Chapter 5

Manual Assembly Lines

5 Introduction

Manual assembly lines are production lines where products are assembled by workers performing specific tasks in a sequential manner. Assembly workers perform these tasks at workstations that are physically located along the assembly line as the product is being assembled. Assembly lines may use manual conveyors or powered conveyors to move product. These lines are highly productive for several reasons:

1. *Job specialization*. Each worker specializes in a specific task, which increases efficiency and reduces errors.
2. *Reduced handling*. Products move along the line, minimizing the time spent moving items between tasks.
3. *Flow of work*. Each work unit should move in a steady and consistent manner along the line-of-flow with minimum travel distances between workstations.
4. *Standardization*. Tasks are standardized, making it easier to train workers and maintain consistent quality.

5.1 Manual Assembly Lines

A ***manual assembly line*** is a production line that consists of a sequence of workstations where assembly tasks are performed by human workers, as illustrated in Figure 5.1.

Figure 5.1. A manual assembly line.

Products are assembled as they move along the line-of-flow. A portion of the total work is completed at each workstation. A common practice is to “launch” base parts onto the beginning of the assembly line at regular, timed intervals. Each part then travels through successive workstations and workers add components that progressively build the product. In manual assembly lines, products are manually passed from one workstation to the next workstation. However, in mechanized conveyors that are belt-driven or chain-driven, base parts are moved along the assembly line until it is transformed into a final product.

Factors that make manual assembly lines a viable option include: (1) high product demand, (2) products made on the line are identical or similar, (3) the total work can be divided into smaller work elements, and (4) it may be technologically impossible or cost prohibitive to automate the assembly process.

There are many benefits associated with manual assembly lines, including specialization of labor, the use of interchangeable parts to make similar products, steady workflow, and line pacing (i.e., each worker must complete their assigned tasks within a certain cycle time to maintain the flow of products along the assembly line).

Mechanized work transport systems use floor, waist-high, and overhead conveyors, automated guided vehicles (AGVs), or other mechanisms to transport products through the production environment.

5.2 Workstations and Manning Level

A ***workstation*** on a manual assembly line is a specific location where a worker performs a defined set of tasks. Some workstations are designed for workers to stand, such as for workers who assemble large products (i.e., automobiles, furniture, appliances). Manual assembly lines that produce large products may have more than one worker per workstation. Other workstations allow workers to sit while they work (i.e., sewing operation, light assembly and fitting of small parts, quality checks and inspections).

The ***manning level*** of a workstation is the number of workers assigned to a specific workstation or a set of workstations. As shown in Eq. 5.1, the manning level, M, of a manual assembly line is equal to the number of workers on the assembly line, w, divided by the number of workstations, n.

$$M = \frac{w}{n} \tag{5.1}$$

When the manning level is greater than one, this implies that utility workers, sometimes called “floaters”, are used in the assembly process. Utility workers are not assigned to specific workstations, but rather help wherever they are needed. They are responsible for functions such as helping workers who fall behind, relieving workers at break time, and light maintenance or repair duties.

Example 1. Manning level

If a production line consists of 20 workstations and has 24 workers, the manning level is

Solution:

$$M = \frac{w}{n} = \frac{24\, workers}{20\, workstations} = 1.2\, workers/workstation$$

5.3 Work Transport Systems

The movement of materials along a manual assembly line can be accomplished either manually or via a mechanized system. However, this could lead to two potential problems. ***Starving*** occurs when the assembly operator has completed the assigned task on the current work unit, but the next unit has not yet arrived at the workstation, so the workstations is “starved” for work. ***Blocking*** occurs when the operator has completed the assigned task on the current work unit but cannot pass the unit to the downstream workstation because either that worker is not yet ready to receive it or the output conveyor line is already full. Therefore, the operator is “blocked” from further production.

Mechanized material handling equipment to move parts along a manual assembly line include powered conveyors and other types of equipment. Sometimes parts are synchronous (paced) or asynchronous (unpaced) in operations using mechanized equipment. The three major categories of work transport systems in a production environment are: (1) continuous transport; (2) synchronous transport; and (3) asynchronous transport.

5.3.1 Continuous Transport System

A continuous transport system involves the steady and unbroken movement of materials or products along a predefined path. This type of system is often used for transporting bulk materials or items that need constant motion. Examples include conveyor belts, pipelines, and automated guided vehicles (AGVs) that operate in a loop.

Characteristics include:

- Continuous flow of materials.
- Ideal for high-volume, repetitive processes.
- Reduced handling and waiting time.
- Minimizes idle time and ensures a consistent workflow.

- Often used in assembly lines, mining operations, and bulk material transport.

5.3.2 Synchronized Transport System

A synchronized transport system is designed to move materials or products at predetermined, paced intervals, ensuring that all parts of the system work in harmony. This system is often seen in automated assembly lines where each station performs its task within a set cycle time.

Characteristics include:

- Movement occurs at fixed intervals, synchronized with production cycles.
- Coordination between different parts of the system to ensure timely material flow.
- Reduces bottlenecks and ensures balanced workload across stations.
- Commonly used in automotive manufacturing and other high-volume production environments.

5.3.3 Asynchronous Transport System

An asynchronous transport system allows materials or products to move independently (unpaced) through the production process, without being tied to a fixed schedule. Each item can move to the next stage as soon as it is ready, based on the completion of the previous task.

Characteristics include:

- Flexible movement of materials based on process requirements.
- Allows for variability in production times and processes.
- Reduces delays caused by synchronization issues.
- Suitable for low-volume, customized, or batch production where tasks have varying completion times.

5.3.4 Comparison of the Three Work Transport Systems

- **Continuous Transport System:** Best for high-volume, uninterrupted processes.
- **Synchronized Transport System:** Ideal for high-volume, fixed-cycle production with coordinated movements.
- **Asynchronous Transport System:** Most suitable for variable, low-volume, or customized production where flexibility is essential.

Each transport system has its specific applications and advantages, depending on the nature of the production process and the requirements for material handling and flow.

5.4 Working with Product Variety

There are three types of manual assembly lines that are designed to deal with differences in assembled products: (1) single model, (2) batch model, and (3) mixed model.

A ***single model assembly line*** produces only one type of product. Every work unit is identical, and the required task performed at each workstation is the same for all units. An example of a single model assembly line is an assembly line dedicated to assembling only one model of a car.

A ***batch model assembly line*** produces batches of different products one after another. Here, the products are so different that they must be made in batches with setups for each batch. It is generally more economical to produce several products in batches on the same line rather than build a separate line for each of the different models. An example of a batch model assembly line is an assembly line that produces different models of a phone in batches.

A ***mixed model assembly line*** produces different models simultaneously without switching the assembly line setup; however, the models are not produced in batches. Instead, they are made simultaneously on the same line. Each workstation is equipped to perform the variety of tasks needed to produce any model that moves through it. While one model is being worked on at one workstation, a different model is being made at the next workstation. Many consumer products are assembled on mixed model assembly lines. Some examples include multiple variations of automobiles, appliances, and laptop computers. There may be differences in available consumer options, and brand name differences, but the differences are so slight that models can be made simultaneously with no downtime.

Advantages of Mixed Model Assembly Line vs. Batch Model Assembly Line:

- No downtime is incurred when changing over between models.
- Build to ship rather than build to hold in inventory.
- Production rates of different models can be adjusted as product demand changes.

Disadvantages of Mixed Model Assembly Line vs. Batch Model Assembly Line:

- Due to the variety of assembled products, assigning tasks to workstations so that they all share an equal workload is more complex on a Mixed Model Assembly Line.

5.5 Common Metrics for Single Model Assembly Lines

Annual demand, D_a, must be reduced to an hourly production rate, R_p, as in Eq. 5.2:

$$R_p = \frac{D_a}{50 S_w H_{sh}} \tag{5.2}$$

Where Rp = average production rate, units/hr; Da = annual demand for the single product to be made on the line, units/yr; Sw = number of shifts/wk; and Hsh = hr/shift. However, if the line operates 52 weeks rather than 50 weeks, then

$$R_p = \frac{D_a}{52 S_w H_{sh}} \tag{5.3}$$

This production rate must be converted to a cycle time, Tc, which is the average time to complete one unit or one work element in a direct time study, as appropriate. Cycle time can be calculated using Eq. 5.4.

$$T_c = \frac{E}{R_p} \tag{5.4}$$

Where Tc = cycle time, min/pc; E = line efficiency (100%, or 1.00, unless stated differently), and Rp = production rate, pc/hr. If line efficiency is 100%, then there are no delays experienced on the assembly line. If delays occur on the assembly line, then the assembly line is performing at less than 100% and the balance delay, *d*, is given by *d* = 100% - line efficiency = 1 – E. Typical values for E for a manual assembly line are in the range of 0.90 to 0.98.

Assuming line efficiency is 100%, observe that cycle time is the inverse of the production rate; that is,

$$T_c = \frac{E}{R_p} = \frac{1}{R_p} \tag{5.5}$$

Example 2. Cycle Time vs. Production Rate

If cycle time equals 4.0 sec/pc, what is the production rate?

Solution:

We assume *E* = 100%, since there is no mention otherwise.

If $T_c = \frac{1}{R_p}$, then by using algebra, we have $R_p = \frac{1}{T_c}$. Hence,

$$R_p = \frac{1}{T_c} = \frac{1}{\frac{4.0\ sec}{pc}} = \frac{1\ pc}{4.0\ sec} \times \frac{60\ sec}{1\ min} \times \frac{60\ min}{1\ hr} = 900\ pc/hr$$

Proof:

$$T_c = \frac{1}{R_p} = \frac{1}{\frac{900\ pc}{hr}} = \frac{1\ hr}{900\ pc} \times \frac{60\ min}{1\ hr} = \frac{60\ sec}{1\ min} = 4\ sec/pc$$

5.6 Work Content Time

The ***work content time***, T_{wc}, is the total amount of time required of all work elements to assemble one unit of product given by

$$T_{wc} = \sum_{k=1}^{n_e} T_{ek} \tag{5.6}$$

where T_{wc} = total work content time, T_{ek} = the time to perform work element k, and n_e = total number of work elements comprising the work content, with k = 1, 2 ,… n_e.

5.7 Number of Workers Required

The number of workers required can be expressed two different ways: (1) ***theoretical number of workers required*** and (2) ***actual number of workers required***, as follows:

$$\text{(theoretical)}: w^* = Min\ Int \geq \frac{T_{wc}}{T_c} \tag{5.7}$$

$$\text{(actual)}: w = MinInt \geq \frac{T_{wc}}{E_r E_b T_c} \tag{5.8}$$

5.8 Repositioning Losses

Repositioning time refers to time lost during each cycle due to repositioning the worker, the work unit, or both. For example, in a U-shaped work cell, a worker who just loaded a part in a machine and hit the Start button to begin a new cycle must reposition him/herself to work on a different machine while the first machine is going through the cycle. The time available per worker to perform assembly operations must be less than the cycle time, T_c.Therefore, repositioning time can be calculated as follows:

$$T_r = (LT_r)(T_c) \tag{5.9}$$

where T_r = repositioning time, LT_r = lost time due to repositioning, and T_c = cycle time.

Service time refers to the time remaining after repositioning time is subtracted from the cycle time, and is given by

$$T_s = T_c - T_r = (1 - LT_r)(T_c) \tag{5.10}$$

where T_s = service time.

Repositioning time diminishes the available time for productive assembly work on the line. ***Repositioning efficiency*** is used to represent these losses, in terms of an efficiency factor as follows:

$$E_r = \frac{T_s}{T_c} = \frac{T_c - T_r}{T_c} \tag{5.11}$$

where E_r = repositioning efficiency.

Hence,

$$T_c - T_r = T_s \tag{5.12}$$

5.9 Measures of Line Balance Efficiency

Due to differences in minimum work element times and precedent constraints, it is virtually impossible to have perfect line balance, whereby all workers have an equal workload and production cycle time requirements are satisfied. One measure to indicate how good a given line balance is includes ***line balance efficiency***, which is the work content time divided by the total available service time on the line.

$$E_b = \frac{T_{wc}}{wT_s} \tag{5.13}$$

where Eb = line balance efficiency, %; Ts = maximum available service time on the line, min/cycle; and w = number of workers.

The complement of line balance efficiency is ***balance delay***, which indicates the amount of time lost due to imperfect balancing as a ratio of the total time available, as in the following equation:

$$d = \frac{wT_s - T_{wc}}{wT_s} = 1 - \frac{T_{wc}}{wT_s} = 1 - E_b \tag{5.14}$$

Where d = balance delay; and the other terms were defined previously. Note that $E_b + d = 1$.

5.10 Worker Requirements

The three factors that reduce a manual assembly line's productivity are line efficiency (E), repositioning efficiency (Er), and line balance efficiency (Eb). Taken together, they comprise the overall labor efficiency on the assembly line, as in the equation below:

$$Labor\ efficiency\ on\ the\ assembly\ line = EE_rE_b \tag{5.15}$$

Using this measure of labor efficiency, we can calculate a realistic value for the ***actual number of workers*** needed on the assembly line:

$$w = Minimum\ Integer \geq \frac{T_{wc}}{E_rE_bT_c} = \frac{T_{wc}}{E_bT_s} \tag{5.16}$$

where w = number of workers required on the assembly line, T_{wc} = total work content time per unit to be accomplished on the assembly line, min/unit.

Example 3

The required production rate for a certain product is 35 units/hr. Its work content time is 65.5 min. The production line for this product includes 4 automated workstations. Because the automated stations are not entirely reliable, the overall line efficiency is expected to be only 90%. All the other stations will have one worker each. It is anticipated that 5% of each cycle will be lost due to worker repositioning. Balance delay is expected to be 6%. Determine (a) cycle time, (b) number of workers, (c) number of workstations, (d) average manning level on the line, including the automated stations, and (e) labor efficiency on the line.

Solution:

(a)

$$T_c = \frac{E}{R_p} = \frac{0.90}{35\ units/hr} = 0.0258 \times \frac{hr}{45\ units} \times \frac{60\ min}{hr} = 1.5429\ min/unit$$

(b)

$$T_r = (LT_r)(T_c) = (0.05)(1.5429\frac{min}{unit}) = 0.0771\ min/unit$$

$$T_s = (1 - LT_r)T_c = (1 - 0.05)T_c = (E_r)(T_c) = 0.95\left(\frac{1.5429\, min}{unit}\right) = 1.4658\, min/unit$$

$Alternatively,$

$$T_s = T_c - T_r = 1.5429\, min/unit - 0.0771\, min/unit = 1.4658\, min/unit$$

$$E_r = \frac{T_s}{T_c} = \frac{T_c - T_r}{T_c} = \frac{1.5429\, min/unit - 0.0771\, min/unit}{1.54293\, min/unit} = 0.95 \times 100 = 95\%$$

$$E_b - 1 - d = 1 - 0.06 = 0.94 \times 100 = 94\%$$

$Theoretical\ no. of\ workers$:

$$w^* = Min\ Int \geq \frac{T_{wc}}{T_c} = \frac{65.5\, min/unit}{(1.5429\, min/unit)} = 47.59, rounded\ up\ to\ 48\ workers$$

$Actual\ no. of\ workers$:

$$w = Min\ Int \geq \frac{T_{wc}}{E_r E_b T_c} = \frac{65.5\, min/unit}{(0.95)(0.94)(1.5429\, min/unit)} = 47.5, rounded\ up\ to\ 48\ workers$$

$Alternatively,$

$$w = Min\ Int \geq \frac{T_{wc}}{T_s E_b} = \frac{65.5\, min/unit}{1.46589\, min/unit(0.94)} = 47.5, rounded\ up\ to\ 48\ workers$$

$$If\ E_r = \frac{T_s}{T_c}, then\ T_s = E_r T_c$$

(c) $n = w + N_a = 48\ workers + 4\ automated\ workstations = 52\ workstations$

(d) $M = \frac{w}{n} = \frac{48}{52} = 0.923\ workers/workstation$

(e) Labor efficiency = $EE_rE_b = (0.90)(0.954)(0.94) = 0.8037 \times 100 = 80.4\%$

5.11 Workstation Considerations

A workstation is a position along the assembly line where one or more workers perform assembly tasks. If the manning level is one for all workstations, meaning one worker per workstation, then the ***number of workstations*** is equal to the number of workers, as in the following equation:

$$n = \frac{w}{M} \tag{5.17}$$

The cycle time on a paced powered conveyor line is determined by the center-to-center spacing between base parts divided by the speed of the conveyor, as follows:

$$T_c = \frac{s_p}{v_c} \tag{5.18}$$

where T_c = cycle time, s_p= center-to-center spacing between base parts, and v_c = velocity of the conveyor.

The ***total length of the assembly line*** is given by

$$L = nL_s \tag{5.19}$$

where L = length of the assembly line, n = number of workstations; and L_s = workstation length.

Constant speed conveyors are a common transport system used on manual assembly lines. Here, base parts are launched onto the beginning of the assembly line at constant time intervals equal to the cycle time, Tc. This, in turn, provides a constant *feed rat*e of base parts, and if the base parts remain fixed to the conveyor during the assembly process, this feed rate will be maintained throughout the assembly line. The feed rate is the reciprocal of the cycle time:

$$f_p = \frac{1}{T_c} \tag{5.20}$$

where f_p = feed rate on the assembly line in terms of units per minute. A constant feed rate on a constant speed conveyor provides a center-to-center spacing between base parts given by:

$$s_p = \frac{v_c}{f_p} \tag{5.21}$$

where s_p = center-to-center spacing between base parts, and v_c = velocity of the conveyor.

Hence,

$$\text{If } s_p = \frac{v_c}{f_p}\text{, then } f_p = \frac{1}{T_c} = \frac{v_c}{s_p} \tag{5.22}$$

It is desirable to allow more time for the worker to complete an assigned task than the cycle time, so that a slight buffer time is allowed in the event a particular work unit takes longer than expected to complete. However, in the long run, the worker must keep pace with the cycle time, otherwise a buildup of parts can result that may create a bottleneck operation.

The amount of time a work unit spends inside the boundaries of a workstation is defined as ***tolerance time***, as in the equation below:

$$T_t = \frac{L_s}{v_c} \tag{5.23}$$

Where T_t = tolerance time, min/part, assuming all workstations' lengths are of equal length. If the workstations have different lengths, L_{si}, then the tolerance times will differ proportionately since v_c is constant.

The total elapsed time that a work unit spends on the assembly line can be expressed as follows:

$$ET = \frac{L}{v_c} = nT_t \tag{5.24}$$

Where *ET* = elapsed time a work unit, or a base part, spends on the conveyor line during its assembly, min.

Example 4

A powered, chain-driven floor conveyor is used to carry base parts along a manual assembly line. The spacing between base parts is 3 m and the speed of the conveyor is 1.5 m/min. The length of each workstation is 4.5 m. The line has 20 workstations and 25 workers. Determine (a) cycle time, (b) feed rate, (c) tolerance time, and (d) elapsed time a base part spends on the assembly line.

Solution:

(a) Cycle time

$$T_c = \frac{s_p}{v_c} = \frac{3.0\ m}{1.5\ m/min} = 2.0\ min/unit$$

(b) Feed rate of parts

$$f_p = \frac{v_c}{s_p} = \frac{1.5\ m/min}{3.0\ m} = 0.50\ units/min$$

Alternative calculation,

$$f_p = \frac{1}{T_c} = \frac{1\ unit}{2.0\ min} = 0.50\ units/min$$

(c)

$$T_t = \frac{L_s}{v_c} = \frac{4.5\ m}{1.5\ m/sec} = 4.5\ m \times \left(\frac{1\ sec}{1.5\ m}\right) = 3.0\ sec/unit$$

(d)

$$Elapsed\ time = ET = nT_t = 20\ workstations \times \left(\frac{3.0\ sec}{unit}\right) = 60\,\frac{sec}{unit} = 1\ min/unit$$

5.12 Summary

In a manual assembly line production environment, understanding and optimizing metrics like cycle time, production rate, total work content time, line balance efficiency, and the number of worker requirements are essential for achieving efficient and productive operations. These factors work together to ensure that the assembly line operates smoothly, meets production targets, and maintains high quality and efficiency. By understanding these concepts and applying the appropriate calculations, industrial engineers can design and optimize manual assembly lines for maximum efficiency and productivity.

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