A + 1.88 B &= 0 \\
1.88 B &= -210.97 - 9.31 A \\
B &= -122.18 - 4.952 A \\
(2) &= (3): 14.24 + 140.92 A + 38.29 B = 12.56 + 22.75 A + 38.02 B \\
(14.24 - 12.56) + (140.92 - 22.75) A + (38.29 - 38.02) B &= 0 \\
1.68 + 118.17 A + 0.27 B &= 0 \\
(4) \rightarrow (5): 1.68 + 118.17 A + 0.27(-112.218 - 4.952 A) &= 0 \\
1.68 + 118.17 A - 30.299 - 1.337 A &= 0 \\
(118.17 - 1.337) A &= 30.299 - 1.68 \\
116.833 A &= 28.619 \\
A &= 0.245 \\
(4) &= B = -122.18 - 4.952(0.245) \\
(5) &= C = -225.21 - 150.23(0.245) - 40.17(-113.431) \\
(1) &= C = 4294.508
\end{align*}
\]

Equation: \( x + 0.245 y - 113.431 z + 4294.508 = 0 \) (6)
(b) The vertical deviation of point (120.22, 75.34, 39.26) from the plane is in the $z$-direction. To find this deviation, compare the $z$ coordinate of 39.26 with the corresponding value of $z$ on the perfect plane, Eq. (6), at $x = 120.22$ and $y = 75.34$.

$$
113.431 = x + 0.245y + 4294.508 = 120.22 + 0.245(75.34) + 4294.508
$$

$$
z = 39.083
$$

The actual surface is higher than the mathematically perfect plane defined by Eq. (6) by a deviation $= 39.26 - 39.083 = 0.177$ mm

Optical Inspection Technologies

22.10 A solid-state camera has a 256 x 256 pixel matrix. The analog-to-digital converter takes 0.18 microseconds ($0.18 \times 10^{-6}$ sec) to convert the analog charge signal for each pixel into the corresponding digital signal. If there is no time loss in switching between pixels, determine the following: (a) How much time is required to collect the image data for one frame? (b) Is the time determined in part (a) compatible with the processing rate of 30 frames per second?

Solution: (a) $256 \times 256 = 65,536$ pixels

ADC time $= 65,536(0.18 \times 10^{-6}) = 11,796.5 \times 10^{-6} s = 0.0118$ s

(b) Comparing this with $1/30 = 0.0333$ sec, the ADC can be completed within the time required.

22.11 The pixel count of a solid-state camera is 640 x 480. Each pixel is converted from an analog voltage signal to the corresponding digital signal by an analog-to-digital converter. The conversion process takes 0.08 microseconds ($0.08 \times 10^{-6}$ sec) to complete. Given this time, how long will it take to collect and convert the image data for one frame? Can this be done 30 times per second?

Solution: $640 \times 480 = 307,200$ pixels

ADC time $= 307,200 (0.08 \times 10^{-6}) = 0.0246$ s

Comparing this with $1/30 = 0.0333$ sec, the ADC can be completed within the time required.

22.12 A high-resolution solid state camera is to have a 1040 x 1392 pixel matrix. An image processing rate of 30 times per second must be achieved, or 0.0333 sec per frame. To allow for time lost in other data processing per frame, the total ADC time per frame must be 80% of the 0.0333 sec, or 0.0267 sec. In order to be compatible with this speed, in what time period must the analog-to-digital conversion be accomplished per pixel?

Solution: $1040 \times 1392 = 1,447,680$ pixels

Let $T_{adc} =$ conversion time per pixel. Then, $1,447,680 T_{adc} = 0.0267 s = 26700 \times 10^{-6}$ s

$$
T_{adc} = \frac{26,700}{1,447,680} \times 10^{-6} = 0.0184 \times 10^{-6} s
$$

22.13 A solid-state camera system has 512 x 512 picture elements. All pixels are converted sequentially by an ADC and read into the frame buffer for processing. The machine vision system will operate at the rate of 30 frames per second. However, in order to allow time for data processing of the contents of the frame buffer, the analog-to-digital conversion of all pixels by the ADC must be completed in 1/80 second. Assuming that 10 nanoseconds ($10 \times 10^{-9}$ sec.) are lost in switching from one pixel to the next, determine the time required to carry out the analog-to-digital conversion process for each pixel, in nanoseconds.

Solution: $512 \times 512 = 262,144$ pixels

Let $T_{adc} =$ conversion time per pixel. And $1/80$ sec $= 12,500,000 \times 10^{-9}$ s

$$
T_{adc} + 10 = \frac{12,500,000}{262,144} \times 10^{-9} = 47.68 \times 10^{-9} \quad T_{adc} = 37.68 \times 10^{-9} s
$$

22.14 A scanning laser device, similar to the one shown in Figure 22.12, is to be used to measure the diameter of shafts that are ground in a centerless grinding operation. The part has a diameter of 0.475 inch with a tolerance of $\pm 0.002$ inch. The four-sided mirror of the scanning laser beam device rotates at 250 rev/min. The collimating lens focuses 30° of the sweep of the mirror into a swath that is 1.000 inch wide. It is assumed that the light beam moves at a constant speed across this swath. The photodetector and timing circuitry is capable of resolving time units as fine as 100 nanoseconds ($100 \times 10^{-9}$ sec.). This resolution should be equivalent to no more than 10% of the tolerance band ($0.004$ inch). (a) Determine the interruption time of the scanning laser beam for a part whose diameter is equal to the nominal size. (b) How much of a difference in interruption time is associated with the
tolerance of ±0.002 inch? (c) Is the resolution of the photodetector and timing circuitry sufficient to achieve the 10% rule on the tolerance band?

**Solution:** (a) 250 rev/min = 4.1667 rev/s. This is 0.240 s/rev.

30° = 30/360 of one revolution; it therefore takes \((30/360)(0.24 \text{ s}) = 0.020 \text{ s}\) to move the 1.000 in swath.

Time for nominal part size = 0.475 \times 0.02 = 0.0095 s

(b) Difference in interruption time associated with ±0.002 in (0.004 in) = 0.004(0.02 s) = 0.00008 s

(c) It takes 0.020 s to traverse the 1.0 in swath.

Time resolution (given) = 10^{-7} s

Linear resolution = \((10^{-7})/(2\times10^{-2}) = 5 \times 10^{-6} = 0.000005 \text{ in}\)

10% of 0.004 in tolerance = 0.0004 in. Linear resolution is more than adequate to satisfy 10% rule.

22.15 Triangulation computations are to be used to determine the distance of parts moving on a conveyor. The setup of the optical measuring apparatus is as illustrated in the text in Figure 22.14. The angle between the beam and the surface of the part is 30°. Suppose for one given part passing on the conveyor, the baseline distance is 6.55 inches, as measured by the linear photosensitive detection system. What is the distance of this part from the baseline?

**Solution:** \(R = L/\tan(30) = \frac{6.55}{0.57735} = 11.345 \text{ in}\)
Chapter 23
PRODUCT DESIGN AND CAD/CAM IN THE PRODUCTION SYSTEM

REVIEW QUESTIONS

23.1 What are manufacturing support systems?

**Answer:** As defined in the text, manufacturing support systems are the procedures and systems used by the firm to manage production and solve the technical and logistics problems associated with designing the products, planning the processes, ordering materials, controlling work-in-process as it moves through the plant, and delivering products to customers.

23.2 What are the six phases of the general design process?

**Answer:** As listed in the text, the six phases of the general design process are (1) recognition of need, (2) problem definition, (3) synthesis, (4) analysis and optimization, (5) evaluation, and (6) presentation (e.g., documenting the design).

23.3 What is computer-aided design?

**Answer:** As defined in the text, computer-aided design (CAD) is any design activity that involves the effective use of the computer to create, modify, analyze, or document an engineering design.

23.4 Name four of the six reasons for using a CAD system to support the engineering design function?

**Answer:** The six reasons listed in the text are (1) to increase the productivity of the designer, (2) to expand the available geometric forms in the design, (3) to improve the quality of the design, (4) to improve design documentation, (5) to create a manufacturing database, and (6) to promote design standardization.

23.5 Give some examples of engineering analysis software in common use on CAD systems.

**Answer:** The text lists the following examples: (1) Mass properties analysis to calculate weight, center of gravity and similar part attributes, (2) interference checking to identify interferences between components in an assembly, (3) tolerance analysis, (4) finite element analysis, (5) kinematic and dynamic analysis, and (6) discrete-event simulation.

23.6 What is rapid prototyping?

**Answer:** Rapid prototyping is a family of fabrication technologies that allow engineering prototypes of solid parts to be made in minimum lead time by fabricating the part directly from the CAD geometric model.

23.7 What is virtual prototyping?

**Answer:** Virtual prototyping involves the use of the CAD geometric model to construct a digital mock-up of the product, enabling the designer and others to obtain the sensation of the real physical product without actually building the physical prototype.

23.8 What is computer-aided manufacturing?

**Answer:** As defined in the text, computer-aided manufacturing (CAM) is the effective use of computer technology in manufacturing planning and control.

23.9 Name four of the seven important applications of CAM in manufacturing planning?

**Answer:** The seven applications listed in the text are (1) computer-aided process planning (CAPP), (2) computer-assisted NC part programming, (3) computerized machinability data systems, (4) computerized work standards, (5) cost estimating, (6) production and inventory planning, and (7) computer-aided line balancing.

23.10 What is the difference between CAD/CAM and CIM?

**Answer:** CAD/CAM is concerned with the engineering functions in design and manufacturing. Computer integrated manufacturing (CIM) includes all of the engineering functions of CAD/CAM, but it also includes the firm’s business functions that are related to manufacturing.

23.11 What is quality function deployment?
**Answer:** As defined in the text, quality function deployment (QFD) is a systematic procedure for defining customer desires and requirements and interpreting them in terms of product features, process requirements, and quality characteristics.
Chapter 24
PROCESS PLANNING AND CONCURRENT ENGINEERING

REVIEW QUESTIONS

24.1 What is process planning?

Answer: Two similar definitions are given in the text: (1) Process planning involves determining the sequence of processing and assembly steps that must be accomplished to make the product. (2) Process planning consists of determining the most appropriate manufacturing and assembly processes and the sequence in which they should be accomplished to produce a given part or product according to specifications set forth in the product design documentation.

24.2 Name four of the seven decisions and details that are usually included within the scope of process planning?

Answer: The seven items listed in the text are (1) interpretation of design drawings, (2) selection of processes and their sequence, (3) selection of equipment, (4) deciding the tools, dies, molds, fixtures, and gages that will be needed, (5) methods analysis, (6) work standards, and (7) cutting tools and cutting conditions.

24.3 What is the name of the document that lists the process sequence in process planning?

Answer: The document is called a route sheet.

24.4 A typical process sequence for a manufactured part consists of four types of operations. Name and briefly describe the four types of operations.

Answer: The four types of operations are (1) basic processes, which determine the starting geometry of the workpart, (2) secondary processes, which transform the starting geometry into the final geometry, (3) operations to enhance physical properties, such as heat treating of metals, and (4) finishing operations, which usually provide a coating on the part surface.

24.5 What is a net shape process?

Answer: A net shape process is one that requires no subsequent processing to establish the final geometry of the part.

24.6 Name five of the eight factors that influence the make-or-buy decision?

Answer: The eight factors listed in Table 24.2 in the text are the following: (1) How do part costs compare between the make and buy alternatives? (2) Is the process available in-house? If not, then buy the part. (3) What is the total production quantity? High quantities favor a make decision. (4) What is the anticipated product life? Longer product lives favor a make decision. (5) Is the component a standard catalog item? If yes, then buy. (6) Is the supplier reliable? If yes, then buy. (7) Is the company’s plant already operating at full capacity? If yes, then buy. (8) Does the company need an alternative supply source? If yes, then at least some of the parts should be purchased.

24.7 Name three of the five benefits derived from computer-aided process planning?

Answer: The five benefits named in the text are (1) process rationalization and standardization to obtain more logical and consistent process plans than when process planning is done manually, (2) increased productivity of process planners, (3) reduced lead time for process planning, (4) improved legibility over manually prepared route sheets, and (5) ability to incorporate other application programs, such as cost estimating and work standards.

24.8 Briefly describe the two basic approaches in computer-aided process planning.

Answer: The two basic approaches are (1) retrieval CAPP and (2) generative CAPP. A retrieval CAPP system is based on the principles of group technology (GT) and parts classification and coding; in this type of CAPP, a standard process plan (route sheet) is stored in computer files for each part code number and then retrieved for new parts that have the same or similar code numbers. A generative CAPP system creates the process plan based on logical procedures similar to those used by a human planner, but the computer plans the process sequence without human assistance and without a set of predefined standard plans.

24.9 What is concurrent engineering?
Answer: As defined in the text, concurrent engineering is an approach used in product development in which the functions of design engineering, manufacturing engineering, and other functions are integrated to reduce the elapsed time required to bring a new product to market.

24.10 Design for Manufacturing and Assembly (DFM/A) includes two aspects: (1) organizational changes and (2) design principles and guidelines. Identify two of the organizational changes that might be made in implementing DFM/A?

Answer: The three possible organizational changes mentioned in the text are (1) create project teams consisting of product designers, manufacturing engineers, and other specialties (e.g., quality engineers, material scientists) to develop the new product design; (2) require design engineers to spend some career time in manufacturing to witness first-hand how manufacturability and assemblability are impacted by a product’s design; and (3) assign manufacturing engineers to the product design department on either a temporary or full-time basis to serve as producibility consultants.

24.11 Name five of the eleven universal design guidelines in DFM/A (Table 24.3).

Answer: The universal DFM/A design guidelines listed in Table 24.3 are the following: (1) Minimize the number of components. (2) Use standard commercially available components. (3) Use common parts across product lines. (4) Design for ease of part fabrication. (5) Design parts with tolerances that are within process capability. (6) Design the product to be foolproof during assembly. (7) Minimize flexible components. (8) Design for ease of assembly. (9) Use modular design. (10) Shape parts and products for ease of packaging. (11) Eliminate or reduce adjustments.

24.12 Name three of the four activities often included within the scope of advanced manufacturing planning?

Answer: The four categories identified in the text are (1) evaluation of new technologies to determine which ones will play a role in the company’s future, (2) managing investment projects that relate to new manufacturing technologies and equipment, (3) facilities planning for new equipment and new buildings, and (4) manufacturing research and development to learn more about processes and technologies of value to the company.
Chapter 25
PRODUCTION PLANNING AND CONTROL SYSTEMS

REVIEW QUESTIONS

25.1 What is production planning?
Answer: As defined in the text, production planning consists of (1) deciding which products to make, how many of each, and when they should be completed; (2) scheduling the delivery and/or production of the parts and products; and (3) planning the manpower and equipment resources needed to accomplish the production plan.

25.2 Name three of the four activities within the scope of production planning?
Answer: The four activities identified in the text are (1) aggregate production planning, (2) master production planning, resulting in the master production schedule, (3) material requirements planning, and (4) capacity planning.

25.3 What is production control?
Answer: As defined in the text, production control consists of determining whether the necessary resources to implement the production plan have been provided, and if not, it attempts to take corrective action to address the deficiencies.

25.4 What is the difference between the aggregate production plan and the master production schedule?
Answer: The aggregate production plan indicates the output levels for the major product lines of the company, both products that are currently being produced and future products. The master production schedule takes the product line quantities listed in the aggregate plan and converts them into a very specific schedule of individual products - a list of the products to be manufactured, when they should be completed and delivered, and in what quantities.

25.5 What is material requirements planning (MRP)?
Answer: As defined in the text, material requirements planning (MRP) is a computational technique that converts the master production schedule for end products into a detailed schedule for the raw materials and components used in the end products. The detailed schedule identifies the quantities of each raw material and component item. It also indicates when each item must be ordered and delivered to meet the master schedule for final products.

25.6 What is the difference between independent demand and dependent demand?
Answer: Independent demand means that demand for a product is unrelated to demand for other items. Final products are examples of items whose demand is independent. Independent demand patterns are usually forecasted. Dependent demand means that demand for the item is directly related to the demand for some other item, usually a final product, so that dependency derives from the fact that the item is a component of the other product. Not only component parts but also the raw materials and subassemblies used in the final product are examples of items subject to dependent demand.

25.7 What are the three main inputs to the MRP processor?
Answer: As identified in the text, the three inputs to the MRP processor are (1) the master production schedule, (2) the bill of materials file and other engineering and manufacturing data, and (3) the inventory record file.

25.8 What are common use items in MRP?
Answer: Common use items are raw materials and components that are used on more than one product. The MRP processor collects these common use items from different products to effect economies in ordering the raw materials and producing the components.

25.9 Name three benefits of a well-designed MRP system?
Answer: The text lists the following six benefits: (1) reduction in inventory, (2) quicker response to changes in demand than is possible with a manual requirements planning system, (3) reduced setup and product...
changeover costs, (4) better machine utilization, (5) improved capacity to respond to changes in the master schedule, and (6) as an aid in developing the master schedule.

25.10 What is capacity planning?

Answer: As defined in the text, capacity planning consists of determining what labor and equipment resources are required to meet the current master production schedule as well as long-term future production needs of the firm. It also serves to identify the limitations of the available production resources so that an unrealistic master schedule is not planned.

25.11 Capacity adjustments can be divided into short-term adjustments and long-term adjustments. Name four of the capacity adjustments for the short term?

Answer: Capacity adjustments for the short term include the following: (1) Employment in the plant can be increased or decreased in response to changes in capacity requirements. (2) Temporary workers can be used to increase capacity. (3) The number of shifts worked per production period can be increased or decreased. (4) The number of labor hours per shift can be increased or decreased, through the use of overtime or reduced hours. (5) Inventory stockpiling to maintain steady employment levels during slow demand periods. (6) Order backlogs - deliveries of the product to the customer could be delayed during busy periods when production resources are insufficient to keep up with demand. (7) Subcontracting - letting jobs to other shops during busy periods, or taking in extra work during slack periods.

25.12 What is shop floor control?

Answer: As defined in the text, shop floor control (SFC) is the set of activities in production control that is concerned with the release of production orders to the factory, monitoring and controlling the progress of the orders through the various work centers, and acquiring current information on the status of the orders.

25.13 What are the three phases of shop floor control? Provide a brief definition of each activity.

Answer: The three phases of shop floor control are (1) order release, (2) order scheduling, and (3) order progress. Order release provides the documentation needed to process a production order through the factory. Order scheduling assigns production orders to the various work centers in the plant by preparing a dispatch list that indicates which production orders should be accomplished at the various work centers. Order progress monitors the status of the various orders in the plant, WIP, and other characteristics that indicate the progress and performance of production.

25.14 What does the term machine loading mean?

Answer: Machine loading involves assigning orders to work centers in the plant.

25.15 What are carrying costs in inventory control?

Answer: The term carrying costs refers to the costs of holding inventory, which include (1) investment costs of tying money up in inventory, (2) storage costs, and (3) cost of possible obsolescence or spoilage.

25.16 What is a reorder point system in inventory control?

Answer: A reorder point system is a method of determining when to restock an item; specifically, when the inventory level for a given stock item falls to some point specified as the reorder point, then an order is placed to restock the item.

25.17 What is the difference between material requirements planning (MRP) and manufacturing resource planning (MRP II)?

Answer: Manufacturing resource planning includes material requirements planning, but it also adds capacity planning and shop floor control, two features that are absent in material requirements planning.

25.18 What is enterprise resource planning (ERP)?

Answer: As defined in the text, enterprise resource planning (ERP) is a computer software system that organizes and integrates all of the data and business functions of an organization through a single, central database. The functions include sales, marketing, purchasing, operations, logistics, distribution, inventory control, accounting, finance, and human resources. The operations function can include service activities as well as production, so ERP can be used by service provider companies. ERP operates on a company-wide basis; it is not a plant-based system as MRP applications often are.
PROBLEMS
Order-Point Inventory Systems

25.1 The annual demand for a certain part is 2000 units per year. The part is produced in a batch model manufacturing system. Annual holding cost per piece is $3.00. It takes 2 hours to set up the machine to produce the part, and cost of system downtime is $150/hr. Determine (a) the most economical batch quantity for this part and (b) the associated total inventory cost.

Solution: (a) \( EOQ = \sqrt{\frac{2(2000)(150 \times 2)}{300}} = \sqrt{400,000} = 633 \text{ pc} \)
(b) \( TIC = \frac{3(633)}{2} + \frac{300(2000)}{633} = 949.50 + 947.87 = $1897.37/yr \)

25.2 Annual demand for a made-to-stock product is 60,000 units. Each unit costs $8.00 and the annual holding cost rate is 24%. Setup time to change over equipment for this product is 6 hr, and the downtime cost of the equipment is $120/hr. Determine (a) economic order quantity and (b) total inventory costs.

Solution: (a) \( EOQ = \sqrt{\frac{2(60,000)(120 \times 6)}{(24 \times 8)}} = \sqrt{45,000,000} = 6708 \text{ pc} \)
(b) \( TIC = \frac{1.92(6708)}{2} + \frac{(120 \times 6)(60,000)}{6708} = 6439.68 + 6440.07 = $12,879.75/yr \)

25.3 Demand for a certain product is 25,000 units/yr. Unit cost is $10.00. Holding cost rate is 30%/yr. Changeover (setup) time between products is 10.0 hr, and downtime cost during changeover is $200/hr. Determine (a) economic order quantity, (b) total inventory costs, and (c) total inventory cost per year as a proportion of total production costs.

Solution: (a) \( EOQ = \sqrt{\frac{2(25,000)(200 \times 10)}{(0.30 \times 10)}} = \sqrt{33,333,333} = 5774 \text{ pc} \)
(b) \( TIC = \frac{3(5774)}{2} + \frac{2000(25,000)}{5774} = 8660 + 8660 = $17,320/yr \)
(c) \( TC = DaCp + TIC = 25,000(10) + 17,320 = $267,320/yr \)
Proportion = 15,000/267,320 = 0.0561 = 5.61%

25.4 A part is produced in batches size of 3000 pieces. Annual demand is 60,000 pieces, and piece cost is $5.00. Setup time to run a batch is 3.0 hr, cost of downtime on the affected equipment is figured at $200/hr, and annual holding cost rate is 30%. What would the annual savings be if the product were produced in the economic order quantity?

Solution: Currently at \( Q = 3000, TIC = \frac{0.30(5)(3000)}{2} + \frac{200(3)(60,000)}{3000} = 2250 + 12,000 = $14,250/yr \)
\( EOQ = \sqrt{\frac{2(60,000)(200 \times 3)}{(0.30 \times 5)}} = \sqrt{48,000,000} = 6928 \text{ pc} \)
At \( EOQ = 6928, TIC = \frac{150(6928)}{2} + \frac{600(60,000)}{6928} = 5196 + 5196.30 = $10,392.30/yr \)
Savings = 14250 - 10392.30 = $3857.70/yr

25.5 In the previous problem, (a) how much would setup time have to be reduced in order to make the batch size of 3000 pieces equal to the economic order quantity? (b) How much would total inventory costs be reduced if the EOQ = 3000 units compared to the EOQ calculated in the previous problem? (c) How much would total inventory costs be reduced if the setup time were equal to the value obtained in part (a) compared to the 3.0 hr used in the previous problem?
Solution: (a) \( EOQ = 3000 = \sqrt{\frac{2(60,000)(200T_{su})}{1.50}} \)

\( (3000)^2 = 9,000,000 = \frac{2(60,000)(200T_{su})}{1.50} = 16,000,000 T_{su} \)

\( T_{su} = 0.5625 \text{ hr} = 33.75 \text{ min.} \)

Difference (reduction) = 3.0 - 0.5625 = 2.4375 hr

(b) At \( EOQ = 3000, \) \( TIC = \frac{150(3000)}{2} + \frac{(200 \times 0.5625)(60,000)}{3000} = \$4500/yr \)

Compared to \( TIC at \ EOQ = 6928 \text{ pc in Problem 25.4, Savings} = 10392.30 - 4500 = \$5892.30 \)

(c) Compared to \( TIC at Q = 3000 \text{ pc in Problem 25.4, Savings} = 14250 - 4500 = \$9750.00 \)

25.6

A certain machine tool is used to produce several components for one assembled product. To keep in-process inventories low, a batch size of 100 units is produced for each component. Demand for the product is 3000 units per year. Production downtime costs an estimated $250/hr. All parts produced on the machine tool are approximately equal in value: $9.00/unit. Holding cost rate is 30%/yr. In how many minutes must the changeover between batches be accomplished so that 100 units is the economic order quantity?

Solution: \( EOQ = 100 = \sqrt{\frac{2(3000)(250T_{su})}{0.30 \times 9.00}} \)

\( (100)^2 = \frac{2(3000)(250T_{su})}{2.70} = 555,555.55 T_{su} \)

\( T_{su} = \frac{10,000}{555,555.55} = 0.018 \text{ hr} = 1.08 \text{ min.} \)

25.7

Annual demand for a certain part is 10,000 units. At present the setup time on the machine tool that makes this part is 5.0 hr. Cost of downtime on this machine is $200/hr. Annual holding cost per part is $1.50. Determine (a) EOQ and (b) total inventory costs for this data. Also, determine (c) EOQ and (d) total inventory costs if the changeover time could be reduced to six minutes.

Solution: (a) \( EOQ = \sqrt{\frac{2(10,000)(200 \times 5.0)}{1.50}} = 3641 \text{ pc} \)

(b) \( TIC = \frac{150(3641)}{2} + \frac{1000(10,000)}{3641} = 2730.75 + 2746.50 = \$5477.25/yr \)

(c) If \( T_{su} = 6.0 \text{ min.} = 0.1 \text{ hr, } EOQ = \sqrt{\frac{2(10,000)(200 \times 0.1)}{1.50}} = 516 \text{ pc} \)

(d) \( TIC = \frac{150(516)}{2} + \frac{200(0.1)(10,000)}{516} = 387 + 387.60 = \$774.60/yr \)

25.8

A variety of assembled products are made in batches on a batch model assembly line. Every time a different product is produced, the line must be changed over which causes lost production time. The assembled product of interest here has an annual demand of 12,000 units. The changeover time to set up the line for this product is 6.0 hours. The company figures that the hourly rate for lost production time on the line due to changeovers is $200/hr. Annual holding cost for the product is $7.00 per product. The product is currently made in batches of 1000 units for shipment each month to the wholesale distributor. (a) Determine the total annual inventory cost for this product in batch sizes of 1000 units. (b) Determine the economic batch quantity for this product. (c) How often would shipments be made using this EOQ? (d) How much would the company save in annual inventory costs, if it produced batches equal to the EOQ rather than 1000 units?

Solution: (a) At \( Q = 1000, \) \( TIC = \frac{7.00(1000)}{2} + \frac{(200 \times 6)(12,000)}{1000} = 3500 + 14,400 = \$17,900/yr \)

(b) \( EOQ = \sqrt{\frac{4,114,286}{2}} = 2028 \text{ pc} \)

(c) Using this EOQ, number of batches per year = \( 12,000/2028 = 5.92, \) cycle time per batch = \( 2.028 \text{ months} \)
(d) At $Q = EOQ = 2028$, TIC = \[ \frac{1.00(2028)}{2} + \frac{1200(12,000)}{2028} = 7098 + 7100.59 = $14,198.59/yr \]
Savings = $17,900 – 14,199 = $3701

25.9 A two-bin approach is used to control inventory for a certain low-cost hardware item. Each bin holds 500 units of the item. When one bin becomes empty, an order for 500 units is released to replace the stock in that bin. The order lead time is slightly less than the time it takes to deplete the stock in one bin. Accordingly, the chance of a stock-out is low and the average inventory level of the item is about 250 units, perhaps slightly more. Annual usage of the item is 6000 units. Ordering cost is $50. (a) What is the imputed holding cost per unit for this item, based on the data given? (b) If the actual annual holding cost per unit is 5 cents, what lot size should be ordered? (c) How much does the current two-bin approach cost the company per year, compared to using the economic order quantity?

Solution: (a) $EOQ = 500 = \sqrt{\frac{2(6000)(50)}{C_h}}$

$(500)^2 C_h = 2(6000)(50)$

$C_h = 600,000$

$b = \frac{2(6000)(50)}{0.05} = \sqrt{12,000,000} = 3464$ pc

(b) If $C_h = $0.05, $EOQ = \sqrt{\frac{2(6000)(50)}{0.05}} = \sqrt{12,000,000} = 3464$ pc

(c) With current two-bin approach ($Q = 500$), TIC = \[ \frac{0.05(500)}{2} + \frac{50(6000)}{500} = 12.50 + 600 = $612.50/yr \]

With $EOQ = 3098$, TIC = \[ \frac{0.05(3464)}{2} + \frac{50(6000)}{3464} = 86.60 + 86.60 = $173.20/yr \]

Two-bin approach costs an extra ($612.50 - 173.20) = $439.30/yr

Work-In-Process Inventory Costs

25.10 A workpart costing $80 is processed through the factory. The manufacturing lead time for the part is 12 weeks, and the total time spent in processing during the lead time is 30 hours for all operations at a rate of $35 per hour. Nonoperation costs total $70 during the lead time. The holding cost rate used by the company for work-in-process is 26%. The plant operates 40 hours per week, 52 weeks per year. If this part is typical of the 200 parts per week processed through the factory, determine the following: (a) the holding cost per part during the manufacturing lead time, (b) the total annual holding costs to the factory. (c) If the manufacturing lead time were to be reduced from 12 weeks to 8 weeks, how much would the total holding costs be reduced on an annual basis?

Solution: (a) $C_1 = \Sigma(C_i T_i + C_w) = 35(30) + 70 = 1120$

Holding cost/pc = (80 + 1120/2)(26%/52)(12) = (640)(.005)(12) = $38.40/pc during MLT

(b) Total annual holding cost = (200 parts/week)(52 weeks/yr)(38.40/pc) = $399,360/yr

(c) If MLT were reduced from 12 weeks to 8 weeks, the total annual holding cost would be reduced to ($8/12)(399,360) = $266,240/yr

Check: Holding cost/pc = (640)(.005)(8) = $25.60/pc during MLT

Total annual holding cost = (200 parts/week)(52 weeks/yr)(25.60/pc) = $266,240/yr

25.11 A batch of large castings is processed through a machine shop. The batch size is 20. Each raw casting costs $175. There are 22 machining operations performed on each casting at an average operation time of 0.5 hour per operation. Setup time per operation averages 5 hours. The cost rate for the machine and labor is $40 per hour. Nonoperation costs (inspection, handling between operations, etc.) average $5 per operation per part. The corresponding nonoperation time between each operation averages three working days. The shop works five 8-hour days per week, 52 weeks per year. Interest rate used by the company is 25% for investing in WIP inventory, and storage cost rate is 14% of the value of the item held. Both of these rates are annual rates. Determine the following: (a) manufacturing lead time for the batch of castings, (b) total cost to the shop of each casting when it is completed, including the holding cost, (c) total holding cost of the batch for the time it spends in the machine shop as work-in-process.

Solution: (a) $MLT = 22(5 + 20x0.5 + 24) = 858$ hr = 21.45 weeks
(b) \( C_p = 22(40 \times 0.5 + 5) = \$550/pc \)
\( h = s + i = 14\% + 25\% = 39\% = 0.39/52 = 0.0075/week \)
\( TC_{pc} = 175 + 550 + (175 + 550/2)(0.0075)(21.45) = 725 + 72.39 = \$797.39/pc \)

(c) Total holding cost per batch = 72.39 x 20 = \$1447.80/batch

### Material Requirements Planning

25.12 Using the master schedule of Figure 25.2(b), and the product structures in Figures 25.4 and 25.5, determine the time-phased requirements for component C6 and raw material M6. The raw material used in component C6 is M6. Lead times are as follows: for P1, assembly lead time is 1 week; for P2, assembly lead time is 1 week; for S2, assembly lead time is 1 week; for S3, assembly lead time is 1 week; for C6, manufacturing lead time is 2 weeks; and for M6, ordering lead time is 2 weeks. Assume that the current inventory status for all of the above items is zero units on hand, and zero units on order. The format of the solution should be similar to that presented in Figure 25.7.

**Solution:**

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25.13 Solve previous Problem 25.12 except that the current inventory on hand and on order for S3, C6, and M6 is as follows: for S3, inventory on hand is 2 units and quantity on order is zero; for C6, inventory on hand is 5 units and quantity on order is 10 for delivery in week 2; and for M6, inventory on hand is 10 units and quantity on order is 50 for delivery in week 2.

Solution:

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25.14 Material requirements are to be planned for component C2 given the master schedule for P1 and P2 in Figure 25.2(b), and the product structures in Figures 25.4 and 25.5. Assembly lead time for products and subassemblies (P and S levels) is 1 week, manufacturing lead times for components (C level) is 2 weeks, and ordering lead time for raw materials (M level) is 3 weeks. Determine the time-phased requirements for M2, C2, and S1. Assume there are no common use items other than those specified by the product structures for P1 and P2 (Figures 25.4 and 25.5), and that all on-hand inventories and scheduled receipts are zero. Use a format similar to Figure 25.7. Ignore demand beyond period 10.

Solution:

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</table>
In addition, a planned order release for 140 units of M2 should be included in week 0, not shown in our chart.

25.15 Requirements are to be planned for component C5 in product P1. Required deliveries for P1 are given in Figure 25.2(b), and the product structure for P1 is shown in Figure 25.4. Assembly lead time for products and subassemblies (P and S levels) is 1 week, manufacturing lead times for components (C level) is 2 weeks, and ordering lead time for raw materials (M level) is 3 weeks. Determine the time-phased requirements for M5, C5, and S2 to meet the master schedule. Assume no common use items. On-hand inventories are: 100 units for M5 and 50 units for C5, zero for S2. Scheduled receipts are zero for these items. Use a format similar to Figure 25.7. Ignore demand for P1 beyond period 10.

Solution:

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In addition, a planned order release for 140 units of M2 should be included in week 0, not shown in our chart.
### Gross Requirements

| Item: Component C5 |  |
| Scheduled Receipts |  |
| On hand | 50 | 50 |
| Net Requirements | 150 | 400 |
| Planned Order Releases | 150 | 400 |

### Net Requirements

| Item: Raw material M5 |  |
| Scheduled Receipts |  |
| On hand | 100 | 100 |
| Net Requirements | 50 | 400 |
| Planned Order Releases | 50 | 400 |

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**Solution:**

#### Period 1

| Item: Product P1 |  |
| Scheduled Receipts |  |
| On hand | 0 |  |
| Net Requirements | 50 | 100 |
| Planned Order Releases | 50 | 100 |

#### Period 2

| Item: Subassembly S2 |  |
| Scheduled Receipts |  |
| On hand | 0 |  |
| Net Requirements | 100 | 200 |
| Planned Order Releases | 100 | 200 |

#### Period 3

| Item: Component C5 |  |
| Scheduled Receipts |  |
| On hand | 50 | 50 |
| Net Requirements | 150 | 400 |
| Planned Order Releases | 150 | 400 |

#### Period 4

| Item: Raw material M5 |  |
| Scheduled Receipts |  |
| On hand | 100 | 50 | 50 |
| Net Requirements | -50 | 350 |
| Planned Order Releases | 0 | 350 |

### Order Scheduling

25.17 It is currently day 10 in the production calendar of the XYZ Machine Shop. Three orders (A, B, and C) are to be processed at a particular machine tool. The orders arrived in the sequence A-B-C. The table below indicates the process time remaining and production calendar due date for each order. Determine the sequence of the orders that would be scheduled using the following priority control rules: (a)
first-come-first-serve, (b) earliest due date, (c) shortest processing time, (d) least slack time, and (e) critical ratio.

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<td>A</td>
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<tr>
<td>B</td>
<td>16 days</td>
<td>Day 30</td>
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<tr>
<td>C</td>
<td>6 days</td>
<td>Day 18</td>
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</table>

**Solution:**

(a) First-come-first-serve sequence = A - B - C

(b) Earliest due date sequence = C - A - B

(c) Shortest processing time sequence = A - C - B

(d) Least slack time:

Order A slack time = (20 - 10) - 4 = 6
Order B slack time = (30 - 10) - 16 = 4
Order C slack time = (18 - 10) - 6 = 2

Sequence = C - B - A

(e) Critical ratio:

Order A critical ratio = (20 - 10)/4 = 2.5
Order B critical ratio = (30 - 10)/16 = 1.25
Order C critical ratio = (18 - 10)/6 = 1.33

Sequence = B - C - A

25.18 In previous Problem 25.17, for each solution, (a) through (e), determine which jobs are delivered on time and which jobs are tardy.

**Solution:**

(a) FCFS: sequence = A - B - C

<table>
<thead>
<tr>
<th>Order</th>
<th>Process time</th>
<th>Due date</th>
<th>Start date</th>
<th>Completion</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4 days</td>
<td>Day 20</td>
<td>Day 0</td>
<td>Day 4</td>
<td>On-time</td>
</tr>
<tr>
<td>B</td>
<td>16 days</td>
<td>Day 30</td>
<td>Day 4</td>
<td>Day 20</td>
<td>On-time</td>
</tr>
<tr>
<td>C</td>
<td>6 days</td>
<td>Day 18</td>
<td>Day 20</td>
<td>Day 26</td>
<td>Tardy</td>
</tr>
</tbody>
</table>

(b) Earliest due date: sequence = C - A - B

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<thead>
<tr>
<th>Order</th>
<th>Process time</th>
<th>Due date</th>
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<th>Completion</th>
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<tbody>
<tr>
<td>C</td>
<td>6 days</td>
<td>Day 18</td>
<td>Day 0</td>
<td>Day 6</td>
<td>On-time</td>
</tr>
<tr>
<td>A</td>
<td>4 days</td>
<td>Day 20</td>
<td>Day 6</td>
<td>Day 10</td>
<td>On-time</td>
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<tr>
<td>B</td>
<td>16 days</td>
<td>Day 30</td>
<td>Day 10</td>
<td>Day 26</td>
<td>On-time</td>
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</table>

(c) Shortest processing time: sequence = A - C - B

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<thead>
<tr>
<th>Order</th>
<th>Process time</th>
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<th>Completion</th>
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<tr>
<td>A</td>
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<td>Day 4</td>
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<td>Day 10</td>
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</tr>
<tr>
<td>B</td>
<td>16 days</td>
<td>Day 30</td>
<td>Day 10</td>
<td>Day 26</td>
<td>On-time</td>
</tr>
</tbody>
</table>

(d) Least slack time: Sequence = C - B - A

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<tr>
<th>Order</th>
<th>Process time</th>
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<th>Completion</th>
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<tbody>
<tr>
<td>C</td>
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<td>Day 18</td>
<td>Day 0</td>
<td>Day 6</td>
<td>On-time</td>
</tr>
<tr>
<td>B</td>
<td>16 days</td>
<td>Day 30</td>
<td>Day 6</td>
<td>Day 22</td>
<td>On-time</td>
</tr>
<tr>
<td>A</td>
<td>4 days</td>
<td>Day 20</td>
<td>Day 22</td>
<td>Day 26</td>
<td>Tardy</td>
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</tbody>
</table>

(e) Critical ratio: Sequence = B - C - A

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<tr>
<th>Order</th>
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<tbody>
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<td>Day 30</td>
<td>Day 0</td>
<td>Day 16</td>
<td>On-time</td>
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<td>Days</td>
<td>Day 18</td>
<td>Day 16</td>
<td>Day 22</td>
<td>Status</td>
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<td>C</td>
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<td>Day 26</td>
<td>Tardy</td>
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</table>
**Chapter 26
Just-In-Time and Lean Production**

**REVIEW QUESTIONS**

26.1 Define lean production.

**Answer:** As defined in the text, lean production means doing more and more work with fewer and fewer resources. It also means giving customers what they want and satisfying or surpassing their expectations.

26.2 Name the two pillars of the Toyota production system.

**Answer:** The two pillars of the Toyota production system are (1) just-in-time production and (2) autonamation (automation with a human touch).

26.3 What is the Japanese word for waste?

**Answer:** Muda.

26.4 Name four of the seven forms of waste in production, as identified by Taiichi Ohno.

**Answer:** Taiichi Ohno’s seven forms of waste are (1) production of defective parts, (2) production of more than the number of items needed (overproduction), (3) excessive inventories, (4) unnecessary processing steps, (5) unnecessary movement of people, (6) unnecessary transport and handling of materials, and (7) workers waiting.

26.5 What are three reasons why people and materials are sometimes moved unnecessarily in production operations?

**Answer:** The reasons given in the text are (1) inefficient workplace layout, (2) inefficient plant layout, (3) improper material handling method, (4) production machines spaced too far apart, (5) larger equipment than necessary for the task, (6) conventional batch production.

26.6 What is a just-in-time production system?

**Answer:** As defined in the text, a just-in-time production system produces and delivers exactly the required number of each component to the downstream operation in the manufacturing sequence just at the time when that component is needed. Each component is delivered “just in time.”

26.7 What is the objective of a just-in-time production system?

**Answer:** As indicated in the text, the primary objective of a just-in-time production system is to minimize inventories, especially work-in-process inventories.

26.8 What is the difference between a push system and a pull system in production control?

**Answer:** In a pull system of production control, the order to make and deliver parts at each workstation in the production sequence comes from the downstream station that uses those parts. When the supply of parts at a given workstation is about to be exhausted, that station orders the upstream station to replenish the supply. When this procedure is used throughout the plant, it has the effect of pulling parts through the production system. In a push system, parts at each workstation are produced irrespective of the immediate need for those parts at their respective downstream station. In effect, this production discipline pushes parts through the plant.

26.9 What is a kanban? What are the two types of kanban?

**Answer:** Kanban means “signal card” in Japanese. The kanban system of production control used in the Toyota JIT system is based on the use of cards that authorize (1) parts production and (2) parts delivery in the plant. Accordingly, the two types of kanbans are (1) production kanbans, which authorize the upstream station to produce a batch of parts and (2) transport kanbans, which authorize transport of the parts to the downstream station.

26.10 What is the basic starting point in a study to reduce setup time?

**Answer:** The starting point in setup time reduction is to recognize that there are two types of work elements in the task of setting up a machine: (1) internal elements, which can only be accomplished while the production
machine is stopped, and (2) external elements, which do not require that the machine be stopped. External elements can be accomplished while the previous job is running on the machine.

26.11 What is production leveling?
**Answer:** Production leveling means distributing the changes in product mix and quantity as evenly as possible over time when it is necessary for the production system to adjust to the ups and downs in demand for the final product.

26.12 How is production leveling accomplished?
**Answer:** The approaches mentioned in the text are (1) authorizing overtime during busy periods, (2) using finished product inventories to absorb daily ups and downs in demand, (3) adjusting the cycle times of the production operations, and (4) producing in small batch sizes that are enabled by setup time reduction techniques. In the ideal, the batch size is reduced to one.

26.13 What does autonomation mean?
**Answer:** Taiichi Ohno referred to autonomation as “automation with a human touch.” The notion is that the machines operate autonomously as long as they are functioning properly. When they do not function properly (e.g., when they produce a defective part), they are designed to stop immediately. Autonomation also includes the notion of mistake-proofing the process.

26.14 What is total productive maintenance?
**Answer:** Total productive maintenance (TPM) is a coordinated group of activities whose objective is to minimize production losses due to equipment failures, malfunctions, and low utilization through the participation of workers at all levels of the organization. TPM involves the integration of preventive maintenance and predictive maintenance to avoid emergency maintenance.

26.15 What does the Japanese word “kaizen” mean?
**Answer:** Kaizen means continuous improvement.

26.16 What is a quality circle?
**Answer:** A quality circle is a worker team that is organized to address specific problems that have been identified in the workplace. The problems are not limited to quality. They include problems relating to productivity, cost, safety, maintenance, and other areas of interest to the organization.

26.17 What is visual management?
**Answer:** Visual management refers to a way of managing and organizing operations so that the status of the work situation is evident just by looking at it. If something is wrong, this condition should be obvious to the observer, so that corrective action can be taken immediately. Also called the visual workplace, the principle applies to the entire plant environment.

26.18 What is an andon board?
**Answer:** An andon board is a light panel positioned above a workstation or production line that is used to indicate its operating status. If a problem occurs, such as a line stoppage, the andon board identifies where the problem is and the nature of the problem.

26.19 What is the 5S system?
**Answer:** The 5S system is a set of procedures that is used to organize work areas in the plant. It is also a means of involving workers in the visual management of the factory. The five S’s stand for (1) sort things in the workplace and discard things that are not needed, (2) set in order the things that remain after sorting, (3) shine or clean the workplace, (4) standardize locations for items in the workplace, and (5) self-discipline to sustain the order that has been created.

26.20 What is takt time?
**Answer:** Takt time is defined as the effective daily operating time divided by the daily quantity of units demanded. It is the cycle time that corresponds to the demand rate for the item.

26.21 What are standardized work procedures in the Toyota production system?
**Answer:** Standardized work procedures in the Toyota production system consist of determining the following factors for each task: (1) cycle time, which becomes matched to the takt time for the task, (2) work sequence or standard operations routine, which is the order of work elements performed in the task, and (3) standard work-in-process quantity, which refers to the minimum number of WIP parts needed to avoid workers waiting.

**PROBLEMS**

**Setup Time Reduction**

**26.1** A stamping plant supplies sheet metal parts to a final assembly plant in the automotive industry. The following data are values representative of the parts made at the plant. Annual demand is 150,000 pc (for each part produced). Average cost per piece is $18 and holding cost is 20% of piece cost. Changeover (setup) time for the presses is 5 hours and the cost of downtime on any given press is $200/hr. Determine (a) the economic batch size and (b) the total annual inventory cost for the data. If the changeover time for the presses could be reduced to 10 minutes, determine (c) the economic batch size and (d) the total annual inventory cost.

**Solution:**

(a) \( hC = 0.20(18) = 3.60 \text{ per pc} \) and \( C_{su} = 5(200) = 1000 \text{ per setup} \)

\[
EOQ = \sqrt{\frac{2(150,000)(1000)}{3.60}} = \sqrt{83.33(10^5)} = 9,128.7 \text{ rounded to 9129 pc}
\]

(b) \( TIC = 0.5(9129)(3.60) + 150,000(1,000)/9129 = $32,863 \)

(c) If \( T_{su} = 10 \text{ min} \), \( C_{su} = (10/60)(200) = $33.33 \)

\[
EOQ = \sqrt{\frac{2(150,000)(33.33)}{3.60}} = \sqrt{2.778(10^5)} = 1,666.67 \text{ rounded to 1667 pc}
\]

(d) \( TIC = 0.5(1667)(3.60) + 150,000(33.33)/1667 = $6,000 \)

**26.2** A supplier of parts to an assembly plant in the household appliance industry is required to make deliveries on a just-in-time basis (daily). For one of the parts that must be delivered, the daily requirement is 200 parts, five days per week, 52 weeks per year. However, the supplier cannot afford to make just 200 parts each day; it must produce in larger batch sizes and maintain an inventory the parts from which 200 units are withdrawn for shipment each day. Cost per piece is $20 and holding cost is 24% of piece cost. Changeover time for the production machine used to produce the part is 2 hours and the cost of downtime on this machine is $250/hr. Determine (a) the economic batch size and (b) the total annual inventory cost for the data. It is desired to reduce the batch size from the value determined in part (a) to 200 units, consistent with the daily quantity delivered to the appliance assembly plant. (c) Determine the changeover time that would allow the economic batch size in stamping to be 200 pieces. (d) What is the corresponding total annual inventory cost for this batch size, assuming the changeover time in part (c) can be realized?

**Solution:**

(a) \( hC = 0.24(20) = 4.80 \text{ per pc} \) and \( C_{su} = 2(250) = $500 \text{ per setup} \)

\[
EOQ = \sqrt{\frac{2(52,000)(500)}{4.80}} = \sqrt{10.833(10^6)} = 3,291.4 \text{ rounded to 3291 pc}
\]

(b) \( TIC = 0.5(3291)(4.80) + 52,000(500)/3291 = $15,799 \)

(c) If \( EOQ = 200 \text{ pc} \), find the corresponding setup time.

\[
EOQ = 200 = \sqrt{\frac{2(52,000)(C_{su})}{4.80}}
\]

\[
(200)^2 = 40,000 = 2(52,000)C_{su}/4.80 = 21,667 C_{su}
\]

\[
C_{su} = 40,000/21,667 = 1.846 = 250 T_{su}
\]

\[
T_{su} = 1.846/250 = 0.00738 \text{ hr} = 0.44 \text{ min}
\]

(d) \( TIC = 0.5(200)(4.80) + 52,000(1.846)/200 = 480 + 480 = $960 \)

One might argue that the first term (carrying cost) is irrelevant because the parts are shipped daily and are not held in inventory.

26.3 Monthly usage rate for a certain part is 15,000 units. The part is produced in batches and its manufacturing costs are estimated to be $7.40. Holding cost is 20% of piece cost. Currently the production equipment used to produce this part is also used to produce 19 other parts with similar usage and cost data (assume the data to be
identical for purposes of this problem). Changeover time between batches of the different parts is now 4.0 hours, and cost of downtime on the equipment is $250/hr. A proposal has been submitted to fabricate a fast-acting slide mechanism that will permit the changeovers to be completed in just 5.0 minutes. Cost to fabricate and install the slide mechanism is $200,000. (a) Is this cost justified by the savings in total annual inventory cost that would be achieved by reducing the economic batch quantity from its current value based on a 4-hour setup to the new value based on a 5-minute setup? (b) How many months of savings are required to pay off the $150,000 investment?

Solution: (a) \( hC = 0.20(\$7.40) = \$1.48/pc \) and \( C_{sw} = 4(\$250) = \$100 \) per setup

\[
EOQ = \sqrt{\frac{2(15,000)(12)(1000)}{1.48}} = \sqrt{243.243(10)^6} = 15,596.3 \text{ rounded to } 15,596 \text{ pc}
\]

\( TIC = 0.5(15,596)(1.48) + 12(15,000)(1000)/15,596 = 11541 + 11541 = \$23,083/yr \)

For 20 parts, \( TIC = 20(\$23,083) = \$461,656/yr \)

If \( T_{sw} = 5.0 \text{ min}, C_{sw} = (5/60)(\$250) = \$20.833 \)

\[
EOQ = \sqrt{\frac{2(15,000)(12)(20.833)}{1.48}} = \sqrt{5.06757(10)^6} = 2251.1 \text{ rounded to } 2251 \text{ pc}
\]

\( TIC = 0.5(2251)(1.48) + 12(15,000)(20.833)/2251 = 1665.74 + 1665.90 = \$3331.64/yr \)

For 20 parts, \( TIC = 20(\$3331.64) = \$66,633/yr \)

Annual savings = \$461,656 – \$66,633 = \$395,023

The \$250,000 investment is justified.

(b) Monthly savings = \$395,023/12 = \$32,919

Payback period = \$150,000/\$32,919 = 4.56 months

26.4 An injection-molding machine used to produce 25 different plastic molded parts in a typical year. Annual demand for a typical part is 20,000 units. Each part is made out of a different plastic (the differences are in type of plastic and color). Because of the differences, changeover time between parts is significant, averaging 5 hours to (1) change molds and (2) purge the previous plastic from the injection barrel. One setup person normally does these two activities sequentially. A proposal has been made to separate the tasks and use two setup persons working simultaneously. In that case, the mold can be changed in 1.5 hours and purging takes 3.5 hours. Thus, the total downtime per changeover will be reduced to 3.5 hours from the previous 5 hours. Downtime on the injection-molding machine is \$200/hr. Labor cost for setup time is \$20/hr. Average cost of a plastic molded part is \$2.50, and holding cost is 24% annually. For the 5-hour setup, determine (a) the economic batch quantity, (b) the total number of hours per year that the injection-molding machine is down for changeovers, and (c) the annual inventory cost. For the 3.5-hour setup, determine (d) the economic batch quantity, (e) the total number of hours per year that the injection-molding machine is down for changeovers, and (f) the annual inventory cost.

Solution: For \( T_{sw} = 5.0 \text{ hr}, C_{sw} = 5(\$200) + 5(\$20) = \$1100/\text{setup} \)

\( hC = 0.24(2.50) = \$0.60/pc \)

\[
EOQ = \sqrt{\frac{2(20,000)(1100)}{0.60}} = \sqrt{73.333(10)^6} = 8,563.5 \text{ rounded to } 8564 \text{ pc}
\]

(b) Number of changeovers/yr per part = \frac{20,000}{8564} = 2.335 changeovers/yr

For 25 parts, number of changeovers = 25(2.335) = 58.4 changeovers/yr

At 5 hr/changeover, total time down = 58.4(5.0) = 292 hr

(c) \( TIC = 0.5(8564)(0.60) + 20,000(1,100/8564) = \$5,138 \)

For 25 parts, \( TIC = 25(\$5,138) = \$128,450 \)

(d) For \( T_{sw} = 3.6 \text{ hr}, C_{sw} = 3.5(\$200) + (1.5 + 3.5)(\$20) = \$800/\text{setup} \)

\[
EOQ = \sqrt{\frac{2(20,000)(800)}{0.60}} = \sqrt{53.333(10)^6} = 7303 \text{ pc}
\]

(e) Number of changeovers/yr per part = \frac{20,000}{7303} = 2.739 changeovers/yr

For 25 parts, number of changeovers = 25(2.739) = 68.5 changeovers/yr

At 3.5 hr/changeover, total time down = 68.5(3.5) = 239.6 hr
26.5 In the previous problem, a second proposal has been made to reduce the purging time of 3.5 hours during a changeover to less than 1.5 hours by sequencing the batches of parts so as to reduce the differences in plastic type and color between one part and the next. In the ideal, the same plastic can be used for all parts, thus eliminating the necessity to purge the injection barrel between batches. Thus, the limiting task in changing over the machine is the mold change time, which is 1.5 hours. For the 1.5-hour setup, determine (a) the economic batch quantity, (b) the total number of hours per year that the injection-molding machine is down for changeovers, and (c) the annual inventory cost.

Solution: (a) For \( T_{su} = 1.5 \) hr, \( C_{su} = 1.5(\$200) + 2(1.5)(\$20) = \$360/\text{setup} \)

\[
EOQ = \sqrt{\frac{2(20,000)(360)}{0.60}} = \sqrt{24.0(10)^6} = 4,899 \text{ pc}
\]

(b) Number of changeovers/yr per part = \( \frac{20,000}{4899} = 4.082 \) changeovers/yr

For 25 parts, number of changeovers = \( 25(4.082) = 102.06 \) changeovers/yr

At 5 hr/changeover, total time down = \( 102.06(1.5) = 153.1 \) hr

(c) \( TIC = 0.5(4899)(0.60) + 20,000(360)/4899 = \$2,939.40 \)

For 25 parts, \( TIC = 25(2,939.40) = \$73,485 \)

26.6 The following data apply to sheet metal parts produced at a stamping plant that serves a final assembly plant in the automotive industry. The data are average values representative of the parts made at the plant. Annual demand = 150,000 pc (for each part produced); average cost per piece = $20; holding cost = 25%, changeover (setup) time for the presses = 5 hours; cost of downtime on any given press = $200/hr. (a) Compute the economic batch size and the total annual inventory cost for the data. (b) If the changeover time could be reduced to 15 min., compute the economic batch size and the total annual inventory cost.

Solution: (a) \( EOQ = \sqrt{\frac{2(150,000)(200)(0.25)}{0.25}} = \sqrt{60,000,000} = 7746 \text{ pc} \)

\[
TIC = \frac{5(7746)}{2} + \frac{1000(150,000)}{7746} = 19365 + 19364.83 = \$38,729.83/\text{yr}
\]

(b) If \( T_{su} = 15 \) min = 0.25 hr, \( EOQ = \sqrt{\frac{2(150,000)(200)(0.25)}{0.25}} = \sqrt{3,000,000} = 1732 \text{ pc} \)

\[
TIC = \frac{5(1732)}{2} + \frac{50(150,000)}{1732} = 4330 + 4330 = \$8,660/\text{yr}
\]

26.7 Given the data in the previous problem, it is desired to reduce the batch size from the value determined in that problem to 600 pieces, consistent with the number of units produced daily by the final assembly plant served by the stamping plant. Determine the changeover time that would allow the economic batch size in stamping to be 600 pieces. What is the corresponding total annual inventory cost for this batch size?

Solution: \( EOQ = 600 = \sqrt{\frac{2(150,000)(200T_{su})}{0.25}} = \sqrt{12,000,000T_{su}} \)

\[
(600)^2 = 360,000,000 T_{su}, \quad T_{su} = 360,000/12,000,000 = 0.03 \text{ hr} = 1.8 \text{ min.}
\]

\[
TIC = \frac{5(600)}{2} + \frac{200(0.03)(150,000)}{600} = 1500 + 1500 = \$3000/\text{yr}
\]

26.8 Annual demand for a part is 500 units. The part is currently produced in batches. It takes 2.0 hours to set up the production machine for this part, and the downtime during setup costs $125/hr. Annual holding cost for the part is $5.00. The company would like to produce the part using a new flexible manufacturing system it recently installed. This would allow the company to produce this part as well as others on the same equipment. However, changeover time must be reduced to a minimum. (a) Determine the required changeover (setup) time, in order to produce this part economically in batch sizes of one. (b) If the part were to be produced in
batch sizes of 10 units instead of one, what is the implicit changeover time for this batch quantity? (c) How much are the annual total inventory costs to the company when the batch size = 1 unit?

Solution: (a) \( EOQ = 1 = \sqrt{\frac{2(500)(125T_{su})}{5.00}} = \sqrt{25,000T_{su}} \)

\( (1)^2 = 1 = 25,000 \) \( T_{su} \) \( T_{su} = 1/25,000 = 0.00004 \) hr = 0.0024 min = 0.144 sec

(b) \( EOQ = 10 = \sqrt{\frac{2(500)(125T_{su})}{5.00}} = \sqrt{25,000T_{su}} \)

\( (10)^2 = 25,000 \) \( T_{su} \) \( T_{su} = 100/25,000 = 0.004 \) hr = 0.24 min = 14.4 sec

(c) If \( EOQ = 1, \) \( TIC = \frac{5(1)}{2} + \frac{(125\times0.00004)(500)}{1} = 2.5 + 2.5 = \$5.00/yr \)

Overall Equipment Effectiveness

26.9 A certain production machine has an availability of 97%. Its utilization is 92%. The fraction defect rate of the parts made on the machine is 0.030, and it operates at only 75% of its rated speed. What is the overall equipment effectiveness of this machine?

Solution: \( OEE = 0.97(0.92)(1 – 0.030)(0.75) = 0.649 = 64.9\% \)

Takt Time and Cycle Time

26.10 The weekly demand for a certain part is 950 units. The plant operates 5 days per week, with an effective operating time of 440 min per day. Determine the takt time for this part.

Solution: Daily demand \( Q_{dd} = 950/5 = 190 \) pc/day

Takt time \( T_{takt} = 440/190 = 2.316 \) min/pc

26.11 The monthly usage for a component supplied to an appliance assembly plant is 5,000 parts. There are 21 working days in the month and the effective operating time of the plant is 450 min per day. Currently, the defect rate for the component is 2.2%, and the equipment used to produce the part is down for repairs an average of 22 min per day. Determine the takt time for this part.

Solution: Daily demand \( Q_{dd} = 5000/21 = 238.1 \) pc/day

Takt time \( T_{takt} = 450/238.1 = 1.89 \) min/pc

Defect rate and downtime are ignored to force defect rate and downtime to be zero.

26.12 The monthly demand for a part produced for an automotive final assembly plant is 8,000 units. There are 20 working days in February and the effective operating time of the plant is 900 min per day (two shifts). The fraction defect rate for the component is 0.017, and the automated machine that produces the part has an availability of 96%. Determine the takt time for this part.

Solution: Daily demand \( Q_{dd} = 8,000/20 = 400 \) pc/day

Takt time \( T_{takt} = 900/400 = 2.25 \) min/pc

Defect rate and downtime are ignored to force defect rate and downtime to be zero.