

13 Automated Production Lines

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13.1 Introduction

Automated production lines are typically used for high production of parts that require multiple processing operations. The production line itself consists of geographically dispersed workstations within the plant, which are connected by a mechanized work transport system that ferries parts from one workstation to another in a pre-defined production sequence. In cases where machining operations, such as drilling, milling, and similar rotating cutter processes, are performed at particular workstations, the more accurate term to use is transfer line, or transfer machine. Other potential automated production line applications include: robotic spot-welding, sheet-metal press-working, and electroplating of metals.

KEYPOINT

Automated production lines consist of distributed workstations connected by a mechanized work transport system that moves the parts from one workstation to another as they enter the system.

END KEYPOINT

Automated production lines are usually expensive to implement, and—as examples of fixed automation—their layout is relatively hard to change once built into the production plant's infrastructure. The following are the conditions that normally suit the used of automated production lines:

BULLETLIST

High product demand, requiring high production quantities

Stable product design, as automated production lines cannot accommodate frequent design changes

Long product life—typically several years

Multiple operations, involving the use of a number of workstations

ENDLIST

KEYPOINT

The conditions that determine the use of automated production lines include: high product demand; stable product design; long product life; and multiple operations.

END KEYPOINT

Once these conditions are met, the following benefits are usually seen to accrue from using automated production lines:

NUMLIST

Low amount of direct labour

Low product cost

High production rate

Minimal work-in-progress and production lead time

Minimal use of factory floor space

ENDLIST

In this unit a general overview of automated production lines is offered, which examines the fundamentals of automated lines (i.e. system configuration, workpart transfer mechanisms, storage buffers, and control of the production line), as well as the applications of production lines for machining systems and system design considerations. This is followed by an analysis of transfer lines, both with no internal parts storage, and with internal storage buffers.

13.2 Learning Objectives

After completing this unit, and the assigned reading and exercises supplied, you should be able to:

BULLET LIST

Define the concept of automated production lines

Specify the components of automated production

Outline the system configurations used in automated production

Explain the types of transfer mechanism that may be used for workpart transfer

Describe the Geneva mechanism

Outline how storage buffers may be deployed in automated production lines

List the basic control functions that can be distinguished in the operation of an automatic transfer machine

Explain the concept of a transfer line

Outline the approaches that may be used for system design

List the three areas that can be considered for analysis in connection with transfer lines

Specify common metrics used to assess transfer lines with no internal parts storage

Explain how storage buffers affect transfer line downtime

Specify the factors involved in considering the overall line efficiency for a two-stage transfer line

ENDLIST

13.3 Fundamentals of Automated Production Lines

An automated production line has multiple workstations that are automated and linked together by a work handling system that transfers parts from one station to the next, as in Figure 13.1. Starting—un-processed—parts enter the automated production line and undergo a system of automated processing at various workstations along the fixed production line; the parts are passed from workstation to workstation by means of a mechanized work transport system, until the completely processed parts pass out of the automated production line after the last process occurs to the part at the final workstation in the system.

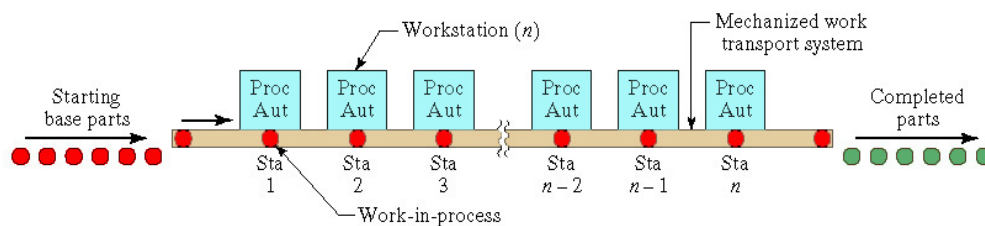


Figure 13.1: General configuration of an automated production line

KEYPOINT

In automated production un-processed parts enter the production line and undergo a system of automated processing at various workstations along the fixed production line, with parts being moved from one workstation to the next by means of a mechanized work transport system, until the last process occurs to

the part at the final workstation in the system, at which point the part exits the automated production line.

END KEYPOINT

The line may also include inspection stations to perform intermediate quality checks on parts in the system, as well as a number of manually-operated workstations that accomplish tasks that have not been automated owing to reasons of economy or difficulty. Each station performs a different operation, so all the operations are required to complete one work unit; this means that the parts' route through the production line is fixed and cannot be changed. Multiple parts are processed simultaneously, with one part undergoing processing at each workstation in the system. This means, in the simplest automated production lines, that the number of parts in the system is found to be equal to the number of workstations that the system has; however, in more complicated configurations, provision may have been made for some form of part storage, so this calculation may not be accurate where buffering is manifest.

KEYPOINT

The automated production may consist of, besides automated workstations, manual workstations and inspection stations.

END KEYPOINT

The automated production line operates in cycles with the slowest workstation processing time setting the pace for the whole line. Each cycle consists of the processing time plus the time taken to transfer parts from one workstation to the next.

Certain layouts of transfer lines may allow the use of pallet fixtures for part handling (see Unit 8), the description of which has seen the emergence of the term palletized transfer lines to describe these. The alternative method of workpart location is simply to index the parts themselves from station to station; this is described as a free transfer line, and is less expensive than the palletized transfer line as pallet fixtures do not have to be custom-designed for the work transport system. However, certain workpart geometries mandate the use of pallets and pallet fixtures, in which case a system of returning them to the front of the line must be devised.

KEYPOINT

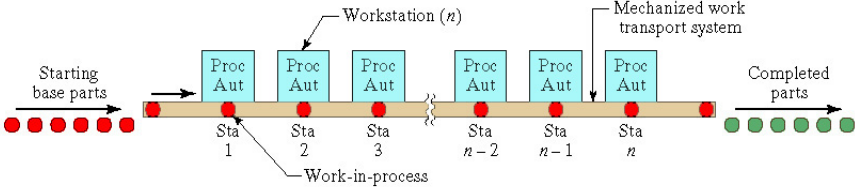
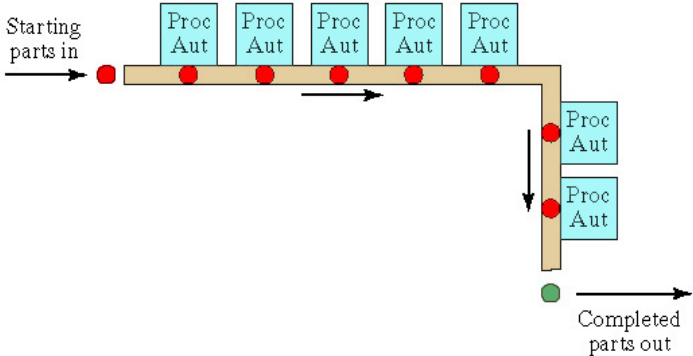
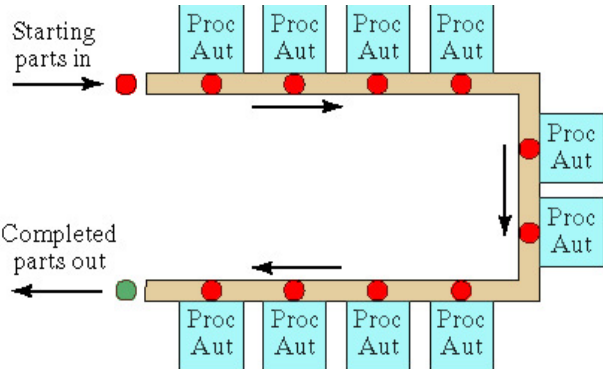
For transfer line layouts either palletized transfer lines (that use pallets and pallet fixtures) or free transfer lines (that use no special fixtures or workpart holders) may be favoured.

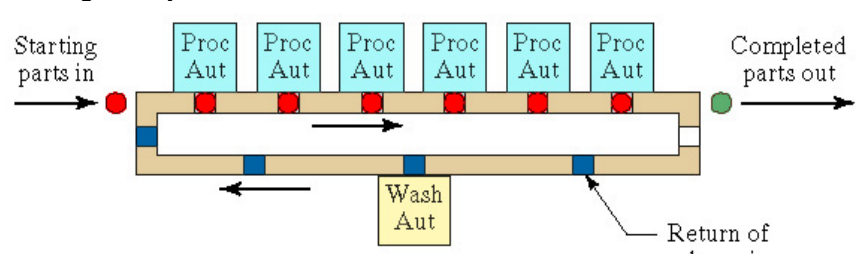
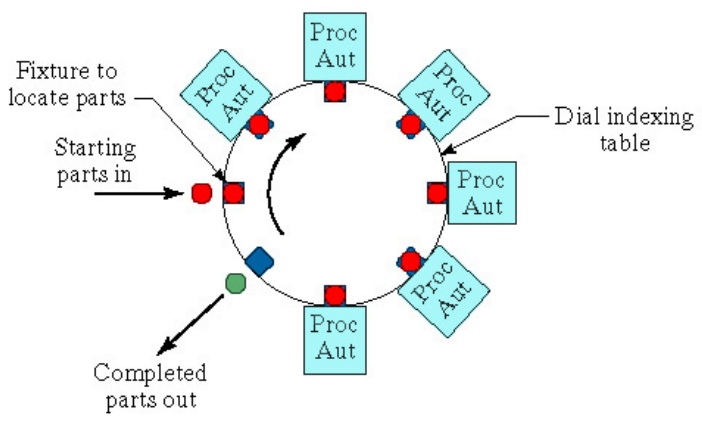
END KEYPOINT

13.3.1 System Configurations

A number of system configurations for the automated production line exist; these are detailed in Table 13.1.

Table 13.1: System configurations for the automated production line

Configuration	Description
<p>In-line</p> 	<p>Consists of a sequence of workstations in a straight-line arrangement. Common for machining big work pieces, such as automotive engine blocks, engine heads, and transmission cases. Can accommodate a large number of workstations, and buffer storage can also be planned for the configuration.</p>
<p>Segmented in-line:</p> <p>L-shaped layout</p>  <p>U-shaped layout</p> 	<p>Consists of two or more straight-line transfer sections, where the segments are usually perpendicular to each other. Layout designs include the L-shaped layout, the U-shaped layout, and the Rectangular layout. Reasons for favouring segmented in-line over in-line configurations include: floor space considerations; re-orientation of workparts to present different surfaces for machining in different line segments; the swift return of work-holding fixtures (in the rectangular arrangement).</p>

<p>Rectangular layout</p> 	
<p>Rotary</p> 	<p>Consists of a circular worktable around which workparts are fixed to workholders. The worktable rotates to move each workpart, in turn, into each automated workstation which is located around the circumference of the worktable. The worktable is often called a dial, and the equipment is referred to as a dial indexing machine, or simply, indexing machine. Commonly limited to smaller workparts and relatively few workstations, and they cannot readily accommodate buffer storage capacity. However they require less floor space, and are generally less expensive than other configurations.</p>

KEYPOINT

A number of system configurations for the automated production line exist; these include: in-line configurations; segmented in-line configurations (for example, L-shaped layouts, U-shaped layouts, and Rectangular layouts); and rotary configurations.

END KEYPOINT

Sometimes a mix of the above configurations may be favoured in particular cases. For example in Figure 13.2; here is illustrated two transfer lines that perform metal machining operations on a rear truck axle. The first line consists of a segmented in-line configuration, in the rectangular layout; the second line is in the conventional in-line configuration. There also exists a number of buffer storage locations within the configuration, particularly from one transfer line to the next.

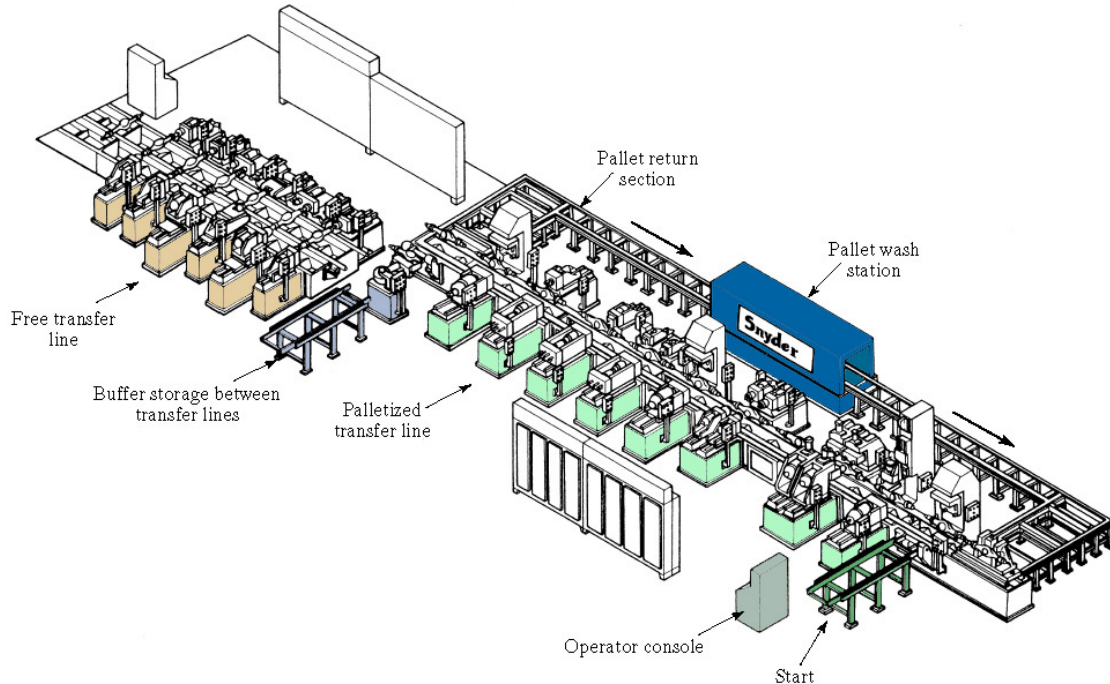


Figure 13.2: Two machining transfer lines

KEYPOINT

A mix of the automated production line configurations may be favoured in certain manufacturing environments.

END KEYPOINT

13.3.2 Workpart Transfer Mechanisms

The function of the workpart transfer system is to move parts between stations on the production line, a function performed by means of transfer mechanisms that are either synchronous or asynchronous. Synchronous transfer is the traditional method of moving parts within a production system, but asynchronous transfer has the following advantages:

BULLETLIST

- Greater flexibility

Fewer pallet fixtures needed

Easy to rearrange or expand the production system

ENDLIST

These advantages must be offset by a higher first cost, and the fact that asynchronous transfer is hard to regulate accurately as moving parts pass between station workheads.

KEYPOINT

Transfer mechanisms in the workpart transfer system may be synchronous or asynchronous.

END KEYPOINT

Here we examine two types of workpart transfer mechanism: linear transport systems for in-line systems (with synchronous and asynchronous transfer); and rotary indexing mechanisms for dial indexing machines (with synchronous transfer only).

13.3.2.1 Linear Transfer Systems

Types of linear transfer systems used for workpart transfer include powered roller conveyors, belt conveyors, chain driven conveyors, and cart-on-track conveyors previously described in unit 8. The typical installation of a conveyor system for workpart transfer is depicted in Figure 13.3. Work carriers attached to the conveyor ensure that workparts are transferred in a synchronous fashion from one workstation to the next, while the 'over-and-under' design of the conveyor belt ensures a continuous supply of empty carriers for reloading. The belt conveyor can also be used for asynchronous transfer of parts by using friction between the belt and the part to move parts between stations. Parts are stopped in their forward motion by means of pop-up pins, or other stopping mechanisms.

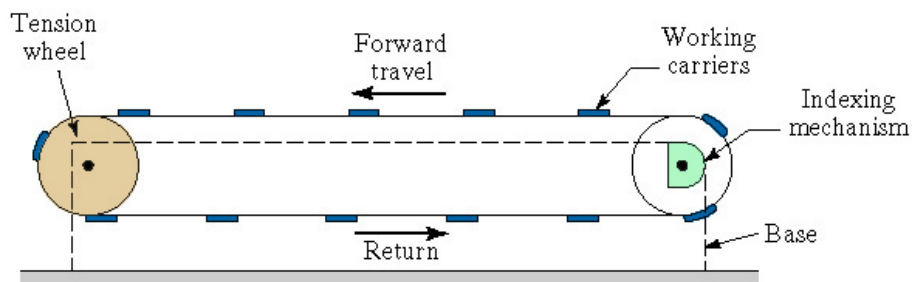


Figure 13.3: Side view of chain or belt conveyor deploying work carriers, used for linear workpart transfer

Cart-on-track conveyors provide asynchronous movement of parts, and are designed to position their carts within about $\pm 0.12\text{mm}$, which is adequate for many processing operations. Other mechanisms for locating carts may also be used, such as pin-in-hole devices and detente devices.

Linear transfer lines also come in the form of walking beam transfer systems, where parts are moved synchronously by means of a transfer beam that lifts parts from their respective stations and transfers them one position ahead. Parts are lowered into specially-designed 'nests' that position them for processing at the next station, then the transfer beam retracts to make ready for the next transfer cycle. This action sequence is illustrated in Figure 13.4.

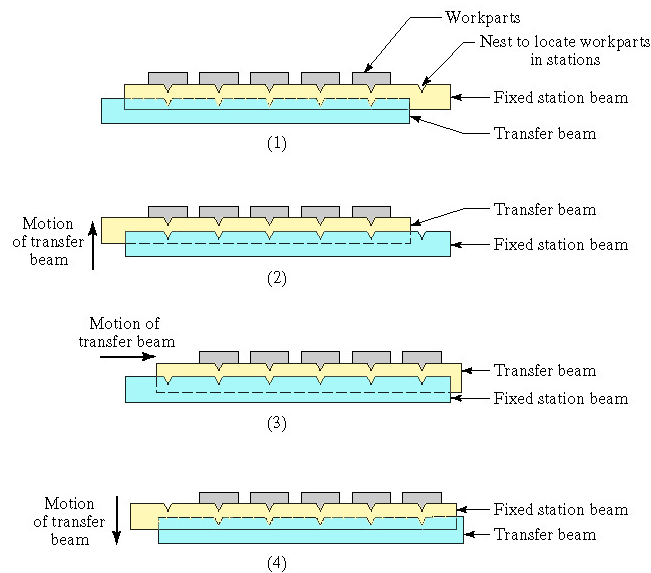


Figure 13.4: Operation of the walking beam system

KEYPOINT

Linear transfer systems used for workpart transfer include powered roller conveyors, belt conveyors, chain driven conveyors, and cart-on-track conveyors, as well as the walking beam transfer system.

END KEYPOINT

13.3.2.2 Rotary Indexing Mechanisms

Several mechanisms can be used to generate the type of rotary power required by rotary indexing machines. Two of these are the Geneva mechanism, and the cam drive.

The Geneva mechanism (see Figure 13.5) uses a continuously rotating driver to index the table through a partial rotation.

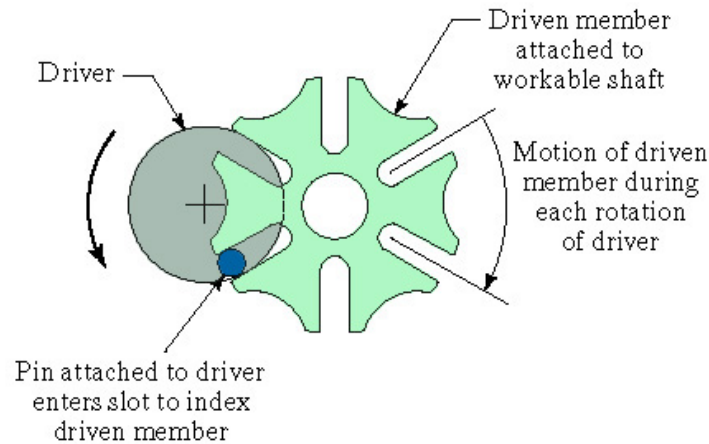


Figure 13.5: Six-slotted Geneva mechanism

If the driven member has six slots for a six station dial indexing table, each turn of the driver results in a 1/6th rotation of the worktable, or 60°. The driver only causes motion of the table through a portion of its own rotation. The operation of the mechanism may be shown by reference to Figure 13.6, which shows the rotation of Geneva mechanism with four slots.

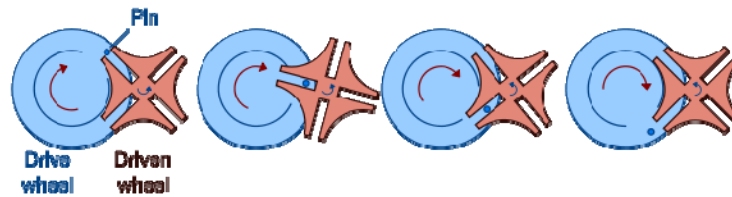


Figure 13.6: The operation of a four-slot Geneva mechanism

For a six-slotted Geneva, which we focus upon here, 120° of driver rotation is used to index the table, with the remaining 240° being dwell time for the table, during which the processing operation must be completed on the work unit. In general:

$$\theta = \frac{360}{n_s}$$

where θ is the angle of rotation of the worktable during indexing (degrees of rotation); and n_s is the number of slots in the Geneva. The angle of driver rotation during indexing is 2θ , and the angle of driver rotation during the dwell time is given by:

$$360 - 2\theta$$

The number of slots of the Geneva mechanism determines the number of workstation positions around the periphery of the rotary index machine. Geneva mechanisms with four, five, six, or eight slots are common. Given the rotational speed of the driver, we can determine total cycle time as:

$$T_c = \frac{1}{N}$$

where T_c is the cycle time; and N is the rotational speed of the driver. Of the total cycle time, the dwell time, or available service time per cycle, this is determined by:

$$T_s = \frac{180 + \theta}{360N}$$

where T_s is the available service or processing time or dwell time. The indexing time is determined by:

$$T_r = \frac{180 - \theta}{360N}$$

where T_r is the indexing (or repositioning) time.

LEARNING ACTIVITY 13.1

Learn more about the Geneva mechanism at web-sites:

http://en.wikipedia.org/wiki/Geneva_drive

<http://emweb.unl.edu/Mechanics-Pages/em373honors-S2001/em373/geneva/geneva.htm>

<http://www.me.berkeley.edu/~adarsh/Geneva.pdf>

http://digital.library.cornell.edu/k/kmoddl/pdf/002_010.pdf

Write a short report on your findings and post to the discussion board.

END LEARNING ACTIVITY 13.1

EXAMPLE 13.1

A rotary indexing table is driven by a five-slotted Geneva mechanism. The driver rotation is 50 revolutions per minute. Determine:

NUMLIST

1. The total cycle time of the indexing table
 2. The available processing time for the indexing table
 3. The time lost each cycle to index the table (repositioning time)
- ENDLIST

Express all answers in seconds.

SOLUTION:

1. The total cycle time is determined by:

$$T_c = \frac{1}{N}$$

N is 50 revs/min.

$$\Rightarrow T_c = 1/50 = 0.02 \text{ minutes} = 1.2 \text{ seconds (total cycle time)}$$

2. First determine the angle of rotation of worktable for five-slot Geneva mechanism using formula:

$$\theta = \frac{360}{n_s}$$

$$\Rightarrow \theta = 360/5 = 72^\circ$$

Now use this to determine available processing time by formula:

$$T_s = \frac{180 + \theta}{360N}$$

$$\Rightarrow T_s = 180 + 72 / 360(50) = 252 / 18000 = 0.014 \text{ minutes} = 0.84 \text{ seconds (available processing time)}$$

3. To determine repositioning time, use formula:

$$T_r = \frac{180 - \theta}{360N}$$

$$\Rightarrow T_r = 180 - 72 / 360(50) = 108 / 18000 = 6 \times 10^{-3} \text{ minutes} = 0.36 \text{ seconds (repositioning time)}$$

END EXAMPLE 13.1

KEYPOINT

Geneva mechanisms may be used to drive rotary indexing machine. It uses a continuously rotating driver to index the table through a partial rotation.

END KEYPOINT

Cam drive mechanisms may also be favoured as an alternative to the Geneva mechanism (see Figure 13.7). They provide an accurate and reliable method of indexing a rotary dial table. Additionally it can be designed to provide a variety of velocity and dwell characteristics that are more complex than those that can be created by means of the Geneva mechanism. Its major disadvantage is its expense: cam drives have to be custom-designed for each operation that they are required for.

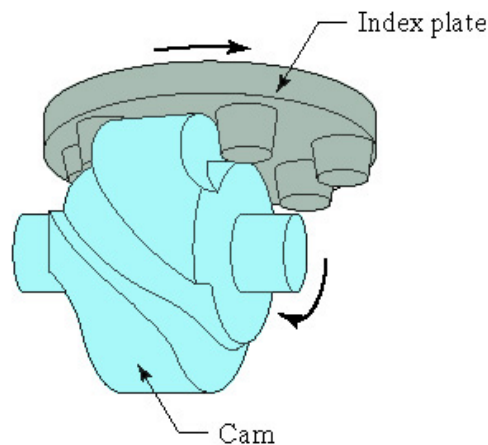


Figure 13.7: Cam mechanism to drive dial indexing table

KEYPOINT

Cam drive mechanisms provide an accurate and reliable method of indexing a rotary dial table, and provide additional advantages over Geneva mechanisms, but are relatively expensive to produce.

END KEYPOINT

13.3.3 Storage Buffers

Automated production lines may also contain storage buffers, which act as temporary storage for parts that are traversing the line, before being released from the buffer so that they may proceed to downstream workstations. Storage buffers are either manually operated or automated. In automated versions, a mechanism is used to accept parts from upstream workstations, a place is designated as storage for the incoming parts, and a mechanism subsequently releases the parts, as required, to supply downstream workstations. Storage capacity—the number of parts a particular storage buffer may hold—is an important metric for determining storage effectiveness; as well as the location and arrangement of storage buffers—which may be located between every pair of adjacent workstations, or between lines stages containing multiple workstations. The latter arrangement is illustrated in Figure 13.8.

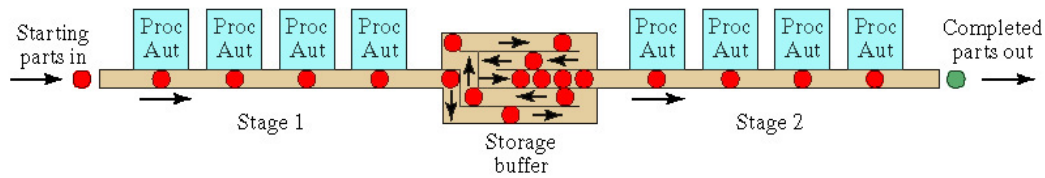


Figure 13.8: Storage buffer between two stages of a production line

KEYPOINT

Storage buffers may be deployed on automated production lines in manual or automated arrangements. Automated versions consist of mechanisms for capturing and releasing parts to the production line, and a structure storage buffer for holding the parts.

END KEYPOINT

The following are advantage associated with storage buffers in automated production lines:

BULLETLIST

They reduce the impact of station breakdowns—storage buffers can supply lines that are continuing to operate, whilst other lines are down for repair.

They provide a bank of parts to supply the line—parts may be collected into a storage unit and automatically fed to a downstream manufacturing system, thus permitting untended operation of the system between refills.

They provide a place to put the output of the line.

They allow for curing time or other process delay—curing may be required for some operations (e.g. paint to dry, or adhesives to bond); the storage buffer can provide sufficient time for this to occur before supplying parts to the downstream station.

They smooth cycle time variations—cycle time variations may occur on the line, so that by means of storage buffers downtimes or time delays may be avoided or offset to the benefit of the overall cycle time.

ENDLIST

Storage buffers are usually deployed more readily with in-line transfer machines than rotary index systems. In cases where storage buffers are used for rotary index machines, buffers are located:

NUMLIST

Before the system to provide a bank of raw starting workparts;

Following the system, to accept the output of the system; or

Between pairs of adjacent dial indexing machines.
ENDLIST

13.3.4 Control of the Production Line

In this section we examine: the basic control functions that are accomplished to run the line; and controllers used on automated lines.

13.3.4.1 Control Functions

Three basic control functions can be distinguished in the operation of an automatic transfer machine; these are described in Table 13.2.

Table 13.2: Control functions for the production line

Control function	Description
Sequence control	This co-ordinates the set of actions of the transfer system and associated workstations, so that the various activities of the production line are carried out with split-second timing and accuracy. In automated production lines sequence control includes both logic control and sequencing (see Unit 7).
Safety monitoring	This ensures that the production line does not operate in an unsafe manner, prioritizing human safety first, and equipment safety second. Safety monitoring is accomplished by sensors integrated with the production line, which complete a safety feedback loop and avoid hazardous operation. Safety devices used include interlocks on equipment that activate during maintenance, and tool monitoring systems to avoid excessive tool wear during production.
Quality control	Here certain quality attributes of the workparts are monitored, so that defective work units may be detected and rejected by the production line. Inspection devices for quality control are sometimes integrated into individual workstations; at other times, separate inspection stations are included in the line for the sole purpose of checking the desired quality characteristic (see Unit 11).

KEYPOINT

The basic control functions that can be distinguished in the operation of an automatic transfer machine include: sequence control; safety monitoring; and quality control.

END KEYPOINT

13.3.4.2 Line Controllers

Programmable logic controllers are used for automated production line control. Other control systems may be developed using PCs supplied with control software, and designed for the factory environment. Computer control has the following advantages:

BULLETLIST

Computer control can be upgraded, to keep in step with developments of the automated production line.

Computer control can record operational data for subsequent analysis, or for legal reasons. Data retained includes process performance metrics, equipment reliability metrics, and product quality statistics.

Computer control can create diagnostic routines to expedite maintenance and repair when line breakdowns occur.

Computer control can generate preventative maintenance schedules.

Computer control offers a more convenient human-machine interface between the operator and the automated line.

ENDLIST

KEYPOINT

Programmable logic controllers are used for line control in automated production lines.

END KEYPOINT

13.4 Applications of Automated Production Lines

Automated production lines are found in both processing and assembly environments, but here we focus upon processing applications, in particular operations of machining. Other processes that can be performed include sheet-metal forming and cutting, rolling mill operations, spot welding, painting, and plating operations.

13.4.1 Machining Systems

Machining operations commonly performed on transfer lines include milling, drilling, reaming, tapping, grinding, and similar rotational cutting tool operations. Less common applications include turning and boring operations.

In a transfer line, the workstations containing machining workheads are arranged in an in-line or segmented in-line configuration and the parts are moved between stations by various types of transfer mechanisms. It is the most highly automated and productive system in terms of the number of operations that can be performed to accommodate complex work geometries and the rates of production that can be achieved. It is also very expensive. As the number of

workstations in the transfer line increases, the reliability of the system decreases. Variations in transfer line design include:

BULLETLIST

Workpart transport can be synchronous or asynchronous

Workparts can be transported with or without pallet fixtures, depending on part geometry and ease of handling

A variety of monitoring and control features can be included to manage the line
ENDLIST

Transfer lines have also been designed for ease of changeover to allow different but similar workparts to be produced on the same line.

KEYPOINT

A transfer line consists of a number of workstations containing machining workheads, arranged in an in-line or segmented in-line configuration, with the parts being moved between stations by various types of transfer mechanisms.

END KEYPOINT

A rotary transfer machine consists of a horizontal circular worktable, upon which are fixed the workparts to be processed, and around whose periphery are located stationary workheads. The worktable is indexed to present each workpart to each workhead to accomplish the sequence of machining operations, as shown in Figure 13.9. The rotary transfer machine is limited by the part sizes it can handle, and by the pre-specified number of workstations that can be contained around the table periphery.

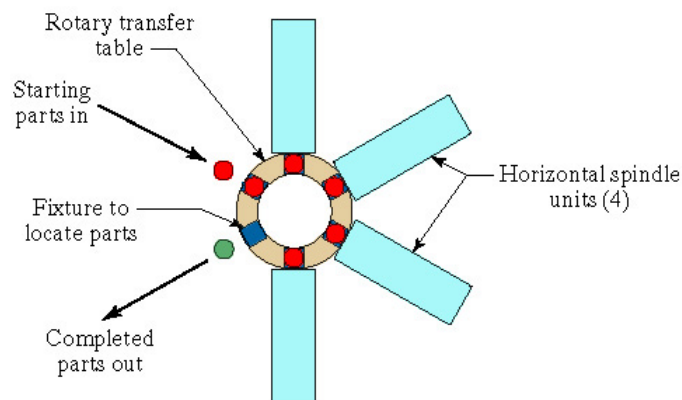


Figure 13.9: Plan view of a rotary transfer system

KEYPOINT

A rotary transfer machine consists of a horizontal circular worktable, upon which are fixed the workparts to be processed, and around whose periphery are located stationary workheads.

END KEYPOINT

Two variants of the regular rotary transfer system may be specified; these are:

BULLETLIST

Centre column machine—this consists of a number of vertical machining heads mounted on a central column in addition to the regular stationary heads located around the periphery of the table. This increases the number of machining operations that may be performed (see Figure 13.10).

Trunnion machine—consisting of a vertically-oriented worktable, or trunnion, to which are attached workholders to fix the parts for machining. The trunnion allows for machining on opposite sides of the workpart, as it indexes around a horizontal axis. Additional workheads may be located around the periphery of the trunnion to increase the number of machining directions.

ENDLIST

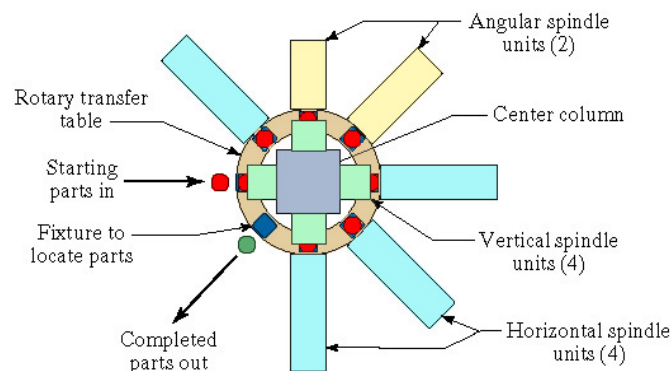


Figure 13.10: Plan view of centre column machine

KEYPOINT

Variants of the rotary transfer machine include the centre column machine, and the trunnion machine.

END KEYPOINT

13.4.2 System Design Considerations

Typically the system has to be custom-built to pre-defined specifications. The manufacturing company usually turns the job over to a specialist machine tool builder, and provides specifications (drawings, layouts, configurational data etc.) so that the machine tool builder may accurately create the system design. Often several machine tool builders are invited to submit proposals, with each resultant proposal being based upon the machinery components that comprise the machine builder's product line, plus an analysis of the system requirements from the customer's point of view. The proposed line may consist of standard workheads, spindles, feed units, drive motors, transfer mechanisms, bases, and

other standard modules, all assembled into a special configuration to match the machining requirements of the particular part.

Another method of system design is to use standard machine tools and to connect them with standard or special material handling devices. The transfer system is represented by the hardware already in place for material handling, which moves work between the standard machines. This is often called a link line, which uses—as much as possible—existing plant equipment and machinery, thus minimizing the amount of additional equipment that has to be purchased. Clearly the link line approach is more cost-effective, and thus more attractive to companies; however, link lines tend to favour simpler part shapes and therefore fewer operations and workstations. System configuration is also limited by the equipment that the company already has in place.

KEYPOINT

There are two approaches to system design: outsourcing the task to a specialist machine tool builder, who creates a system design from customer specifications, and their own product line; or, creating the system internally by producing a link line, consisting of standard machine tools and standard material handling equipment.

END KEYPOINT

13.5 Analysis of Transfer Lines

Three areas are considered for analysis:

BULLETLIST

Line balancing—where the total processing work accomplished on the automated line must be divided as evenly as possible among the workstations. Work tasks are easier to divided into balanced segments in manual assembly lines, where operator flexibility may be relied on; however, technological considerations complicates the issue for the automated production line.

Process technology—this refers to the body of knowledge about the theory and principles of the particular manufacturing processes used on the production line. Many of the problems encountered in machining can be solved by direct application of good machining principles.

System reliability—that is, determining the overall reliability of the system put in place. In a highly complex and integrated system, the failure of any one component can stop the entire system. We examine scenarios of transfer lines with no internal parts storage, and scenarios of transfer lines with internal storage buffers.

ENDLIST

We shall first focus upon the issue of system reliability.

KEYPOINT

Three areas that can be considered for analysis in connection with transfer lines are line balancing, process technology consideration, and system reliability determination.

END KEYPOINT

13.5.1 Transfer Lines with No Internal Parts Storage

The mathematical models developed below can also be used to investigate rotary indexing machines. The following assumptions underpin the following equations in this sub-section:

BULLETLIST

Workstations perform machining operations, not assembly operations

Processing times at each station are constant, though not necessarily equal

Workpart transport is synchronous

There are no internal storage buffers

ENDLIST

Given these assumptions, we can turn first to an analysis of cycle time. In the operation of an automated production line, parts are introduced into the first workstation to be processed, before being transfer to the next workstation, there to be processed again, and so on, to the end of the line. The ideal cycle time of the production line is thus given by the processing time at the slowest station, plus the transfer time; that is:

$$T_c = \text{Max}\{T_{si}\} + T_r$$

where T_c is ideal cycle time on the line; T_{si} is the processing time at station i ; and T_r is repositioning time, also known as the transfer time. The slowest station establishes the pace of the production line, with faster stations experiencing some idle time. Stoppages of the line can occur owing to random breakdowns of equipment, workpart issues, and the initiation of planned work-stoppages for the line. Whatever the reason, downtime occurrences over different periods of time must be considered in our analysis, as they appear; and so we find that, because of downtime occurrences, the actual average production cycle time is longer than the ideal cycle time calculated above. The actual average production time is given by:

$$T_p = T_c + FT_d$$

where T_p is the actual average production time; F is the downtime frequency; and T_d is average downtime per line stop, including the time required for the repair crew to initiate actions, determine the problem, fix it, and restart the line.

Therefore, FT_d is the downtime averaged on a per cycle basis. Of course the stoppage of a single station in the transfer line with no buffer storage, means the whole line experiences downtime; since all workstations are inter-dependent, the downtime experienced by one station causes all the other stations in the line to experience idle time until the problem station is fixed and restarted. If we let p_i be the probability, or frequency, of a failure at station i , where $i = 1, 2, 3, \dots, n$, and where n is the number of workstations on the production line; then the frequency of line stops per cycle is:

$$F = \sum_{i=1}^n p_i$$

where F is the expected frequency of line stops per cycle (the same F as in the above equation). If all p_i are assumed to be equal (that is, $p_1 = p_2 = \dots = p_n = p$), which would be unusual but is useful for our approximations here, then:

$$F = np$$

Other performance metrics that can be measured include the actual average production rate (R_p), which is the reciprocal of T_p :

$$R_p = \frac{1}{T_p}$$

Accordingly, the ideal production rate (R_c) is given by the reciprocal of the ideal cycle time:

$$R_c = \frac{1}{T_c}$$

In terms of automated production systems, line efficiency refers to the proportion of uptime on the line and is really a measure of reliability. Line efficiency is calculated as:

$$E = \frac{T_c}{T_p} = \frac{T_c}{T_c + FT_d}$$

where E is the proportion of uptime on the production line. The proportion of downtime can similarly be measured as:

$$D = \frac{FT_d}{T_p} = \frac{FT_d}{T_c + FT_d}$$

where D is the proportion of downtime on the line. Of course:

$$E + D = 1.0$$

Cost of unit produced is an economic measure that is often applied. This cost includes starting material cost, cost of time on production line, and tooling cost. It is expressed as:

$$C_{pc} = C_m + C_o T_p + C_t$$

where C_{pc} is cost per piece; C_m is cost of starting material; C_o is cost per minute to operate the line; T_p is the average production time per piece; and C_t is the cost of tooling per piece. This equation does not include costs of scrap, inspection, or rework.

KEYPOINT

Common metrics used for transfer lines with no internal parts storage include: ideal cycle time; actual average production time; frequency of line stops; actual average production rate; actual ideal production rate; line efficiency; and piece cost.

END KEYPOINT

To summarize these parameters, we can say that:

BULLETLIST

As the number of workstations in a transfer line are increased, the line efficiency and production rate are adversely affected.

As the reliability of individual workstations decreases, line efficiency and production rate are adversely affected.

ENDLIST

Generally p_i has been found the hardest parameter to determine. Usually previous experience and the use of historical data from similar workstations is required to make a first approximation, which can subsequently be refined as the transfer line moves into operation, and begins to generate its own statistical information.

KEYPOINT

Generally, as the number of workstations in a transfer line are increased, the line efficiency and production rate are found to be adversely affected; while, similarly, as reliability of individual workstations decreases, line efficiency and production rate are found to be adversely affected.

END KEYPOINT**EXAMPLE 13.2**

A transfer machine with 12 stations has an ideal cycle time of 39 seconds. The frequency of line stops is 0.085 stops per cycle. When a line stop occurs, the average downtime is 5.5 minutes. Determine (a) average production rate in parts per hour, (b) line efficiency, and (c) proportion downtime.

Solution:

(a) First determine average production time:

$$T_p = T_c + FT_d$$

Convert seconds to minutes.

$$\Rightarrow \text{Cycle time: } 39 \text{ seconds} = 0.65 \text{ minutes}$$

$$T_p = 0.65 + 0.085(5.5) = 1.1175 \text{ minutes}$$

Now determine the average production rate:

$$R_p = \frac{1}{T_p}$$

$$R_p = 1 / 1.1175 = 0.895 \text{ parts per minute} = 53.7 \text{ parts per hour.}$$

(b) Line efficiency:

$$E = \frac{T_c}{T_p}$$

$$E = 0.65 / 1.1175 = 0.582 = 58.2\%$$

(c) Proportion Downtime:

$$D = \frac{FT_d}{T_p}$$

$$D = 0.085(5.5) / 1.1175 = 0.418 = 41.8\%$$

END EXAMPLE 13.2

13.5.2 Transfer Lines with Internal Storage Buffers

Downtime can be caused by starving or blocking. Starving refers to when an automated production line is prevented from performing its cycle because of the absence of a part to work on; this usually occurs when the machine upstream is blocked and so doesn't deliver a part in a timely manner. Blocking refers to the scenario encountered when a machine is prevented from performing its work cycle because it cannot pass the part just completed to the next workstation.

Downtime, as described above, can be reduced by adding one or more parts storage buffers between workstations. Storage buffers divide the line into stages that can operate independently for a number of cycles—the number depending on the storage capacity of the buffer. If one storage buffer is used, the line is divided into two stages; if two storage buffers are used at different workstations, the line is segmented into three stages, and so forth. The upper limit on the number is to place storage between every pair of adjacent stations. The number of line stages will then equal the number of workstations. For an n -stage line, there will be $n - 1$ storage buffers, not including the raw parts inventory at the front of the line or finished parts inventory at the end of the line. For any number of stages in an automated production line, the storage buffers allow each stage to operate somewhat independently, with the degree of independence being determined by the capacity of the upstream and downstream buffers.

KEYPOINT

Storage buffers reduce transfer line downtime, by reducing the effects of starving and blocking. Storage buffers allow each stage of the transfer line to operate with some degree of independence.

END KEYPOINT

There are two extreme cases of storage buffer effectiveness; this is where there is no buffer storage capacity at all, and where there are infinite capacity storage buffers (which, of course, cannot be achieved in practice, but can be used as a theoretical basis here). We shall now consider these two states. In the analysis that follows the assumption that the ideal cycle time (T_c) is the same for all stages is made.

If there is no storage capacity at all, then there is only one stage to the automated production line. When a station breaks down, the entire line stops. We have already analysed this scenario in the previous section dealing with transfer lines with no internal parts storage. It can be re-written here as the line efficiency of a zero capacity storage buffer (E_0):

$$E_0 = \frac{T_c}{T_c + FT_d}$$

The other theoretical case is that of an automated production line with infinite capacity storage buffers. If we assume that each storage buffer is half full (which means it can accept an infinite number of parts into its buffer system, and can output an infinite number as supply to the next workstation), then each stage is totally independent of the rest of the line, and starving and blockage cannot occur.

All transfer lines with storage buffers are affected by the bottleneck stage, the slowest stage of the line that limits overall line efficiency. The downstream stages can only process parts at the output rate of the bottleneck stage, and upstream stages with higher production rates, will only accumulate inventory in the buffer ahead of the bottleneck stage. Practically, therefore, the bottleneck stage determines the upper limit on the efficiency of the entire line. If the ideal cycle time is the same for all stages, then the efficiency of a stage k is given by:

$$E_k = \frac{T_c}{T_c + F_k T_{dk}}$$

where the subscript k is used to identify the stage. The overall line efficiency is given by:

$$E_\infty = \text{Min.}\{E_k\}$$

for $k = 1, 2, 3, \dots, K$; where the subscript ∞ identifies E_∞ as the efficiency of a line whose storage buffers all have infinite capacity.

We have examined the theoretical upper and lower limits of storage buffers when applied to automated production lines; of course, upon the application of storage buffers in an automated production line, we are carried beyond a production line with no storage buffers, but not beyond one with buffers of infinite capacities. Hence the actual value of line efficiency for a given buffer capacity b falls somewhere in the middle:

$$E_0 < E_b < E_\infty$$

KEYPOINT

The actual value of line efficiency for a given buffer capacity falls somewhere between the two extremes of having no storage buffers at all, and having buffers of infinite capacities.

END KEYPOINT

Let us now consider realistic levels of buffer storage capacity. In this case we evaluate the problem of evaluating E_b for a two-stage automated production line ($K = 2$). The two-stage line is divided by a storage buffer of capacity b , expressed

in terms of the number of workparts it can store. The buffer receives the output of stage 1 and forwards it to stage 2, temporarily storing any parts not immediately needed by stage 2 up to its capacity b . Ideal cycle time is the same for both stages, and we assume the downtime distributions of each stage are the same, with mean downtime equal to T_d . Let F_1 and F_2 equal the breakdown rates of stages 1 and 2, respectively. The breakdown rates are not necessarily equal.

In the long term both stages have equal efficiencies, since if stage 1 efficiency > stage 2 efficiency, this would simply lead to a build-up of its storage buffer to its capacity, and thereafter it would be blocked until relieved by stage 2; similarly, if stage 2 efficiency > stage 1 efficiency, stage 2 would eventually be starved as its buffer becomes depleted. The overall line efficiency for the two-stage line can be expressed as:

$$E_b = E_0 + D_1' h(b) E_2$$

where E_b is overall line efficiency for a two-stage line with buffer capacity b ; E_0 is the line efficiency for the same line with no internal storage; and $(D_1' h(b) E_2)$ represents the improvement in efficiency that results from having a storage buffer with $b > 0$. The term D_1' can be thought of as the proportion of total time that stage 1 is down, defined as follows:

$$D_1' = \frac{F_1 T_d}{T_c + (F_1 + F_2) T_d}$$

The term $h(b)$ is the proportion of the downtime D_1' (when stage 1 is down) that stage 2 could be up and running within the limits of storage buffer capacity b . There are different downtime distributions based on the assumption that the two stages are never down at the same time; this gives different values for $h(b)$. E_2 corrects for the unrealistic assumption in the calculation of $h(b)$ that both stages are never down at the same time. It is more realistic to assume that there are periods when both stages will suffer breakdowns during the same period of time. This gives the following:

$$E_2 = \frac{T_c}{T_c + F_2 T_d}$$

KEYPOINT

The overall line efficiency for a two-stage line is dependent on the proportion of time an individual stage is down, plus a consideration of how long the other stage is running, with a correcting factor for the assumption that the two stages never breakdown at the same time.

END KEYPOINT

Using the analysis above, it may be reasonable to infer that further efficiencies can be obtained if more storage buffers are supplied, to create a transfer line with more than two stages. Here we do not consider further possibilities; however, we can offer general prescriptions regarding efficiency improvements for the case of infinite buffer capacity. These prescriptions are as follows:

BULLETLIST

If E_o and E_∞ are nearly equal in value, little advantage is gained by the addition of storage buffers to the line. If E_∞ is significantly greater than E_o , then storage buffers offer the possibility of significantly improving line performance.

In multi-stage automated production lines, workstations should be divided into stages so as to make the efficiencies of all stages as equal as possible. This allows for the achievement of maximum differences between them, and no single stage will stand out as a significant bottleneck.

If any buffers are nearly always empty or nearly always full, this indicates that the production rates of the stages on either side are out of balance and that the storage buffer is not serving a useful purpose.

The maximum possible line efficiency is achieved by setting the number of stages equal to the number of stations, and by using large capacity buffers.

The “law of diminishing returns” operates in multi-stage automated lines. It is seen when (1) the number of storage buffers is increased, and line efficiency improves at an ever decreasing rate; and (2) when the storage buffer capacity is increased, and line efficiency improves at an ever decreasing rate.

ENDLIST

EXAMPLE 13.3

A transfer line with 34 stations has an ideal cycle time of 0.65 minutes, an average downtime of 8.6 minutes per line stop occurrence, and a station failure frequency of 0.02 for all stations. After analysis, the system designer proposes to locate a storage buffer between stations 27 and 28 to improve line efficiency. Determine, first, the **current** line efficiency and production rate; and, second, the maximum possible line efficiency and production rate that would result from installing the **proposed** storage buffer.

Solution:

Current status

Determine average production time:

$$T_p = T_c + FT_d$$

$$T_p = 0.65 + 0.02(34)8.6 = 0.65 + 5.85 = 6.498 \text{ minutes per piece}$$

Line Efficiency:

$$E = \frac{T_c}{T_p}$$

$$E = 0.65 / 6.498 = 0.1000 = 10\%$$

Average Production Rate:

$$R_p = \frac{1}{T_p}$$

$$R_p = 1 / 6.498 = 0.1539 \text{ parts per minute} = 9.23 \text{ parts per hour}$$

Proposed status (with added storage buffer)

Average production time (up to station 27):

$$T_p = T_c + FT_d$$

where $T_{p1} = T_{p2} = \dots = T_{pn}$

$$T_p = 0.65 + 0.02(27)8.6 = 0.65 + 4.644 = 5.294 \text{ minutes per piece}$$

Maximum possible Line Efficiency:

$$E_{\infty} = \text{Min.}\{E_k\}$$

$$E_{\infty} = 0.65 / 5.294 = 0.123 = 12.3\%$$

Maximum Production Rate:

$$R_p = \frac{1}{T_p}$$

$$R_p = 1 / 5.294 = 0.1889 = 11.33 \text{ parts per hour.}$$

END EXAMPLE 13.3

13.6 Unit Review

BULLETLIST

Automated production lines consist of distributed workstations connected by a mechanized work transport system that moves the parts from one workstation to another as they enter the system.

The conditions that determine the use of automated production lines include: high product demand; stable product design; long product life; and multiple operations.

In automated production un-processed parts enter the production line and undergo a system of automated processing at various workstations along the fixed production line, with parts being moved from one workstation to the next by means of a mechanized work transport system, until the last process occurs to the part at the final workstation in the system, at which point the part exits the automated production line.

The automated production may consist of, besides automated workstations, manual workstations and inspection stations.

For transfer line layouts either palletized transfer lines (that use pallets and pallet fixtures) or free transfer lines (that use no special fixtures or workpart holders) may be favoured.

A number of system configurations for the automated production line exist; these include: in-line configurations; segmented in-line configurations (for example, L-shaped layouts, U-shaped layouts, and Rectangular layouts); and rotary configurations.

A mix of the automated production line configurations may be favoured in certain manufacturing environments.

Transfer mechanisms in the workpart transfer system may be synchronous or asynchronous.

Linear transfer systems used for workpart transfer include powered roller conveyors, belt conveyors, chain driven conveyors, and cart-on-track conveyors, as well as the walking beam transfer system.

Geneva mechanisms may be used to drive rotary indexing machine. It uses a continuously rotating driver to index the table through a partial rotation.

Cam drive mechanisms provide an accurate and reliable method of indexing a rotary dial table, and provide additional advantages over Geneva mechanisms, but are relatively expensive to produce.

Storage buffers may be deployed on automated production lines in manual or automated arrangements. Automated versions consist of mechanisms for capturing and releasing parts to the production line, and a structure storage buffer for holding the parts.

The basic control functions that can be distinguished in the operation of an automatic transfer machine include: sequence control; safety monitoring; and quality control.

Programmable logic controllers are used for line control in automated production lines.

A transfer line consists of a number of workstations containing machining workheads, arranged in an in-line or segmented in-line configuration, with the parts being moved between stations by various types of transfer mechanisms.

A rotary transfer machine consists of a horizontal circular worktable, upon which are fixed the workparts to be processed, and around whose periphery are located stationary workheads.

Variants of the rotary transfer machine include the centre column machine, and the trunnion machine.

There are two approaches to system design: outsourcing the task to a specialist machine tool builder, who creates a system design from customer specifications, and their own product line; or, creating the system internally by producing a link line, consisting of standard machine tools and standard material handling equipment.

Three areas that can be considered for analysis in connection with transfer lines are line balancing, process technology consideration, and system reliability determination.

Common metrics used for transfer lines with no internal parts storage include: ideal cycle time; actual average production time; frequency of line stops; actual average production rate; actual ideal production rate; line efficiency; and piece cost.

Generally, as the number of workstations in a transfer line are increased, the line efficiency and production rate are found to be adversely affected; while, similarly, as reliability of individual workstations decreases, line efficiency and production rate are found to be adversely affected.

Storage buffers reduce transfer line downtime, by reducing the effects of starving and blocking. Storage buffers allow each stage of the transfer line to operate with some degree of independence.

The actual value of line efficiency for a given buffer capacity falls somewhere between the two extremes of having no storage buffers at all, and having buffers of infinite capacities.

The overall line efficiency for a two-stage line is dependent on the proportion of time an individual stage is down, plus a consideration of how long the other stage is running, with a correcting factor for the assumption that the two stages never breakdown at the same time.

ENDLIST

13.7 Self-Assessment Questions

NUMLIST

What is an automated production line? What conditions determine their use?

What components are deployed in automated production?

What system configurations are used in automated production?

What types of transfer mechanism may be used for workpart transfer?

What is the Geneva mechanism?

How are storage buffers deployed in automated production lines?

What are the basic control functions that can be distinguished in the operation of an automatic transfer machine?

What is a transfer line?

How may system design be carried-out?

What are the three areas that can be considered for analysis in connection with transfer lines?

What common metrics are used to assess transfer lines with no internal parts storage?

How do storage buffers affect transfer line downtime?

What factors are involved in the consideration of overall line efficiency for a two-stage transfer line?

ENDLIST

13.8 Answers to Self-Assessment Questions

NUMLIST

Automated production lines consist of distributed workstations connected by a mechanized work transport system that moves the parts from one workstation to another as they enter the system. The conditions that determine the use of automated production lines include: high product demand; stable product design; long product life; and multiple operations.

The automated production may consist of, besides automated workstations, manual workstations and inspection stations.

A number of system configurations for the automated production line exist; these include: in-line configurations; segmented in-line configurations (for example, L-shaped layouts, U-shaped layouts, and Rectangular layouts); and rotary configurations.

Transfer mechanisms in the workpart transfer system may be synchronous or asynchronous.

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actual average production rate; actual ideal production rate; line efficiency; and piece cost.

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The overall line efficiency for a two-stage transfer line is dependent on the proportion of time an individual stage is down, plus a consideration of how long the other stage is running, with a correcting factor for the assumption that the two stages never breakdown at the same time.

END LIST