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) \( \theta = \frac{360}{5} = 72^\circ \quad T_o = \frac{180 + 72}{360(48)} = 0.01458333 \text{ min} = 0.875 \text{ sec} \)

(c) \( T_r = \frac{180 - 72}{360(48)} = 0.00625 \text{ min} = 0.375 \text{ sec} \)

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) \( \theta = 360/6 = 60^\circ \quad T_o = \frac{360 + 60}{360N} = \frac{0.667}{N} = 2.5 \text{ sec (given)} \)

\[ N = \frac{0.667}{2.5 \text{ sec}} = 0.2667 \text{ rev/sec} = 16 \text{ rev/min} \]

(b) \( T_r = \frac{180 - 60}{360(0.2667)} = 1.25 \text{ sec} \)

16.3 Solve the previous problem except that the Geneva has eight slots.

Solution: (a) \( \theta = 360/8 = 45^\circ \quad T_o = \frac{360 + 45}{360N} = \frac{0.62}{N} = 2.5 \text{ sec (given)} \)

\[ N = \frac{0.625}{2.5} = 0.25 \text{ rev/sec} = 15 \text{ rev/min} \]
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: \[ C_{pc} = 0.55 + 42(0.8)/60 + 0.27 = 0.55 + 0.56 + 0.27 = 1.38/pc \]

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 150 cycles. This procedure takes a total of 12.0 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) \[ F_1T_{d1} = 0.075(4) = 0.3 \text{ min} \]
\[ F_2T_{d2} = \frac{12.0}{150} = 0.08 \text{ min} \]
\[ T_p = 0.5 + 0.3 + 0.08 = 0.88 \text{ min} \]
\[ R_p = \frac{1}{0.88} = 1.13636 \text{ pc/min} = 68.2 \text{ pc/hr} \]
(b) \[ E = \frac{0.5}{0.88} = 0.5682 = 56.82\% \]
(c) \[ D = \frac{0.38}{0.88} = 0.4318 = 43.18\% \]

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) \[ T_c = T_o + T_r = 2.5 + 1.25 = 3.75 \text{ min} \]
\[ T_p = 3.75/60 + 0.06(3.5) = 0.0625 + 0.21 = 0.2725 \text{ min} \]
\[ R_p = \frac{1}{0.2725} = 3.67 \text{ pc/min} = 220.2 \text{ pc/hr} \]
(b) \[ E = 0.0625/0.2725 = 0.2294 = 22.94\% \]

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 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) \[ T_p = 0.58 + 9.2/20 = 0.58 + 0.46 = 1.04 \text{ min} \]
\[ E = \frac{0.58}{1.04} = 0.5577 = 55.77\% \]
(b) \[ R_p = 60/1.04 = 57.69 \text{ pc/hr} \]
Weekly production = 40(57.69) = **2307.7 pc/wk**.

16.9 A 22-station in-line transfer machine has an ideal cycle time of 0.35 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-S  7-10/06, 06/04/07

Solution: (a) \( R_c = \frac{1}{T_c} = \frac{1}{0.35} = 2.857 \text{ pc/min} = 171.4 \text{ pc/hr} \)

(b) \( F = np = 22(0.01) = 0.22 \)

(c) \( T_p = 0.35 + 0.22(8) = 0.35 + 1.76 = 2.11 \text{ min} \)
\[ R_p = \frac{1}{T_p} = \frac{1}{2.11} = 0.4739 \text{ pc/min} = 28.44 \text{ pc/hr} \]

(d) \( E = \frac{0.35}{2.11} = 0.1659 = 16.59\% \)

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) \( R_p = 1/2.15 = 0.465 \text{ pc/min} = 27.9 \text{ pc/hr} \)

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) \( T_c = 1.32 + 0.18 = 1.50 \text{ min} \)
\( F = 0.02 + 0.01 + 0.04 + 0.01 = 0.08 \)
\( T_p = 1.50 + 0.08(8.0) = 1.50 + 0.64 = 2.14 \text{ min/pc} \)
\( D = \frac{0.64}{2.14} = 0.299 = 29.9\% \)

(b) \( R_p = 1/2.14 = 0.467 \text{ pc/min} = 28.04 \text{ pc/hr} \)

(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 14 cycles. Average downtime per occurrence is 9.5 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: \( T_p = 0.85 + \frac{1}{14}(9.5) = 0.85 + 0.6786 = 1.5286 \text{ min/pc} \)
\( C_{pc} = ($72.00/hr)(1.5286/60) = $1.834/pc. \)

With computer system: \( T_p = 0.85 + \frac{1}{14}(7.5) = 0.85 + 0.5357 = 1.3857 \text{ min/pc} \)
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) \( T_c = 0.42 + 0.08 = 0.50 \) min

\[ T_d = \frac{793 + 78}{158} = 5.513 \text{ min} \]

\[ QT_p = QT_c + QFT_d = 2400 \text{ min} = 0.5Q + 158T_d \]

\[ 0.5Q + 158(5.513) = 2400 \]

\[ 0.5Q = 2400 - 871 = 1529 \]

\[ Q = 1529/0.5 = 3058 \text{ pc} \]

(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: \( p = 26/3058 = 0.0085 \text{ breakdowns/pc} \)

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) \( T_c = 1.10 + 0.15 = 1.25 \) 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) \( E = 1.25/2.125 = 0.588 = 58.8\% \)

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(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 0.50 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>400 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 = 400 + 300 + 150 = 850 min
Number of downtime occurrences = 70 + 45 + 25 = 140 occurrences
(a) Total uptime = 2400 - 850 = 1550 min
Number of parts = (1550 min)/(0.50 min/pc) = 3100 pc
(b) \( E = \frac{1550}{2400} = 0.646 = 64.6\% \)
(c) \( R_p = \frac{3100 \text{ pc}}{2400 \text{ min}}(60) = 77.5 \text{ pc/hr} \)
(d) Transfer system failures: \( p = \frac{25}{3100} = 0.008065 \)

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 \( A = \frac{MTBF - MTTR}{MTBF} = \frac{50 - 9}{50} = 0.82 \)
\( E = A = 0.82 = 82\% \)
\( E = T_c/T_p, \text{ therefore } T_p = T_c/E = 1.0/0.82 = 1.2195 \text{ min/pc} \)
\( R_p = \frac{1}{1.2195} = 0.82 \text{ pc/min} = 49.2 \text{ pc/hr} \)

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 \( n \) = 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) \( T_c = 0.1 + \frac{36}{n} \)
\( FFT_a = pnT_a = 0.005n(8.0) = 0.04n \)
\( T_p = 0.1 + \frac{36}{n} + 0.04n \)
\( \frac{dT_p}{dn} = -\frac{36}{n^2} + 0.04 = 0 \), rearranging, \( \frac{36}{n^2} = 0.04 \)
\( n^2 = 36/0.04 = 900 \), \( n = 30 \text{ stations} \)

(b) \( T_c = 0.1 + \frac{36}{30} + 0.04(30) = 0.1 + 1.2 + 1.2 = 2.5 \text{ min/pc.} \)
\( R_p = \frac{1}{2.5} = 0.4 \text{ pc/min} = 24 \text{ pc/hr} \)
(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 6.0 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) \( T_p = 0.75 + 30(0.01)(6.0) = 0.75 + 1.8 = 2.55 \text{ min/pc} \)
\[
E = \frac{0.75}{2.55} = 0.2941 = 29.41\%
\]
\[
R_p = \frac{1}{2.55} = 0.392 \text{ pc/min} = 23.53 \text{ pc/hr}
\]
(b) \( T_p = 0.75 + 15(0.01)(6.0) = 0.75 + 0.90 = 1.65 \text{ min/pc} \)
\[
E = \frac{0.75}{1.65} = 0.4545 = 45.45\%
\]
\[
R_p = \frac{1}{1.65} = 0.6061 \text{ pc/min} = 36.36 \text{ pc/hr}
\]

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) \( T_p = 0.75 + 10(0.01)(6.0) = 0.75 + 0.60 = 1.35 \text{ min/pc} \)
\[
E = \frac{0.75}{1.35} = 0.5555 = 55.55\%
\]
\[
R_p = \frac{1}{1.35} = 0.7407 \text{ pc/min} = 44.44 \text{ pc/hr}
\]
(b) \( T_p = \ldots = T_p29 = 0.75 + 0.01(6.0) = 0.75 + 0.06 = 0.81 \text{ min/pc} \)
\[
E = \frac{0.75}{0.81} = 0.926 = 92.6\%
\]
\[
R_p = \frac{1}{0.81} = 1.235 \text{ pc/min} = 74.1 \text{ pc/hr}
\]

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 \( (T_d = 6.0 \text{ min}) \) is a constant.

**Solution:** From previous Problem 16.18, \( E_o = 0.2941 \) and \( E = 0.4545 \)
\[
D' = \frac{15(0.01)(6.0)}{2.55} = 0.3529, \quad r = \frac{F_1}{F_2} = 1.0
\]
\[
T_p = \frac{6.0}{0.75} = 8.0. \quad \text{If } b = 20, \text{ then } B = 2 \text{ and } L = 4 \text{ in Eq. (16.27)}
\]
\[
h(20) = \frac{2}{2 + 1} + 4 \left( \frac{0.75}{6.0} \right) \left( \frac{1}{(2 + 1)(2 + 2)} \right) = \frac{2}{3} + \frac{4}{12} = 0.7083
\]
\[
E = 0.2941 + 0.3529(0.7083)(0.4545) = 0.4077 = 40.77\%
\]
(b) \( R_p = \frac{E}{T_c} = \frac{0.4077}{0.75} = 0.5436 \text{ pc/min} = 32.62 \text{ pc/hr}
\]

16.21 Solve Problem 16.20 but assume that the downtime \( (T_d = 6.0 \text{ min}) \) follows the geometric repair distribution.

**Solution:** From previous Problem 16.20, \( E_o = 0.2941 \) and \( E = 0.4545 \)
\[
D' = \frac{15(0.01)(6.0)}{2.55} = 0.3529, \quad r = \frac{F_1}{F_2} = 1.0
\]
\[
h(20) = \frac{20(0.75 / 6.0)}{2 + (20 - 1)(0.75 / 6.0)} = \frac{2.5}{4.375} = 0.5714
\]
\[
E = 0.2941 + 0.3529(0.5714)(0.4545) = 0.3858 = 38.58\%
\]
(b) \( R_p = \frac{E}{T_c} = \frac{0.3858}{0.75} = 0.5143 \text{ pc/min} = 30.86 \text{ pc/hr}
\]

16.22 In the transfer line of Problems 16.20 and 16.22, 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:** \( F_1 = 11(0.01) = 0.11 \), \( T_p1 = 0.75 + 0.11(6.0) = 0.75 + 0.66 = 1.41 \text{ min/pc} \)
\( F_2 = 19(0.01) = 0.19 \), \( T_p2 = 0.75 + 0.19(6.0) = 0.75 + 1.14 = 1.89 \text{ min/pc} \)
\[
E_o = \text{Min}\{E_o, E_1\} = \text{Min}\{(0.75/1.41), (0.75/1.89)\} = \text{Min}\{0.5319, 0.3968\} = 0.3968
\]
\[
R_p = 0.3968/0.75 = 0.5291 \text{ pc/min} = 31.74 \text{ pc/hr}
\]
16.23 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: \( T_p = 0.5 + 20(0.01)(5) = 1.5 \) min

\[
E = \frac{0.5}{1.5} = 0.333 = 33.3\%
\]

\[
R_p = \frac{60}{1.5} = 40 \text{ pc/hr}
\]

\[
C_{pc} = \frac{20(4.80)}{40} = \$2.40/\text{pc}
\]

(b) For the proposed two-stage line: \( T_d/T_c = 10 \), \( b = 20 \); \( B = 2 \), \( L = 0 \)

\[
h(25) = \frac{2}{3} = 0.6667
\]

\[
E_o = \frac{0.5}{1.5} = 0.3333, \quad E_2 = \frac{0.5}{1.0} = 0.5, \quad \text{and} \quad D_1' = \frac{0.01(10)(10)}{15} = 0.3333
\]

\[
E = 0.3333 + 0.3333(0.6667)(0.5) = 0.4444
\]

\[
T_p = \frac{0.5}{0.4444} = 1.125 \text{ min}, \quad R_p = \frac{60}{1.125} = 53.33 \text{ pc/hr}
\]

\[
C_{pc} = \frac{(20)(4.80 + 12.00)}{53.33} = \$2.025/\text{pc}
\]

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 42 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>
Solution: (a) \( T_c = 1.25 + 0.1 = 1.35 \text{ min/cycle} = 1.35 \text{ min/pc.} \)

\[
T_d = \frac{42(60)}{246} = 10.244 \text{ min/occurrence}, \quad F = \frac{246}{1689} = 0.1456
\]

\( T_p = 1.35 + 0.1456(10.244) = 1.35 + 1.492 = 2.842 \text{ min/pc.} \)

\( R_p = 1/2.842 = 0.352 \text{ pc/min} = 21.11 \text{ pc/hr} \)

\( E_o = 1.35/2.842 = 0.475 = 47.5\% \)

(b) Stage 1: \( T_c = 1.25 + 0.1 = 1.35 \text{ min/cycle} = 1.35 \text{ min/pc.} \)

Assume \( T_d = 10.244 \text{ min/occurrence}, \) as above, for both stages.

\[
F_1 = \frac{15 + 18 + 23 + 31 + 9}{1689} = 96/1689 = 0.0568
\]

\[
T_p = 1.35 + 0.0568(10.244) = 1.35 + 0.582 = 1.932 \text{ min/pc.} \)

\( R_p = 1/1.932 = 0.5175 \text{ pc/min} = 31.052 \text{ pc/hr} \)

\( E_1 = 1.35/1.932 = 0.6988 = 69.88\% \)

Stage 2:

\( T_c = 1.10 + 0.1 = 1.20 \text{ min/pc.} \) Assume \( T_d = 10.244 \text{ min/occurrence}, \) as above.

\[
F_2 = \frac{27 + 47 + 30 + 21 + 25}{1689} = 150/1689 = 0.0888
\]

\[
T_p = 1.20 + 0.0888(10.244) = 1.20 + 0.91 = 2.11 \text{ min/pc.} \)

\( R_p = 1/2.11 = 0.474 \text{ pc/min} = 28.44 \text{ pc/hr} \)

\( E_2 = 1.20/2.11 = 0.5687 = 56.87\% \)

Since \( T_c \neq T_c \), use average value in the calculations: \( T_c = \frac{1.35 + 1.20}{2} = 1.275 \text{ min} \)

\[
\frac{T_f}{T_c} = 10.244 = 8.03 \rightarrow B = 2 \text{ and } L = 3.93
\]

\[
h(20) = 0.6396 \left( 1 - 0.6396^2 \right) + 3.93 \left( \frac{1.275}{10.244} \right) \frac{0.6396^2(1-0.6396)^2}{(1-0.6396^3)(1-0.6396^4)}
\]

\( h(20) = 0.5119 + 0.0271 = 0.5390 \)

\( E = 0.4750 + 0.0271(0.5390) = 0.5078 \)

\( R_p = 0.5078/1.275 = 0.4019 \text{ pc/min} = 25.31 \text{ pc/hr} \)

(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: \( T_c = 1.35 \text{ min} \) \( F_1 = (96 + 22)/1689 = 118/1689 = 0.0699 \)

Assume \( T_d = 10.244 \text{ min/occurrence}, \) as above, for both stages.

\[
T_p = 1/2.842 = 0.352 \text{ pc/min} = 21.11 \text{ pc/hr} \)

\( E_o = 1.35/2.842 = 0.475 = 47.5\% \)

Stage 2:

\( T_c = 1.20 \text{ min} \) \( F_2 = (150 - 22)/1689 = 128/1689 = 0.0758 \)

\[
T_p = 1/2.11 = 0.474 \text{ pc/min} = 28.44 \text{ pc/hr} \)

\( E_2 = 1.20/2.11 = 0.5687 = 56.87\% \)

Since \( T_c \neq T_c \), use average value in the calculations: \( T_c = \frac{1.35 + 1.20}{2} = 1.275 \text{ min} \)

\[
\frac{T_f}{T_c} = 10.244 = 8.03 \rightarrow B = 2 \text{ and } L = 3.93
\]

\[
h(20) = 0.6396 \left( 1 - 0.6396^2 \right) + 3.93 \left( \frac{1.275}{10.244} \right) \frac{0.6396^2(1-0.6396)^2}{(1-0.6396^3)(1-0.6396^4)}
\]

\( h(20) = 0.5119 + 0.0271 = 0.5390 \)

\( E = 0.4750 + 0.0271(0.5390) = 0.5078 \)

\( R_p = 0.5078/1.275 = 0.4019 \text{ pc/min} = 25.31 \text{ pc/hr} \)
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: \( C_{pc} = 4.50 + 66(2.842/60) + 1.25 = \$8.88/pc \).

Two stage line in which division into stages is between stations 6 and 7: \( C_{pc} = 4.50 + 72/25.31 + 1.25 = \$8.59/pc \).

Two stage line in which division into stages is between stations 7 and 8. See solution of Problem 16.24(c): \( C_{pc} = 4.50 + 72/27.23 + 1.25 = \$8.39/pc \).

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 (\( b = 0 \)): \( T_p = 1.0 + 16(0.01)(10) = 2.6 \) 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

\( T_p = 1.0 + 8(0.01)(10) = 1.8 \) min/pc

\( E_1 = E_2 = 1/1.8 = 0.5555 \)

\( D'_{1} = (8x0.01x10)/(1+16x0.01x10) = 0.3077 \) h/(b) = \( B/B+1 \), \( b = 10, 20, 30, 40, etc. \)

Buffer cost = 0.1B/min, \( C_L = (2.0 + 0.1B)/min \)

\( E = 0.3846 + 0.3077 \left( \frac{B}{B+1} \right)(0.5555) + 0.1709 \left( \frac{B}{B+1} \right) = \frac{0.5555B + 0.3846}{B+1} \)

\( T_p = T_e/E \).

\( C_{pc} = C_LT_p = C_LT_e/E \)

Using these terms for \( E, T_p \) and \( C_{pc}, C_{pc} = (2.0 + 0.1B) \left( \frac{B+1}{0.5555B + 0.3846} \right) \)

\( b = 0 \) \( C_{pc} = (2.0+.1x0)(0+1)/.3846 = \$5.20/pc \)

\( b = 1 \) \( C_{pc} = (2.0+.1x1)(1+1)/.9401 = \$4.468/pc \)

\( b = 2 \) \( C_{pc} = (2.0+.1x2)(2+1)/1.4956 = \$4.413/pc \)

\( b = 3 \) \( C_{pc} = (2.0+.1x3)(3+1)/2.0511 = \$4.485/pc \)

\( b = 4 \) \( C_{pc} = (2.0+.1x4)(4+1)/2.6066 = \$4.604/pc \)

\( b = 5 \) \( C_{pc} = (2.0+.1x5)(5+1)/3.1621 = \$4.744/pc \)

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 (\( p_i = p \) 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 $14,000. 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 $14,000 investment to pay for itself?

Solution: \( F = np = 20p \)

\( T_p = T_e + 20pT_d \)

\( T_p = T_e/E = 0.8/0.4 = 2.0 \) min/pc.

\( 2.0 = 0.8 + 20p(3) = 0.8 + 60p \)

\( 60p = 2.0 - 0.8 = 1.2 \)

\( p = 1.2/60 = 0.02 \)

\( C_{pc} = C_LT_p = \$4.00 = C_L(2.0), C_L = \$2.00/min \)

Two stage line each with 10 stations: \( E_o = 0.4 \)

\( E_2 = 0.8/(0.8+10x0.02x3) = 0.8/1.4 = 0.5714 \)

\( D'_{1} = 0.6/2.0 = 0.3 \)
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With constant repair time, \( b = 15 \rightarrow B = 4, L = 0 \) and \( h(b) = h(15) = 4/(4+1) = 0.8 \)
\[
E = 0.4 + 0.3(0.8)(0.5714) = .5371
\]
\[
T_p = T/E = 0.8/0.5371 = 1.4895 \text{ min}
\]
\[
C_p = 2.00(1.4895) = 2.979/\text{pc}
\]
Break-even point \( Q \):
\[
4.00Q = 14,000 + 2.979Q
\]
\[
Q = 14,000 - 1.021Q = 14,000
\]

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 \( B = \infty, F = 9(0.01) = 0.09 \)
\[
T_p = 1.0 + 0.09(8.0) = 1.0 + 0.72 = 1.72 \text{ min/pc.}
\]
\[
E_{\infty} = 1.0/1.72 = 0.5814 \quad E_2 = 0.5814
\]
\[
\Delta E = 0.5814 - 0.4098 = 0.1716
\]
\[
80\% \Delta E = 0.80(0.1716) = 0.1373
\]
\[
E = 0.4098 + 0.1373 = 0.5471 = E \text{ at 80\% improvement}
\]
\[
Eb = Eo + D_1 h(b) = 0.1373
\]
\[
D_1 = 0.72/2.44 = 0.2951
\]
\[
h(b) = 0.1373/0.2951 = 0.80
\]
\[
r = \frac{F_1}{F_2} = 1.0, \text{ therefore } h(b) = \frac{B}{B+1} + L \frac{T_c}{T_d} \left( \frac{1}{(B+1)(B+2)} \right)
\]
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 \( L \).
\[
h(b) = 0.80 = \frac{B}{B+1}, \quad 0.80(B+1) = B \quad 0.80B + 0.80 = B \quad 0.80 = 0.20B
\]
\[
B = 4 \rightarrow b = B \frac{T_c}{T_d} = 4(8/1) = 32 \text{ buffer capacity}
\]

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, \( T_{wc} = 18 \text{ min} \)
\[
T_c = 0.1 + \frac{18}{n} \quad T_p = 0.1 + \frac{18}{n} + 0.005n(8.0) = 0.1 + \frac{18}{n} + 0.04n
\]
\[
\frac{dT_p}{dn} = -\frac{18}{n^2} + 0.04 = 0 \quad n^2 = 18/0.04 = 450 \quad n = 21.2, \text{ use } n = 21 \text{ stations}
\]

(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.
\[
E_b = E_o + D_1 h(b)E_2
\]
\[
E_2 = 0.9571/1.7971 = 0.5326 D_1 = \frac{0.005(21)(8)}{0.9571 + 0.005(42)(8)} = 0.3185
\]
16.30 A 20-station transfer line presently operates with a line efficiency $E = 1/3$. 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 $E = 1/3$ to $E = 2/5$.

**Solution:** $E = 1/3$ = 0.3333, $T_p = T_c/E = 1.0/0.3333 = 3.0$ min/pc

$T_p = T_c + npT_d = 1.0 + 20p(8.0) = 1.0 + 160p = 3.0$

$p = 2/160 = 0.0125$

Two stage line: $E_b = E_o + D'_1h(b)E_2$

Given $E_o = 0.3333$, $D'_1 = \frac{10(0.0125)(8)}{1.0 + 20(0.0125)(8)} = 0.3333$

$E_2 = \frac{1.0}{1.0 + 10(0.0125)(8)} = 0.50$

Use Eq. (16.29): $h(b) = \frac{b(1/8)}{2 + (b-1)(1/8)} = \frac{0.125b}{2 + 0.125(b-1)} = \frac{0.125b}{1.875 + 0.125b}$

$E_b = 0.3333 + 0.3333 \left( \frac{0.125b}{1.875 + 0.125b} \right)(0.50)$

Target $E = 2/5 = 0.40 = 0.3333 + 0.1667\left( \frac{0.125b}{1.875 + 0.125b} \right)$

$0.40 - 0.3333 = 0.0667 = 0.1667\left( \frac{0.125b}{1.875 + 0.125b} \right)$

$\frac{0.125b}{1.875 + 0.125b} = \frac{0.0667}{0.1667} = 0.40$

$0.4(1.875 + 0.125b) = 0.125b$

$0.75 + 0.05b = 0.125b$

$b = 10$ pc buffer capacity