Chapter 4

Manual Assembly Lines

Manual assembly lines are work systems consisting of multiple workers who are organized to produce a single product or a limited range of products.[1] They are usually associated with the mass production of assembled products such as automobiles, appliances, and other consumer products for which demand is high. The assembly workers perform various tasks at workstations that are physically located along the line-of-flow of the product as it is being made. In assembly lines, the workers usually accomplish their tasks on work units that are moved by a powered conveyor. In addition, some of the workstations may be equipped with portable powered tools for the assembly operations. Factors favoring the use of manual assembly lines include the following:

- Demand for the product is high or medium.
- The products made on the line are identical or similar.
- The total work required to assemble the product can be divided into small work elements.

[1]This chapter is based largely on Chapter 17 in [1].

TABLE 4.1 Products Usually Made on Manual Assembly Lines

Audio equipment	Lamps	Stoves
Automobiles	Luggage	Telephones
Cameras	Microwave ovens	Toasters, toaster ovens
Cooking ranges	Personal computers and printers, monitors, scanners, etc.	Trucks, light and heavy
Dishwashers	Power tools (drills, saws, etc.)	Videocassette players
Dryers (laundry)	Pumps	Washing machines (laundry)
Electric motors	Refrigerators	
Furniture		

- It is technologically impossible or economically infeasible to automate the assembly operations.

Table 4.1 provides a list of products characterized by these factors that are usually made on manual assembly lines.

Several reasons can be given to explain why manual assembly lines are so productive compared to alternative methods in which multiple workers each perform all of the tasks to assemble the products:

- *Specialization of labor.* When a large job is divided into small tasks and each task is assigned to one worker, the worker becomes highly proficient at performing the single task. Each worker becomes a specialist. One of the major explanations of specialization of labor is the ***learning curve*** (Chapter 19).
- *Interchangeable parts.* This means that each component is manufactured to sufficiently close tolerances that any part of a certain type can be selected at random for assembly with its mating component. Without interchangeable parts, assembly would require filing and fitting of mating components, rendering assembly line methods impractical.
- *Work flow.* In the context of assembly line technology, work flow means that each work unit should move steadily along the line and travel minimum distances between stations.
- *Line pacing.* Workers on an assembly line are usually required to complete their assigned tasks on each product unit within a certain cycle time, which paces the line to maintain a specified production rate. Pacing is generally implemented by means of a mechanized conveyor.

4.1 FUNDAMENTALS OF 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 depicted in Figure 4.1. Products are assembled as they move along the line. At each station, a portion of the total work is performed on each unit. The common practice is to "launch" base parts onto the beginning of the line at regular intervals. Each base part travels through successive stations and workers add components that progressively build the product. A mechanized material transport system is typically used to move the base part along the line as it is gradually transformed into the final product. However, in some manual lines the product is manually passed from

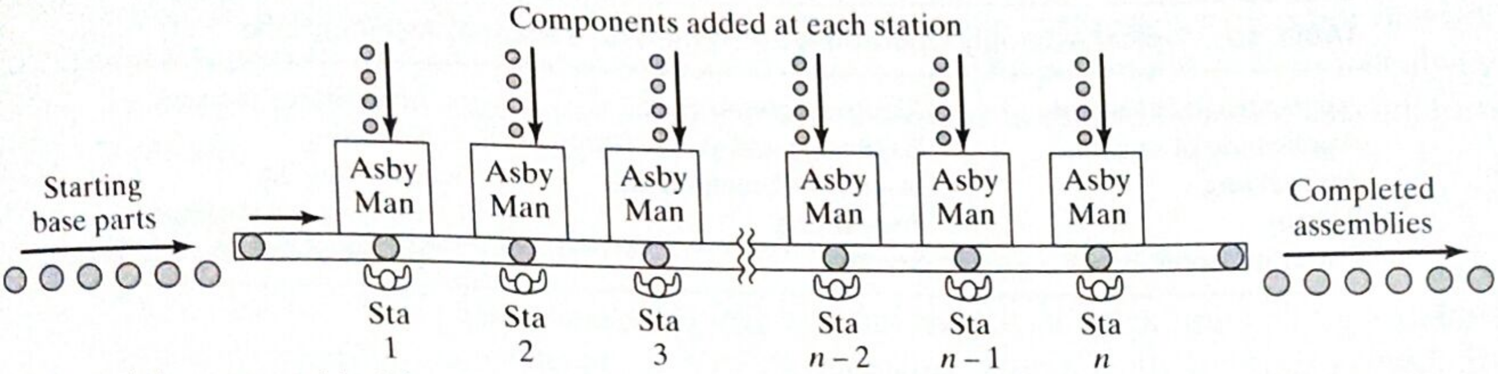


Figure 4.1 Configuration of a manual assembly line.

station to station. The production rate of an assembly line is determined by its slowest station. Stations capable of working faster are ultimately limited by the slowest station.

Manual assembly line technology has made a significant contribution to the development of American industry in the twentieth century (Historical Note 4.1). It remains an important work system throughout the world for producing assembled products in large quantities.

HISTORICAL NOTE 4.1 ORIGINS OF THE MANUAL ASSEMBLY LINE

The origins of the manual assembly line can be traced to the meat industry in Chicago and Cincinnati. In the mid- and late 1800s, meat-packing plants used unpowered overhead conveyors to move the slaughtered stock from one worker to the next. These unpowered conveyors were later replaced by power-driven chain conveyors to create "disassembly lines," which were the predecessor of the assembly line. The work organization permitted meat cutters to concentrate on single tasks (specialization of labor).

American automotive industrialist Henry Ford had observed these meat-packing operations. In 1913, he and his engineering colleagues designed an assembly line in Highland Park, Michigan, to produce magneto flywheels. Productivity increased fourfold. Flushed by success, Ford applied assembly line techniques to chassis fabrication. Using chain-driven conveyors and workstations arranged for the convenience and comfort of his assembly line workers, productivity was increased by a factor of eight, compared to previous single-station assembly methods. These and other improvements resulted in dramatic reductions in the price of the Model T Ford, which was the main product of the Ford Motor Company at the time. American consumers could now afford an automobile because of Ford's achievement in cost reduction. This stimulated further development and the use of production line techniques, including automated transport lines. It also forced Ford's competitors and suppliers to imitate his methods, and the manual assembly line became intrinsic to American industry.

4.1.1 Assembly Workstations

A ***workstation*** on a manual assembly line is a designated location along the work flow path at which one or more work elements are performed by one or more workers. The work elements represent small portions of the total work that must be accomplished to

TABLE 4.2 Typical Assembly Operations Performed on a Manual Assembly Line

Application of adhesive	Electrical connections	Snap fitting of parts
Application of sealants	Expansion and shrink fitting	Soldering
Arc welding	Insertion of components	Spot-welding
Brazing	Press fitting	Stapling and stitching
Cotter pin applications	Riveting	Threaded fastener applications

assemble the product. Typical assembly operations performed at stations on a manual assembly line are listed in Table 4.2. A given workstation also includes the tools (hand tools or powered tools) required to perform the task assigned to the station.

Some workstations are designed for workers to stand, while others allow workers to sit. When the workers stand, they can move about the station area to perform their assigned tasks. This is common for assembly of large products such as cars, trucks, and major appliances. The typical case is when the product is moved by a conveyor at constant velocity through the station. The worker begins the assembly task near the upstream side of the station and moves along with the work unit until the task is completed, then walks back to the next work unit and repeats the cycle. For smaller assembled products (such as small appliances, electronic devices, and subassemblies used on larger products), the workstations are usually designed to allow the workers to sit while they perform their tasks. This is more comfortable and less fatiguing for the worker and is generally more conducive to precision and accuracy in the assembly task.

Manual assembly lines that produce large items (e.g., cars, trucks) may have more than one worker per station. The ***manning level*** of workstation i, symbolized M_i, is the number of workers assigned to that station; where $i = 1, 2, \ldots, n$; and n = number of workstations on the line. The generic case is one worker: $M_i = 1$. In cases where the product is large, such as a car or a truck, multiple workers are often assigned to one station, so that $M_i > 1$. Multiple manning conserves valuable floor space in the factory and reduces line length and throughput time because fewer stations are required. The average manning level of a manual assembly line is simply the total number of workers on the line divided by the number of stations; that is,

$$M = \frac{w}{n} \tag{4.1}$$

where M = average manning level of the line, workers/station; w = number of workers on the line; and n = number of stations on the line. This seemingly simple ratio is complicated by the fact that manual assembly lines often include more workers than those assigned to stations, so that M is not a simple average of M_i values. These additional workers, called ***utility workers***, are not assigned to specific workstations; instead they are responsible for functions such as (1) helping workers who fall behind, (2) relieving workers for personal breaks, and (3) maintenance and repair duties. Including the utility workers in the worker count, we have

$$M = \frac{w_u + \sum_{i=1}^{n} w_i}{n} \tag{4.2}$$

where w_u = number of utility workers assigned to the system and w_i = number of workers assigned specifically to station i for $i = 1, 2, \ldots, n$. The parameter w_i is almost always an integer, except for the unusual case where a worker is shared between two adjacent stations.

4.1.2 Work Transport Systems

There are two basic ways to accomplish the movement of work units along a manual assembly line: (1) manually or (2) by a mechanized system. Both methods provide the fixed routing (pure sequential work flow, Section 3.1.1) that is characteristic of production lines.

Manual Methods of Work Transport. In manual work transport, the units of product are passed from station to station by hand. Two problems result from this mode of operation: starving and blocking. When ***starving*** occurs, the assembly operator has completed the assigned task on the current work unit, but the next unit has not yet arrived at the station. The worker is thus starved for work. When ***blocking*** occurs, the operator has completed the assigned task on the current work unit but cannot pass the unit to the downstream station because that worker is not yet ready to receive it. The operator is therefore blocked from working.

To mitigate the effects of these problems, storage buffers are sometimes used between stations. In some cases, the work units made at each station are collected in batches and then moved to the next station. In other cases, work units are moved individually along a flat table or unpowered conveyor. When the task is finished at each station, the worker simply pushes the unit toward the downstream station. Space is often allowed for one or more work units in front of each workstation. This provides an available supply of work for the station, as well as room for completed units from the upstream station. Hence, starving and blocking are minimized. The trouble with this method of operation is that it can result in significant work-in-process, which is economically undesirable. Also, workers are unpaced in lines that rely on manual transport methods, and production rates tend to be lower.

Mechanized Work Transport. Powered conveyors and other types of mechanized material-handling equipment are widely used to move units along a manual assembly line. These systems can be designed to provide paced or unpaced operation of the line. There are three major categories of work transport systems in production lines: (a) continuous transport, (b) synchronous transport, and (c) asynchronous transport.

A ***continuous transport system*** uses a continuously moving conveyor that operates at constant velocity. This method is common on manual assembly lines. The conveyor usually runs the entire length of the line. However, if the line is very long, such as the case of an automobile final assembly plant, it is divided into segments with a separate conveyor for each segment.

Continuous transport can be implemented in two ways: (1) work units are fixed to the conveyor, and (2) work units are removable from the conveyor. In the first case, the product is large and heavy (e.g., automobile, washing machine) and cannot be removed from the conveyor. The worker must therefore walk along with the product at the speed of the conveyor in order to accomplish the assigned task.

In the case where work units are small and lightweight, they can be removed from the conveyor for the physical convenience of the operator at each station. Another convenience for the worker is that the assigned task at the station does not need to be completed within a fixed cycle time. Flexibility allows each worker to deal with technical problems that may be encountered with a particular work unit. However, on average, each worker must maintain a production rate equal to that of the rest of the line. Otherwise, the line will produce ***incomplete units***, which occurs when parts that were supposed to be added at a station are not added because the worker runs out of time.

In ***synchronous transport systems***, all work units are moved simultaneously between stations with a quick, discontinuous motion, and then positioned at their respective stations. This type of system is also known as ***intermittent transport***, which describes the motion experienced by the work units. Synchronous transport is not common for manual lines, due to the requirement that the task must be completed within a certain time limit. This can result in incomplete units and excessive stress on the assembly workers. Despite its disadvantages for manual assembly lines, synchronous transport is often ideal for automated production lines.

In an ***asynchronous transport system***, a work unit leaves a given station when the assigned task has been completed and the worker releases the unit. Work units move independently, rather than synchronously. At any moment, some units are moving between workstations while others are positioned at stations. With asynchronous transport systems, small queues of work units are permitted to form in front of each station. This tends to be forgiving of variations in worker task times.

4.1.3 Coping with Product Variety

Because human workers are flexible in terms of the variety of tasks they can perform, manual assembly lines can be designed to deal with differences in assembled products. Three types of assembly line can be distinguished: (1) single model, (2) batch model, and (3) mixed model.

A ***single model line*** produces many units of one product, and there is no variation in the product. Every work unit is identical, and so the task performed at each station is the same for all product units. This line type is intended for products with high demand.

Batch model and mixed model lines are designed to produce two or more models, but different approaches are used to cope with the model variations. As its name suggests, a ***batch model line*** produces each model in batches. Workstations are set up to produce the required quantity of the first model, then the stations are reconfigured to produce the next model, and so on. Products are often assembled in batches when demand for each product is medium. It is generally more economical to use one assembly line to produce several products in batches than to build a separate line for each different model.

When we state that the workstations are set up, we are referring to the assignment of tasks to each station on the line, including the special tools needed to perform the tasks, and the physical layout of the station. The models made on the line are usually similar, and the tasks to make them are therefore similar. However, differences exist among models so that a different sequence of tasks is usually required, and tools used at a given workstation for the last model might not be the same as those required for the next model. One model may take more total time than another, requiring the line to be operated at a slower pace. Worker retraining or new equipment may be needed to produce each new model. For these kinds of reasons, changes in the station setup are required before production of the next model can begin. These changeovers result in lost production time on a batch model line.

A ***mixed model line*** also produces more than one model; however, the models are not produced in batches. Instead, they are made simultaneously on the same line. While one model is being worked on at one station, a different model is being made at the next station. Each station is equipped to perform the variety of tasks needed to produce any model that moves through it. Many consumer products are assembled on mixed model lines. Examples are automobiles and major appliances, which are characterized by model variations, differences in available options, and even brand name differences in some cases.

The advantages of a mixed model line over a batch model line include the following: (1) no production time is lost when changing over between models; (2) high inventories typical of batch production are avoided; and (3) production rates of different models can be adjusted as product demand changes. On the other hand, the problem of assigning tasks to workstations so that they all share an equal workload is more complex on a mixed model line. Scheduling (determining the sequence of models) and logistics (getting the right parts to each workstation for the model currently at that station) are more difficult in this type of line.

4.2 ANALYSIS OF SINGLE MODEL ASSEMBLY LINES

The relationships developed in this section and the algorithms described in the following section are applicable to single model assembly lines. With a little modification, the same relationships and algorithms can be applied to batch model and mixed model assembly lines.

The assembly line must be designed to achieve a production rate R_p sufficient to satisfy demand for the product. Product demand is often expressed as an annual quantity, which can be reduced to an hourly rate. Management must decide how many shifts per week the line will operate and how many hours per shift. Assuming that the plant operates 50 weeks per year, the required hourly production rate is given by

$$R_p = \frac{D_a}{50 S_w H_{sh}} \tag{4.3}$$

where R_p = average production rate, units/hr; D_a = annual demand for the single product to be made on the line, units/yr; S_w = number of shifts/wk; and H_{sh} = hr/shift. If the line operates 52 weeks rather than 50, then $R_p = D_a/52S_wH_{sh}$. If a time period other than a year is used for product demand, then the equation can be adjusted by using consistent time units in the numerator and denominator.

This production rate must be converted to a cycle time T_c, which is the time interval at which the line will be operated. The cycle time must take into account the reality that some production time will be lost due to occasional equipment failures, power outages, lack of a certain component needed in assembly, quality problems, labor problems, and other reasons. As a consequence of these losses, the line will be up and operating only a certain proportion of time out of the total shift time available; this uptime proportion is referred to as the ***line efficiency***. The cycle time can be determined as

$$T_c = \frac{60E}{R_p} \tag{4.4}$$

where T_c = cycle time of the line, min/cycle; R_p = required production rate, as determined from equation (4.3), units/hr; the constant 60 converts the hourly production rate to a cycle time in minutes; and E = line efficiency, the proportion of shift time that the line is up and operating. Typical values of E for a manual assembly line are in the range 0.90 to 0.98. The cycle time T_c establishes the ideal cycle rate for the line:

$$R_c = \frac{60}{T_c} \tag{4.5}$$

where R_c = cycle rate for the line, cycles/hr; and T_c is in min/cycle, as in equation (4.4). This rate R_c must be greater than the required production rate R_p because the line efficiency E is less than 100%. R_p and R_c are related to E as follows:

$$E = \frac{R_p}{R_c} \tag{4.6}$$

An assembled product requires a certain total amount of time to build, called the ***work content time*** T_{wc}. This is the total time of all work elements that must be performed to make one unit of the product. It represents the total amount of work that is accomplished on the product by the assembly line. It is useful to compute a theoretical minimum number of workers that will be required on the assembly line to produce a product with known T_{wc} and specified production rate R_p. The approach is basically the same as the one used in Section 2.4 to compute the number of workers required to achieve a specified workload. Making use of equation (2.13), we determine the number of workers on the production line:

$$w = \frac{WL}{AT} \tag{4.7}$$

where w = number of workers on the line; WL = workload to be accomplished in a given time period; and AT = available time in the period. The time period of interest will be 60 min. The ***workload*** in that period is the hourly production rate multiplied by the work content time of the product; that is,

$$WL = R_p T_{wc} \tag{4.8}$$

where R_p = production rate, pc/hr; and T_{wc} = work content time, min/pc.

Equation (4.4) can be rearranged to the form $R_p = 60E/T_c$. Substituting this into equation (4.8), we have

$$WL = \frac{60ET_{wc}}{T_c}$$

The available time AT is 1 hr (60 min) multiplied by the proportion uptime on the line; that is,

$$AT = 60E$$

Substituting these terms for WL and AT into equation (4.7), the equation reduces to the ratio T_{wc}/T_c. Since the number of workers must be an integer, we can state

$$w^* = \text{Minimum Integer} \geq \frac{T_{wc}}{T_c} \tag{4.9}$$

where w^* = theoretical minimum number of workers. If we assume one worker per station ($M_i = 1$ for all $i, i = 1, 2, \ldots, n$; and the number of utility workers $w_u = 0$), then this ratio also gives the theoretical minimum number of workstations on the line.

Achieving this minimum value in practice is very unlikely. Equation (4.9) ignores two factors that exist in a real assembly line and tend to increase the number of workers above the theoretical minimum value:

- *Repositioning losses.* Some time will be lost at each station for repositioning of the work unit or the worker. Thus, the time available per worker to perform assembly is less than T_c.
- *The line balancing problem.* It is virtually impossible to divide the work content time evenly among all workstations. Some stations are bound to have an amount of work that requires less time than T_c. This tends to increase the number of workers.

The following sections will focus on repositioning losses and imperfect balancing. We will consider the simplest case where one worker is assigned to each station ($M_i = 1$). Thus, when we refer to a certain station, we are referring to the worker at that station, and vice versa.

4.2.1 Repositioning Losses

Repositioning losses on a production line occur because some time is required each cycle to reposition the worker, or the work unit, or both. For example, on a continuous transport line with work units attached to the conveyor and moving at a constant speed, time is required for the worker to walk from the unit just completed to the upstream unit entering the station. In other conveyorized systems, time is required to remove the work unit from the conveyor and position it at the station for the worker to perform his or her task on it. In all manual assembly lines, there is some lost time for repositioning.

We will define T_r as the time required each cycle to reposition the worker or the work unit or both. In our subsequent analysis, we assume that T_r is the same for all workers, although repositioning times may actually vary among stations.

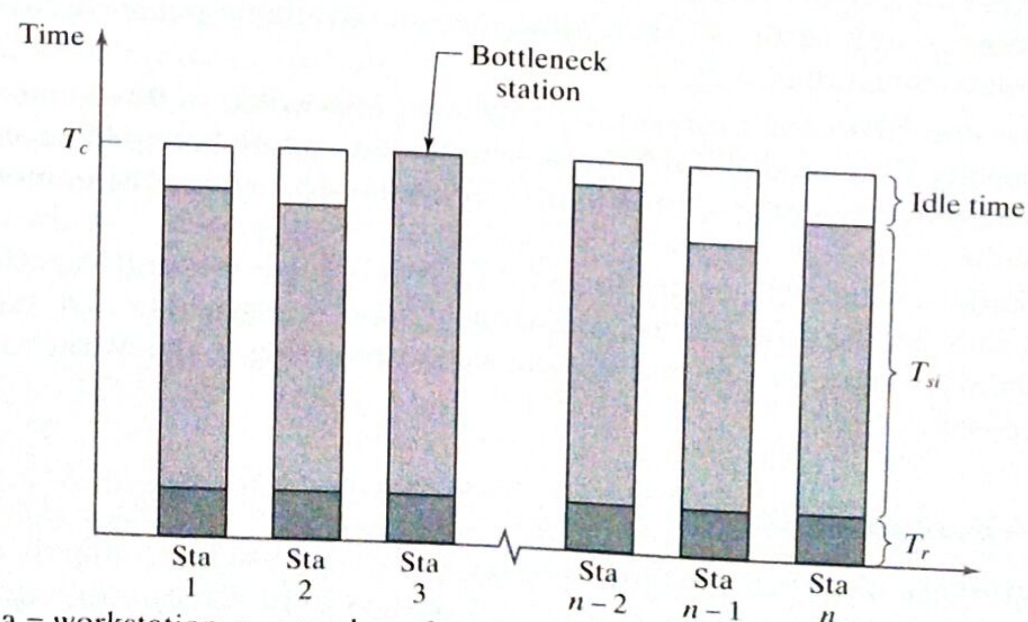
The repositioning time T_r must be subtracted from the cycle time T_c to obtain the available time remaining to perform the actual assembly task at each workstation. Let us refer to the time to perform the assigned task at each station as the ***service time***. It is symbolized T_{si}, where i is used to identify station i, $i = 1, 2, \ldots, n$. Service times will vary among stations because the total work content cannot be allocated evenly among them. Some stations will have more work than others. There will be at least one station at which T_{si} is maximum. This is sometimes referred to as the ***bottleneck station*** because it establishes the cycle time for the entire line. This maximum service time can be no greater than the difference between the cycle time T_c and the repositioning time T_r; that is,

$$\text{Max}\{T_{si}\} \leq T_c - T_r \qquad \text{for } i = 1, 2, \ldots n \tag{4.10}$$

where $\text{Max}\{T_{si}\}$ = maximum service time among all stations, min/cycle; T_c = cycle time for the assembly line from equation (4.4), min/cycle; and T_r = repositioning time (assumed the same for all stations), min/cycle. For simplicity of notation, let us use T_s to denote this maximum allowable service time; that is,

$$T_s = \text{Max}\{T_{si}\} \leq T_c - T_r \tag{4.11}$$

At all stations where T_{si} is less than T_s, workers will be idle for a portion of the cycle, as portrayed in Figure 4.2. When the maximum service time does not consume the entire available time $T_c - T_r$ (that is, when $T_s < T_c - T_r$), then this means that the line could be



Sta = workstation, n = number of stations on the line, T_r = repositioning time, T_{si} = service time, T_c = cycle time

Figure 4.2 Components of cycle time at several stations on a manual assembly line. At the slowest station, the bottleneck station, idle time is zero; at other stations idle time exists.

operated at a faster pace than T_c from equation (4.4). In this case, the cycle time T_c is usually reduced so that $T_c = T_s + T_r$; this allows the production rate to be increased slightly.

Repositioning losses reduce the amount of time that can be devoted to productive assembly work on the line. These losses can be expressed in terms of an efficiency factor as follows:

$$E_r = \frac{T_s}{T_c} = \frac{T_c - T_r}{T_c} \tag{4.12}$$

where E_r = ***repositioning efficiency***, and the other terms are defined above.

4.2.2 The Line Balancing Problem

The work content performed on an assembly line consists of many separate and distinct work elements. Invariably, the sequence in which these elements can be performed is restricted, at least to some extent. And the line must operate at a specified production rate, which reduces to a required cycle time as defined by equation (4.4). Given these conditions, the line balancing problem is concerned with assigning the individual work elements to workstations so that all workers have an equal amount of work while simultaneously achieving the specified production rate of the line. We discuss the terminology of the line balancing problem in this section and present some of the algorithms to solve it in Section 4.3.

Minimum Rational Work Elements. A ***minimum rational work element*** is a work element that has a specific limited objective on the assembly line, such as adding a component to the base part, joining two components, or performing some other small portion of the total work content. A minimum rational work element cannot be subdivided any further without loss of practicality. For example, fastening two parts together with a bolt and nut would be defined as a minimum rational work element. It makes no sense to divide this element into smaller units of work. The sum of the work element times is equal to the work content time; that is,

$$T_{wc} = \sum_{k=1}^{n_e} T_{ek} \tag{4.13}$$

where T_{ek} = time to perform work element k, min; and n_e = number of work elements into which the work content is divided; that is, $k = 1, 2, \ldots, n_e$.

In line balancing, we make the following assumptions about work element times: (1) element times are constant values, and (2) T_{ek} values are additive; that is, the time to perform two or more work elements in sequence is the sum of the individual element times. In fact, we know these assumptions are not quite true. Work element times are variable, leading to the problem of task time variability. And there is often motion economy that can be achieved by combining two or more work elements, thus violating the additivity assumption. Nevertheless, these assumptions are made to allow solution of the line balancing problem.

The task time at station i, or service time as we are calling it, T_{si}, is composed of the work element times that have been assigned to that station; that is,

$$T_{si} = \sum_{k \in i} T_{ek} \tag{4.14}$$

An underlying assumption in this equation is that each T_{ek} is less than the maximum service time T_s.

Different work elements require different times, and when the elements are grouped into logical tasks and assigned to workers, the station service times T_{si} are likely not to be equal. Thus, simply because of the variation among work element times, some workers will be assigned more work, while others will be assigned less. Although service times vary from station to station, they must add up to the work content time:

$$T_{wc} = \sum_{i=1}^{n} T_{si} \tag{4.15}$$

Precedence Constraints. In addition to the variations in element times that make it difficult to obtain equal service times for all stations, there are restrictions on the order in which the work elements can be performed. Some elements must be done before others. For example, to create a threaded hole, the hole must be drilled before it can be tapped. A machine screw that will use the tapped hole to attach a mating component cannot be fastened before the hole has been drilled and tapped. These technological requirements on the work sequence are called ***precedence constraints***. As we shall see, they complicate the line balancing problem.

Precedence constraints can be presented graphically in the form of a ***precedence diagram***, which indicates the sequence in which the work elements must be performed. Work elements are symbolized by nodes, and the precedence requirements are indicated by arrows connecting the nodes. The sequence proceeds from left to right. Figure 4.3

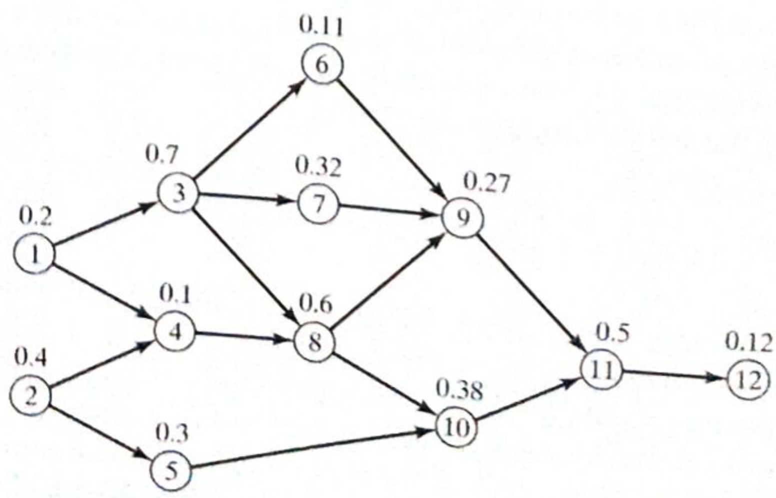


Figure 4.3 Precedence diagram for Example 4.1. Nodes represent work elements, and arrows indicate the sequence in which the elements must be done. Element times are shown above each node.

presents the precedence diagram for the following example, which illustrates the terminology and some of the equations presented here.

Example 4.1 A Problem for Line Balancing

A small electrical appliance is to be produced on a single model assembly line. The work content of assembling the product has been reduced to the work elements listed in Table 4.3. The table also lists the standard times that have been established for each element, as well as the precedence order in which they must be performed. The line is to be balanced for an annual demand of 100,000 units/yr. The line will operate 50 wk/yr, 5 shifts/wk, and 7.5 hr/shift. Manning level will be 1 worker/station. Previous experience suggests that the uptime efficiency for the line will be 96%, and repositioning time lost per cycle will be 0.08 min. Determine (a) total work content time T_{wc}, (b) required hourly production rate R_p to achieve the annual demand, (c) cycle time T_c, (d) theoretical minimum number of workers required on the line, and (e) service time T_s to which the line must be balanced.

TABLE 4.3 Work Elements for Example 4.1

No.	Work Element Description	T_{ek} (min)	Must Be Preceded by
1	Place frame in workholder and clamp	0.2	—
2	Assemble plug, grommet to power cord	0.4	—
3	Assemble brackets to frame	0.7	1
4	Wire power cord to motor	0.1	1,2
5	Wire power cord to switch	0.3	2
6	Assemble mechanism plate to bracket	0.11	3
7	Assemble blade to bracket	0.32	3
8	Assemble motor to brackets	0.6	3,4
9	Align blade and attach to motor	0.27	6,7,8
10	Assemble switch to motor bracket	0.38	5,8
11	Attach cover, inspect, and test	0.5	9,10
12	Place in tote pan for packing	0.12	11

Solution **(a)** The total work content time is the sum of the work element times in Table 4.3.

$$T_{wc} = 4.0 \text{ min}$$

(b) Given the annual demand, the hourly production rate is

$$R_p = \frac{100{,}000}{50(5)(7.5)} = 53.33 \text{ units/hr}$$

(c) The corresponding cycle time T_c with an uptime efficiency of 96% is

$$T_c = \frac{60(0.96)}{53.33} = 1.08 \text{ min}$$

(d) The minimum number of workers is given by equation (4.9):

$$w^* = \left(\text{Min Int} \geq \frac{4.0}{1.08} = 3.7\right) = 4 \text{ workers}$$

(e) The available service time against which the line must be balanced is

$$T_s = 1.08 - 0.08 = 1.00 \text{ min}$$

Measures of Line Balance Efficiency. Owing to the differences in minimum rational work element times and the precedence constraints among the elements, it is virtually impossible to obtain a perfect line balance. Measures must be defined to indicate how good a given line balancing solution is. One possible measure is ***balance efficiency***, which is the work content time divided by the total available service time on the line:

$$E_b = \frac{T_{wc}}{wT_s} \tag{4.16}$$

where E_b = balance efficiency, often expressed as a percentage; T_s = the maximum available service time on the line (Max$\{T_{si}\}$), min/cycle; and w = number of workers. The denominator in equation (4.16) gives the total service time available on the line to devote to the assembly of one product unit. The closer the values of T_{wc} and wT_s, the less idle time on the line. E_b is therefore a measure of how good the line balancing solution is. A perfect line balance yields a value of E_b = 1.00. Typical line balancing efficiencies in industry range between 0.90 and 0.95.

The complement of balance efficiency is ***balance delay***, which indicates the amount of time lost due to imperfect balancing as a ratio to the total time available; that is,

$$d = \frac{(wT_s - T_{wc})}{wT_s} \tag{4.17}$$

where d = balance delay; and the other terms have the same meaning as before. A balance delay of zero indicates perfect balance. Note that $E_b + d = 1$.

Worker Requirements. In our discussion of the assembly line relationships, we have identified three factors that reduce the productivity of a manual assembly line. They can all be expressed as efficiencies:

1. *Line efficiency*, the proportion of uptime on line E, as defined in equation (4.6).
2. *Repositioning efficiency*, E_r, as defined in equation (4.12).
3. *Balancing efficiency*, E_b, as defined in equation (4.16).

Together, they constitute the overall labor efficiency on the assembly line, defined as

$$\text{Labor efficiency on the assembly line} = EE_rE_b \tag{4.18}$$

Using this measure of labor efficiency, we can calculate a more realistic value for the number of workers on the assembly line, based on equation (4.9):

$$w = \text{Minimum Integer} \geq \frac{R_pT_{wc}}{60EE_rE_b} = \frac{T_{wc}}{E_rE_bT_c} = \frac{T_{wc}}{E_bT_s} \tag{4.19}$$

where w = number of workers required on the line; R_p = hourly production rate, units/hr; T_{wc} = work content time per product to be accomplished on the line, min/unit. The trouble with this relationship is that it is difficult to determine values for E, E_r, and E_b before the line is built and operated. Nevertheless, the equation provides an accurate model of the parameters that affect the number of workers required to accomplish a given workload on a single model assembly line.

4.2.3 Workstation Considerations

Let us attach a quantitative definition to some of the assembly line parameters discussed in Section 4.1.1. 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 stations (M_i = 1.0 for $i = 1, 2, \ldots, n$) then the number of stations is equal to the number of workers. In general, for any value of M for the line,

$$n = \frac{w}{M} \tag{4.20}$$

A workstation has a length dimension L_{si}, where i denotes station i. The total length of the assembly line is the sum of the station lengths:

$$L = \sum_{i=1}^{n} L_{si} \tag{4.21}$$

where L = length of the assembly line, m (ft); and L_{si} = length of station i, m (ft). In the case when all L_{si} are equal,

$$L = nL_s \tag{4.22}$$

where L_s = station length, m (ft).

A common transport system used on manual assembly lines is a constant speed conveyor. Let us consider this case in developing the following relationships. Base parts are launched onto the beginning of the line at constant time intervals equal to the cycle time T_c. This provides a constant feed rate of base parts, and if the base parts remain fixed to the conveyor during their assembly, this feed rate will be maintained throughout the line. The feed rate is simply the reciprocal of the cycle time:

$$f_p = \frac{1}{T_c} \tag{4.23}$$

where f_p = feed rate on the line, products/min. A constant feed rate on a constant speed conveyor provides a center-to-center distance between base parts given by

$$s_p = \frac{v_c}{f_p} = v_c T_c \tag{4.24}$$

where s_p = center-to-center spacing between base parts, m/part (ft/part); and v_c = velocity of the conveyor, m/min (ft/min).

In general, it is desirable to allow a worker more time to complete the assigned task than what is provided by the cycle time, so that if a particular work unit takes longer than the average, the worker can still complete the task. In the long run, the worker must keep pace with the cycle time, but he or she may fall behind for an individual work unit. Achieving this time allowance is called ***pacing with margin***, a desirable way to operate the line so as to achieve the desired production rate and at the same time provide for some product-to-product variation in task times at workstations. One way to achieve pacing with margin in a continuous transport system is to provide a tolerance time that is greater than the cycle time. ***Tolerance time*** is defined as the time a work unit spends inside the boundaries of the workstation. It is determined by the length of the station and the conveyor velocity, as follows:

$$T_t = \frac{L_s}{v_c} \tag{4.25}$$

where T_t = tolerance time, min/part, assuming that all station lengths are equal. If stations have different lengths, identified by L_{si}, then the tolerance times will differ proportionally, since v_c is constant. Thus, providing a tolerance time greater than the cycle time is achieved by making the station length greater than the distance traveled by a work unit during T_c.

The total elapsed time a work unit spends on the assembly line can be determined simply as the length of the line divided by the conveyor velocity. It is also equal to the tolerance time multiplied by the number of stations. Expressing these relationships in equation form, we have

$$ET = \frac{L}{v_c} = nT_t \tag{4.26}$$

where ET = elapsed time a work unit (specifically, the base part) spends on the conveyor during its assembly, min.

4.3 LINE BALANCING ALGORITHMS

The objective in line balancing is to distribute the total workload on the assembly line as evenly as possible among the workers. This objective can be expressed mathematically in two alternative but equivalent forms:

$$\text{Minimize } (wT_s - T_{wc}) \quad \text{or} \quad \text{Minimize } \sum_{i=1}^{w}(T_s - T_{si}) \tag{4.27}$$

subject to: (1) $\sum_{k \in i} T_{ek} \leq T_s$ and (2) all precedence requirements are obeyed.

In this section we consider several algorithms to solve the line balancing problem, using the data of Example 4.1 to illustrate (1) the largest candidate rule, (2) the Kilbridge and Wester method, and (3) the ranked positional weights method. These methods are heuristic, meaning they are based on common sense and experimentation rather than mathematical optimization. In each of the algorithms, we assume that the manning level

TABLE 4.4 Work Elements Arranged According to T_{ek} Value for the Largest Candidate Rule

Work Element	T_{ek} (min)	Preceded by
3	0.7	1
8	0.6	3,4
11	0.5	9,10
2	0.4	—
10	0.38	5,8
7	0.32	3
5	0.3	2
9	0.27	6,7,8
1	0.2	—
12	0.12	11
6	0.11	3
4	0.1	1,2

is one, so when we identify station i, we are also identifying the worker at station i. Computer programs based on these and other algorithms have been written to solve large-scale assembly line problems.

4.3.1 Largest Candidate Rule

According to the largest candidate rule, work elements are arranged in descending order based on their T_{ek} values, as in Table 4.4. Given this list, the algorithm consists of the following steps:

1. Assign elements to the worker at the first workstation by starting at the top of the list and selecting the first element that satisfies precedence requirements and does not cause the total sum of T_{ek} at that station to exceed the allowable T_s; when an element is selected for assignment to the station, start back at the top of the list for subsequent assignments.
2. When no more elements can be assigned without exceeding T_s, then proceed to the next station.
3. Repeat steps 1 and 2 for the other stations in turn until all elements have been assigned.

Example 4.2 Largest Candidate Rule

Apply the largest candidate rule to the problem in Example 4.1.

Solution: Work elements are arranged in descending order in Table 4.4, and the algorithm is carried out as presented in Table 4.5. Five workers and stations are required in the solution. Balance efficiency is computed as:

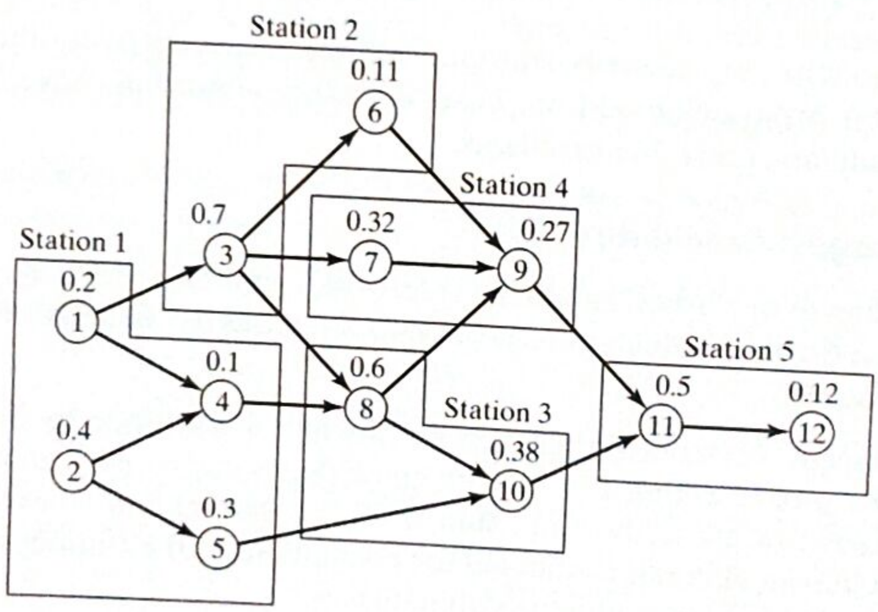
$$E_b = \frac{4.0}{5(1.0)} = 0.80$$

Balance delay $d = 0.20$. The line balancing solution is presented in Figure 4.4.

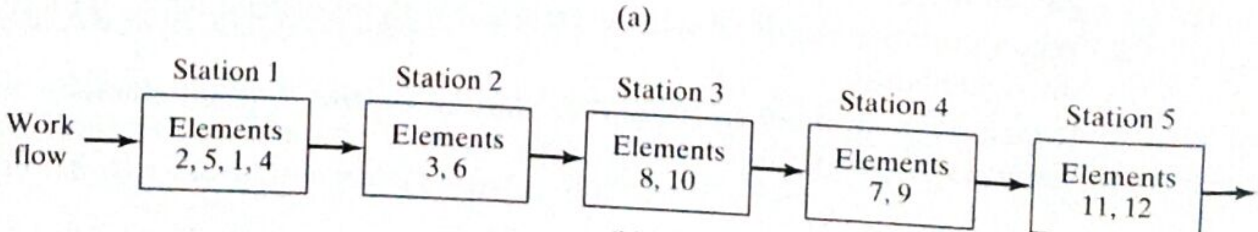
$d = \frac{wT_s - T_{wc}}{wT_s}$

TABLE 4.5 Work Elements Assigned to Stations According to the Largest Candidate Rule

Station	Work Element	T_{ek} (min)	Station Time (min)
1	2	0.4	
	5	0.3	
	1	0.2	
	4	0.1	1.0
2	3	0.7	
	6	0.11	0.81
3	8	0.6	
	10	0.38	0.98
4	7	0.32	
	9	0.27	0.59
5	11	0.5	
	12	0.12	0.62



(a)



(b)

Figure 4.4 Solution for Example 4.2, which indicates (a) assignment of elements according to the largest candidate rule, and (b) physical sequence of stations with assigned work elements. ■

4.3.2 Kilbridge and Wester Method

The Kilbridge and Wester method [3] has received considerable attention since its introduction in 1961, and it has been applied with apparent success to several complicated line balancing problems in industry [4]. It is a heuristic procedure that selects work

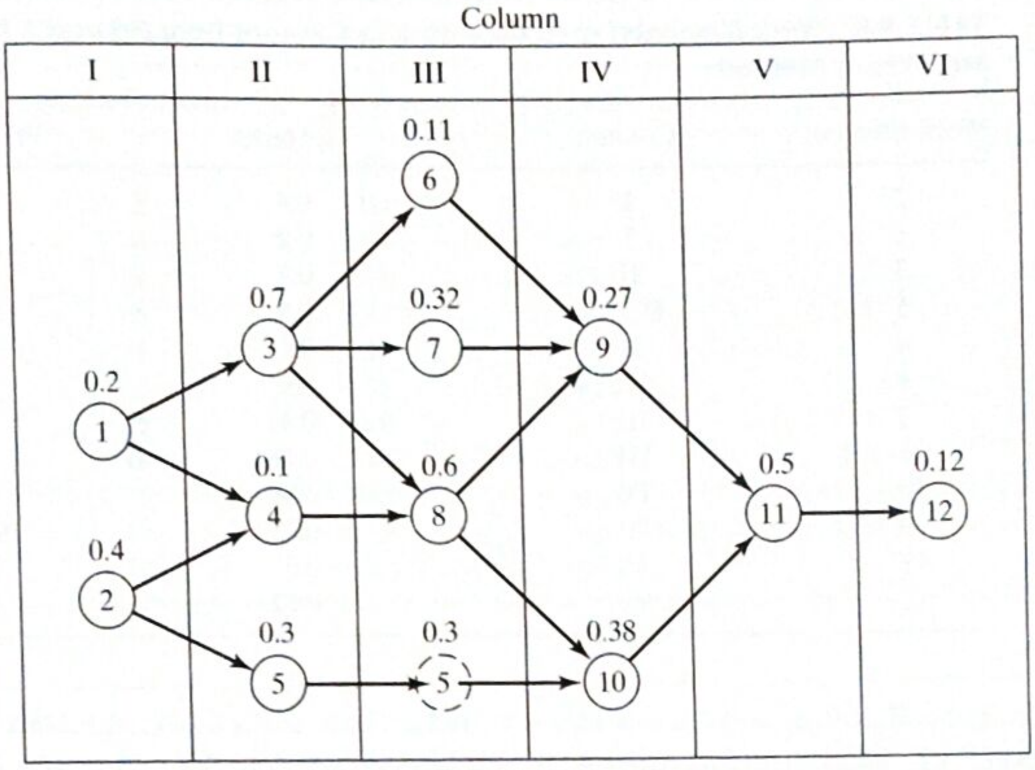


Figure 4.5 Work elements in example problem arranged into columns for the Kilbridge and Wester method.

elements for assignment to stations according to their position in the precedence diagram. This overcomes one of the difficulties with the largest candidate rule in which an element may be selected because of a high T_e value but irrespective of its position in the precedence diagram. In general, the Kilbridge and Wester method provides a superior line balance solution than the largest candidate rule (although this is not the case for our example problem).

In the Kilbridge and Wester method, work elements in the precedence diagram are arranged into columns, as shown in Figure 4.5. The elements can then be organized into a list according to their columns, with the elements in the first column listed first. We have developed such a list of elements for our example problem in Table 4.6. If a given element can be located in more than one column, then list all of the columns for that element, as we have done in the case of element 5. In our list, we have added the feature that elements in a given column are presented in the order of their T_{ek} value; that is, we have applied the largest candidate rule within each column. This is helpful when assigning elements to stations, because it ensures that the larger elements are selected first, thus increasing our chances of making the sum of T_{ek} in each station closer to the allowable T_s limit. Once the list is established, the same three-step procedure is used as before.

Example 4.3 Kilbridge and Wester method

Apply the Kilbridge and Wester method to the problem in Example 4.1.

Solution: Work elements are arranged in order of columns shown in Table 4.6. The Kilbridge and Wester solution is presented in Table 4.7. Five workers are again required and the balance efficiency is once more $E_b = 0.80$. Note that although the balance efficiency is the same as in the largest candidate rule, the allocation of work elements to stations is different.

TABLE 4.6 Work Elements Listed According to Columns from Figure 4.5 for the Kilbridge and Wester Method

Work Element	Column	T_{ek} (min)	Preceded by
2	I	0.4	—
1	I	0.2	—
3	II	0.7	1
5	II, III	0.3	2
4	II	0.1	1, 2
8	III	0.6	3,4
7	III	0.32	3
6	III	0.11	3
10	IV	0.38	5,8
9	IV	0.27	6, 7, 8
11	V	0.5	9, 10
12	VI	0.12	11

TABLE 4.7 Work Elements Assigned to Stations According to the Kilbridge and Wester Method

Station	Work Element	Column	T_{ek} (min)	Station Time (min)
1	2	I	0.4	
	1	I	0.2	
	5	II	0.3	
	4	II	0.1	1.0
2	3	II	0.7	
	6	III	0.11	0.81
3	8	III	0.6	
	7	III	0.32	0.92
4	10	IV	0.38	
	9	IV	0.27	0.65
5	11	V	0.5	
	12	VI	0.12	0.62

■

4.3.3 Ranked Positional Weights Method

The ranked positional weights method was introduced by Helgeson and Birne [2], and it is sometimes identified by their names. In this method, a ranked positional weight value (call it *RPW* for short) is computed for each element. The *RPW* takes into account both the T_{ek} value and its position in the precedence diagram. Specifically, RPW_k is calculated by summing T_{ek} and all other times for elements that follow T_{ek} in the arrow chain of the precedence diagram. Elements are compiled into a list according to their *RPW* value, and the algorithm proceeds using the same three steps as before.

Example 4.4 Ranked Positional Weights Method

Apply the ranked positional weights method to the problem in Example 4.1.

TABLE 4.8 Elements and Their Ranked Positional Weight (*RPW*)

Work Element	*RPW*	T_{ek} (min)	Preceded by
1	3.30	0.2	—
3	3.00	0.7	1
2	2.67	0.4	—
4	1.97	0.1	1, 2
8	1.87	0.6	3, 4
5	1.30	0.3	2
7	1.21	0.32	3
6	1.00	0.11	3
10	1.00	0.38	5, 8
9	0.89	0.27	6, 7, 8
11	0.62	0.5	9, 10
12	0.12	0.12	11

TABLE 4.9 Work Elements Assigned to Stations According to *RPW* Method

Station	Work Element	T_{ek} (min)	Station Time (min)
1	1	0.2	
	3	0.7	0.90
2	2	0.4	
	4	0.1	
	5	0.3	
	6	0.11	0.91
3	8	0.6	
	7	0.32	0.92
4	10	0.38	
	9	0.27	0.65
5	11	0.5	
	12	0.12	0.62

Solution: The *RPW* must be calculated for each element. To illustrate,

$$RPW_{11} = 0.5 + 0.12 = 0.62$$

$$RPW_8 = 0.6 + 0.27 + 0.38 + 0.5 + 0.12 = 1.87$$

Work elements are listed according to *RPW* value in Table 4.8. Assignment of elements to stations proceeds with the solution presented in Table 4.9. Note that the largest T_s value is 0.92 min. This can be exploited by operating the line at this faster rate, with the result that line balance efficiency is improved and the production rate is increased.

$$E_b = \frac{4.0}{5(.92)} = 0.87$$

The cycle time is $T_c = T_s + T_r = 0.92 + 0.08 = 1.00$; therefore,

$R_c = \dfrac{60}{1.0} = 60$ cycles/hr, and from equation (4.6), $R_p = 60 \times 0.96 = 57.6$ units/hr ■

This is a better solution than the previous line balancing methods provided. It turns out that the performance of a given line balancing algorithm depends on the problem to be solved. Some line balancing methods work better on some problems, while other methods work better on other problems.

4.4 OTHER CONSIDERATIONS IN ASSEMBLY LINE DESIGN

The line balancing algorithms described in Section 4.3 are precise computational procedures that allocate work elements to stations based on deterministic quantitative data. However, there may be other opportunities for improvement in the design and operation of a manual assembly line, some of which may increase line performance beyond what the balancing algorithms provide. Some of the considerations are as follows:

- *Methods analysis.* Methods analysis (Part II of the book) involves the study of human work activity to seek out ways in which the activity can be done with less effort, in less time, and with greater effect. This analysis is an obvious step in the design of a manual assembly line, since the work elements need to be defined in order to balance the line. In addition, methods analysis can be used after the line is running to examine workstations that are bottlenecks. The analysis may result in improved hand and body motions, better workplace layout, design of special tools to facilitate manual work elements, or even changes in the product design for easier assembly.
- *Utility workers.* We have previously mentioned utility workers in our discussion of manning levels. Utility workers can be used to relieve congestion at stations that are temporarily overloaded.
- *Preassembly of components.* To reduce the total amount of work done on the regular assembly line, certain subassemblies can be prepared off-line, either by another assembly cell in the plant or by purchasing them from an outside vendor that specializes in the type of processes required. Although it may seem like simply a means of moving the work from one location to another, there are some good reasons for organizing assembly operations in this manner: (1) the required process may be difficult to implement on the regular assembly line, (2) task time variability (e.g., for adjustments or fitting) for the associated assembly operations may result in a longer overall cycle time if done on the regular line, and (3) an assembly cell set up in the plant or a vendor with certain special capabilities to perform the work may be able to achieve higher quality.
- *Storage buffers between stations.* A storage buffer is a location in the production line where work units are temporarily stored. There are several reasons to include one or more storage buffers in a production line: (1) to accumulate work units between two stages of the line when their production rates are different; (2) to smooth production between stations with large task time variations; and (3) to permit continued operation of certain sections of the line when other sections are temporarily down for service or repair. The use of storage buffers generally improves the performance of the line operation.
- *Parallel workstations.* Parallel stations are sometimes used to balance a production line. Their most obvious application is where a particular station has an unusually

long task time that would cause the production rate of the line to be less than required to satisfy product demand. In this case, two stations operating in parallel with both performing the same long task may eliminate the bottleneck.

4.5 ALTERNATIVE ASSEMBLY SYSTEMS

The well-defined pace of a manual assembly line has merit from the viewpoint of maximizing production rate. However, assembly line workers often complain about the monotony of the repetitive tasks they must perform and the unrelenting pace they must maintain when a moving conveyor is used. Poor quality workmanship, sabotage of the line equipment, and other problems have occurred on high production assembly lines. To address these issues, alternative assembly systems are available in which either the work is made less monotonous and repetitious by enlarging the scope of the tasks performed, or the work is automated. The alternative work systems include (1) single-station manual assembly cells, and (2) assembly cells based on worker teams.

A ***single-station manual assembly cell*** consists of a single workplace in which the assembly work is accomplished on the product or on some major subassembly of the product. This method is generally used on products that are complex and produced in small quantities, sometimes one-of-a-kind. The workplace may utilize one or more workers, depending on the size of the product and the required production rate. Custom-engineered products such as machine tools, industrial equipment, and prototype models of complex products (e.g., aircraft, appliances, cars) make use of a single manual station to perform the assembly work on the product.

Assembly by worker teams (Section 3.4.3) involves the use of multiple workers assigned to a common assembly task. The pace of the work is controlled largely by the workers themselves rather than by a pacing mechanism such as a powered conveyor moving at a constant speed. Team assembly can be implemented in several ways. A single-station manual assembly cell in which there are multiple workers is a form of worker team. The assembly tasks performed by each worker are generally less repetitious and broader in scope than the corresponding work on an assembly line.

Reported benefits of worker team assembly systems compared to conventional assembly line include greater worker satisfaction, better product quality, increased capability to accommodate model variations, and greater ability to cope with problems that require more time rather than stopping the entire production line. The principal disadvantage is that these team systems are not capable of the high production rates characteristic of a conventional assembly line.

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REVIEW QUESTIONS

4.1 What is a manual assembly line?

4.2 What are the factors that favor the use of manual assembly lines?

4.3 What are the reasons why manual assembly lines are so productive compared to alternative methods of assembly?

4.4 What does the term *manning level* mean in the context of a manual assembly line?

4.5 What are utility workers on a manual assembly line?

4.6 What is *starving* on a manual assembly line?

4.7 What is *blocking* on a manual assembly line?

4.8 What are the three major categories of work transport in mechanized production lines?

4.9 What are the two types of line that can be designed to cope with product variety? What is the difference between them?

4.10 What does *work content time* mean?

4.11 What are repositioning losses as they are explained in the text?

4.12 What is the line balancing problem in the design of a manual assembly line?

4.13 What is a minimum rational work element in the context of manual assembly lines?

4.14 What is a precedence constraint in the context of manual assembly lines?

4.15 What are the three types of efficiency that must be considered in designing and operating a manual assembly line?

4.16 What does *tolerance time* mean?

4.17 Name the three line balancing algorithms described in the text.

4.18 What are some of the methods by which assembly line balancing efficiency can be improved that are outside the scope of the line balancing algorithms?

PROBLEMS

Manual Assembly Lines

4.1 Determine (a) the required hourly production rate and (b) the cycle time for a manual assembly line that will be used to produce a product with a work content time of 75 min and an annual demand of 150,000 units, if the plant operates 50 wk/yr, 5 days/wk, and 8 hr/day. It is anticipated that the line efficiency will be 94%.

4.2 A manual assembly line has 25 workstations and the manning level is 1.0. The work content time to assemble the product is 29.5 min. Production rate of the line is 40 units/hr. The proportion uptime is 96% and the repositioning time is 9 sec. Determine the balance delay on the line.

4.3 A manual assembly line is being planned for an assembled product whose work content time is 47.2 min. The line will be operated 2000 hr/yr. The annual demand anticipated for the product is 100,000 units. Based on previous assembly lines used by the company, the proportion of uptime on the line is expected to be 94%, the line balancing efficiency will be 92%, and the repositioning time lost each cycle will be 6 sec. The line will be designed with 1 worker/station. Determine (a) the required hourly production rate of the line, (b) the cycle time, (c) the ideal minimum number of workers required, and (d) the actual number of workers required based on the efficiencies given.

4.4 A manual assembly line is being planned for an assembled product whose annual demand is expected to be 175,000 units/yr. The line will be operated two shifts (4000 hr/yr). Work content time of the product is 53.7 min. For planning purposes, the following line parameter values will be used: uptime efficiency = 96%, balancing efficiency = 94%, and repositioning time = 8 sec. Determine (a) the required hourly production rate of the line, (b) the cycle time, (c) the ideal minimum number of workers required, and (d) the actual number of workers required based on the efficiencies given.

4.5 The required production rate for a certain product is 45 units/hr. Its work content time is 71.5 min. The production line for this product includes 5 automated workstations. Because the automated stations are not entirely reliable, the overall line efficiency is expected to be only 88%. All of the other stations will have one worker each. It is anticipated that 6% of each cycle will be lost due to worker repositioning. Balance delay is expected to be 7%. 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.

✓ **4.6** A manual assembly line is being designed for a product whose annual demand is 100,000 units. The line will operate 50 wk/yr, 5 shifts/wk, and 8 hr/shift. Work units will be attached to a continuously moving conveyor. Work content time is 42.0 min. Assume line efficiency is 0.95, balancing efficiency is 0.93 or slightly less, repositioning time is 6 sec, and manning level is 1.4. Determine (a) average hourly production rate to meet demand and (b) number of workers required. (c) If each station on the line is 3 m long, what is the total length of the assembly line?

✓ **4.7** The work content for a product assembled on a manual production line is 48 min. The work is transported using a continuous overhead conveyor that operates at a speed of 5 ft/min. There are 24 workstations on the line, one-third of which have two workers; the remaining stations each have one worker. Repositioning time per worker is 9 sec, and uptime efficiency of the line is 95%. (a) What is the maximum possible hourly production rate if the line is assumed to be perfectly balanced? (b) If the actual production rate is only 92% of the maximum possible rate determined in part (a), what is the balance delay on the line? (c) If the line is designed so that the tolerance time is 1.3 times the cycle time, what is the total length of the production line? (d) What is the elapsed time a product spends on the line?

4.8 A manual assembly line must be designed for a product with annual demand of 150,000 units. The line will operate 50 wk/yr, 10 shifts/wk, and 7.5 hr/shift. Work units will be attached to a continuously moving conveyor. Work content time is 58.0 min. Assume line efficiency is 0.95, balancing efficiency is 0.93, and repositioning time is 8 sec. Determine (a) hourly production rate to meet demand, and (b) number of workers required.

✓ **4.9** The total work content for a product assembled on a manual production line is 33.0 min, and the production rate of the line must be 47 units/hr. Work units are attached to a moving conveyor whose speed is 7.5 ft/min. Repositioning time per worker is 6 sec, and uptime efficiency of the line is 94%. Owing to imperfect line balancing, the number of workers needed on the line must be two more workers than the number required for perfect balance. Assume the manning level is 1.6. (a) How many workers are required on the line? (b) How many workstations will be in the line? (c) What is the balance delay for this line? (d) If the workstations are arranged in a line, and the length of each station is 11 ft, what is the tolerance time in each station? (e) What is the elapsed time a work unit spends on the line?

✓ **4.10** The production rate for a certain assembled product is 45 units/hr. The total assembly work content time is 33 min of direct manual labor. The line operates at 95% uptime. Ten workstations have two workers on opposite sides of the line so that both sides of the product can be worked on simultaneously. The remaining stations have one worker. Repositioning time lost by each worker is 10 sec/cycle. It is known that the number of workers on the line is three more than the number required for perfect balance. Determine (a) number of workers, (b) number of workstations, (c) the balance delay, and (d) manning level.

4.11 A powered overhead conveyor is used to carry washing machine base parts along a manual assembly line. The spacing between base parts is 2.5 m and the speed of the conveyor is 1.2 m/min. The length of each workstation is 3.1 m. The line has 30 stations and 42 workers. Determine (a) cycle time, (b) feed rate, (c) tolerance time, and (d) elapsed time a washing machine base part spends on the line.

✓ **4.12** An automobile final assembly plant is being planned for an annual production of 150,000 cars. The plant will operate one shift, 250 days per year, but the duration of the shift (hr/shift) is to be determined. The plant will be divided into three departments: (1) body shop, (2) paint shop, and (c) general assembly. The body shop welds the car bodies, and the paint shop coats the welded car bodies. Both of these departments are highly automated. The general assembly department has no automation, but a moving conveyor is used to transport the cars through the manual workstations. A total of 14.0 hours of direct labor (work content time) are accomplished in general assembly. Based on previous lines installed by the company, it is anticipated that the following design parameters will apply to the general assembly department: line efficiency = 95%, balance efficiency = 94%, repositioning time = 0.10 min, and manning level = 2.5. If the plant must produce 60 cars per hour, determine the following for the general assembly department: (a) number of hours the shift must operate, (b) number of workers required, and (c) number of workstations.

4.13 In the previous problem, each workstation in the general assembly department will be 6.0 m long, and the tolerance time will be equal to the cycle time. Determine (a) speed of the moving conveyor, (b) center-to-center spacing of car bodies on the line, (c) total length of the line in general assembly, and (d) elapsed time a work unit spends in the department.

✓ **4.14** The production rate for a certain assembled product is 48 units/hr. The assembly work content time is 36.3 min of direct labor. Twelve of the workstations have two workers on opposite sides of the product, and the remaining stations have one worker each. Repositioning time lost per cycle is 0.10 min. The uptime efficiency of the line is 96%. It is known that the number of workers on the line is three more than the number required for perfect balance. Determine (a) number of workers, (b) number of workstations, (c) balance efficiency, (d) average manning level, and (e) overall labor efficiency on the line.

✓ **4.15** The work content time for an appliance product on a manual production line is 90.4 min. The required production rate is 45 units/hr. Work units are attached to a moving overhead conveyor whose speed is 2.5 m/min. Repositioning time per cycle is 9 sec, uptime efficiency is 96%, and manning level is 1.4. Because of imperfect line balancing, the number of workers needed on the line will be 5% more than the number required for perfect balance. The workstations are arranged in one long straight line, and the length of each station is 3.6 m. Determine (a) balance efficiency, (b) total length of the line, and (c) elapsed time a unit spends on the line.

Assembly Line Balancing

4.16 The letters in the table below represent work elements in an assembly precedence diagram. (a) Construct the precedence diagram and (b) determine the total work content time. (c) Use the largest candidate rule to assign work elements to stations using a service time (T_s) of 1.5 min, and (d) compute the balance delay for your solution.

Work element or tasks	A	B	C	D	E	F	G	H	I	J
Time (min)	0.5	0.3	0.8	1.1	0.6	0.2	0.7	1.0	0.9	0.4
Preceding	—	A	A	A	B, C	D	E	F	F	G, H, I

4.17 Solve the previous problem but use the Kilbridge and Wester method in part (c).

4.18 Solve the previous problem but use the ranked positional weights method in part (c).

✓ **4.19** The table below defines the precedence relationships and element times for a new assembled product. (a) Construct the precedence diagram for this job. (b) If the ideal cycle time is 1.1 min and the repositioning time is 0.1 min, what is the theoretical minimum number of workstations required to minimize the balance delay under the assumption that there will be one worker per station? (c) Using the largest candidate rule, assign work elements to stations. (d) Compute the balance delay for your solution.

Work Element	T_e (min)	Immediate Predecessors
1	0.5	—
2	0.3	1
3	0.8	1
4	0.2	2
5	0.1	2
6	0.6	3
7	0.4	4, 5
8	0.5	3, 5
9	0.3	7, 8
10	0.6	6, 9

✓ **4.20** Solve the previous problem but use the Kilbridge and Wester method in part (c).

✓ **4.21** Solve the previous problem but use the ranked positional weights method in part (c).

✓ **4.22** The table below lists the work elements (in minutes) to be performed on an assembly line and the precedence requirements that must be satisfied. Annual demand for the product will be 60,000 units. The line will operate one shift (2000 hr/yr). Expected line efficiency (proportion uptime) is 95%. Repositioning time per cycle is 6 sec. Manning level is 1.0 for all stations. The products will be moved through the line by conveyor at a speed of 4 ft/min. All stations are of equal length, which is 10 ft. Determine (a) theoretical minimum number of workers, (b) actual number of workers, based on previous experience with similar lines in which the highest possible balance efficiency is 93%, (c) tolerance time, and (d) elapsed time a product spends on the line from when it is first launched at the front of the first station until it is finally removed after the last station. (e) Construct the precedence diagram and (f) solve the line balancing problem using the Kilbridge and Wester method.

Work element	1	2	3	4	5	6	7	8	9	10	11	12	13
Time (min)	0.5	0.3	0.8	1.1	0.6	0.2	0.7	1.0	1.2	0.4	0.9	0.1	1.3
Preceded by	—	—	1	1, 2	2	3	4	5	5	6	7	8, 9	10, 11, 12

✗ **4.23** A manual assembly line is being planned to produce a small consumer appliance. The work elements, element times, and precedence constraints are indicated in the table below. The workers will work for 420 min/shift and must produce 350 units/day. A mechanized conveyor, moving at a speed of 1.4 m/min will transport work units through stations. Manning level is 1.0, and repositioning time is 0.1 min. Because worker service time at each station is variable, it has been decided to use a tolerance time that is 1.5 times the cycle time. (a) Determine the ideal minimum number of workers. (b) Use the largest candidate rule to solve the line balancing problem. (c) For your line balancing solution, compute the balancing efficiency. Determine (d) spacing between work units on the line and (e) required length of each workstation to satisfy the specifications of the line.

Work Element	T_e (min)	Immediate Predecessors
1	0.4	—
2	0.5	1
3	0.2	1
4	0.6	—
5	0.25	2
6	0.3	3
7	0.37	4
8	0.15	4
9	0.41	5
10	0.2	6, 7
11	0.3	8
12	0.33	9, 10
13	0.4	11
14	0.62	12, 13

4.24 Solve the previous problem but use the Kilbridge and Wester method in part (b).

4.25 Solve the previous problem but use the ranked positional weights method in part (b).