Chapter 2

Manual Work and Worker–Machine Systems

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others

Part I consists of six chapters that describe the various types of work systems used in production, services, offices, projects, and other work situations. All of these work systems utilize the physical and mental capabilities of humans. In terms of the human participation in the tasks performed, work systems can be classified into the three basic categories depicted in Figure 2.1: (a) manual work systems, (b) worker–machine systems, and (c) automated systems. A ***manual work system*** consists of a worker performing one or more tasks without the aid of powered tools. The tasks commonly require the use of hand tools (e.g., hammers, screwdrivers, shovels). In a ***worker–machine system***, a human worker operates powered equipment (e.g., a machine tool). An ***automated work system*** is one in which a process is performed by a machine without the direct participation of a human worker.

As indicated in Figure 2.1, the work accomplished by a work system is almost always acted upon some object, called the ***work unit***. The state of the work unit is advanced in some way through the process performed on it. In production, the work may alter the geometry of a work part. In logistics, the work may involve transporting

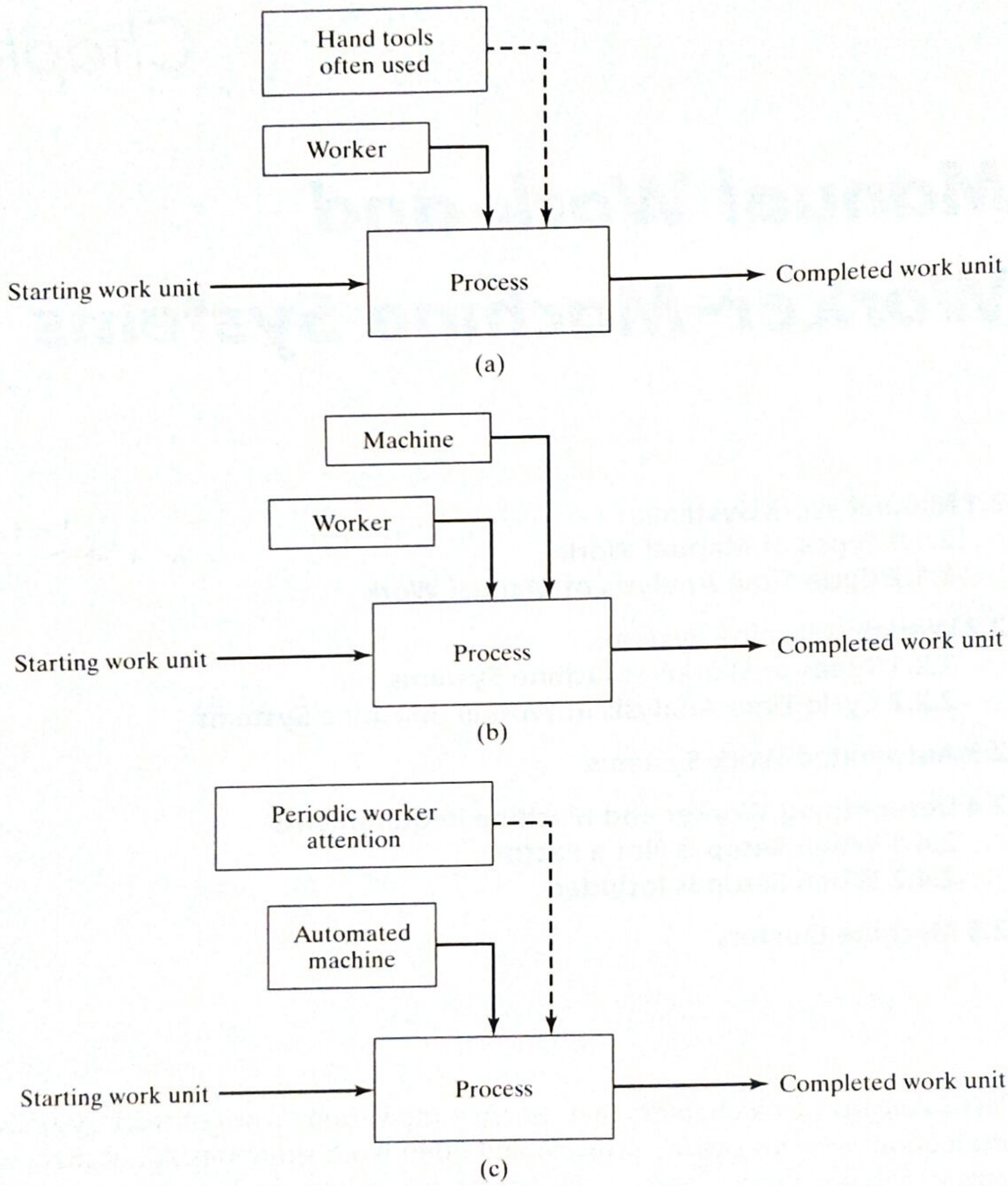

Figure 2.1 Three types of work systems: (a) manual work system, (b) worker–machine system, and (c) automated system.

material from a warehouse to a customer. In service work, a sales prospect is transformed into a paying customer by a persuasive salesperson. In knowledge work, a designer takes a product concept and converts it into specifications and engineering drawings.

In Chapter 2, we discuss the three categories of work systems. These systems are associated mostly with work that is performed by production and logistics workers (Section 1.3, Table 1.4). The emphasis in our coverage is on ***unit operations***—tasks and processes that are treated as being independent of other work activities in a given facility or work site. In Chapter 3 we examine sequential operations. A sequence of operations is usually required to manufacture a product, deliver a service, or process information. We also consider batch processing in Chapter 3, which is a common way of organizing work.

2.1 MANUAL WORK SYSTEMS

Manual work is the most basic form of work, engaging the human body to accomplish some physical task without an external source of power. Hand tools are often used to facilitate the task, but the power to operate them derives from the strength and stamina of a human worker. With or without hand tools, the worker must expend physical energy to accomplish the task. In addition, other human faculties are required, such as hand-eye coordination and mental effort. Our coverage of manual work includes two sections: (1) types of manual work and (2) cycle time analysis of manual work.

2.1.1 Types of Manual Work

Two forms of manual work can be distinguished: (1) pure manual work and (2) manual work using hand tools. ***Pure manual work*** involves only the physical and mental capabilities of the human worker, and no machines, tools, or other implements are employed in performing the task. Examples of pure manual work include the following:

- A material-handling worker moving cartons from the floor onto a conveyor in a warehouse
- Workers loading furniture into a moving van from a house without the use of dollies or other wheeled platforms
- A dealer at a casino table dealing cards
- An office worker filing documents in a file cabinet
- An assembly worker snap-fitting two parts together
- An assembly worker assembling two sheet metal parts with a bolt and nut by hand (tightening is done later using appropriate hand or power tools).

Note that the common characteristic in these examples is that they consist of moving things. Performing manual work without tools almost always involves the movement and handling of objects. Even assembly tasks include moving the parts in order to join them.

Manual tasks are commonly augmented by the use of hand tools. The ability to design and use tools is one of the attributes that distinguish humans from other species on earth. A ***tool*** is a device or implement for making changes to some object (e.g., the work unit), such as cutting, grinding, striking, squeezing, or other process. Instruments used for measurement are also included in the category of tools, even though no physical change in the object results directly from their use. A ***hand tool*** is a small tool that is operated by the strength and skill of the human user. When using hand tools, a ***workholder*** is sometimes employed to grasp the work unit and position it securely during processing. Examples of manual tasks involving the use of hand tools include the following:

- A machinist using a file to round the edges of a rectangular part that has just been milled
- An assembly worker using a screwdriver to tighten a screw
- A painter using a paintbrush to paint the trim around a doorway
- A sculptor using a carving knife to carve a wooden statue
- A grass-cutter using a rake to collect the grass clippings after mowing
- A quality control inspector using a micrometer to measure the diameter of a shaft
- A material-handling worker using a dolly to move cartons in a warehouse
- An office worker using a pen to handwrite entries into a ledger.

2.1.2 Cycle Time Analysis of Manual Work

Manual tasks usually consist of a work cycle that is repeated with some degree of similarity, and each cycle usually corresponds to the processing of one work unit. When a painter is hired to paint the wooden trim around the doorways in a new house, the painting cycle is repeated for each doorway. If the doorways are all the same size, and the wood trim is identical for all doors, then the painting cycle should exhibit a high degree of similarity. If there are differences in the doorways, then the painting cycles will be less similar.

If the work cycle is relatively short, and there is a high degree of similarity from one cycle to the next, we refer to the work as ***repetitive***. If the work cycle takes a long time and the cycles are not similar, the work is ***nonrepetitive***.[1] In either case, the task can be divided into work elements that consist of logical groupings of motions performed by the worker. The cycle time T_c is therefore the sum of the work element times

$$T_c = \sum_{k=1}^{n_e} T_{ek} \tag{2.1}$$

where T_{ek} = time of work element k, where k is used to identify the work elements, min; and n_e = number of work elements into which the cycle is divided. Our focus in this section is on repetitive work. Consider the following example of a pure manual task.

Example 2.1 A Repetitive Manual Task

An assembly worker performs a repetitive manual task consisting of inserting 8 plastic pegs into 8 holes in a flat wooden board. A slight interference fit is involved in each insertion. The worker holds the board in one hand and picks up the pegs from a tray with the other hand and inserts them into the holes, one peg at a time. The workplace layout is shown in Figure 2.2 (a), and the sequence of work elements is given in the table below. Can the work method be improved in order to reduce the cycle time?

[1] There is no clear boundary between repetitive and nonrepetitive work. When referring to repetitive work cycles, we usually mean a cycle time of a few minutes or less, and the motion patterns are intended to be identical for every cycle, so that cycle-to-cycle variations in time and work content tend to be random.

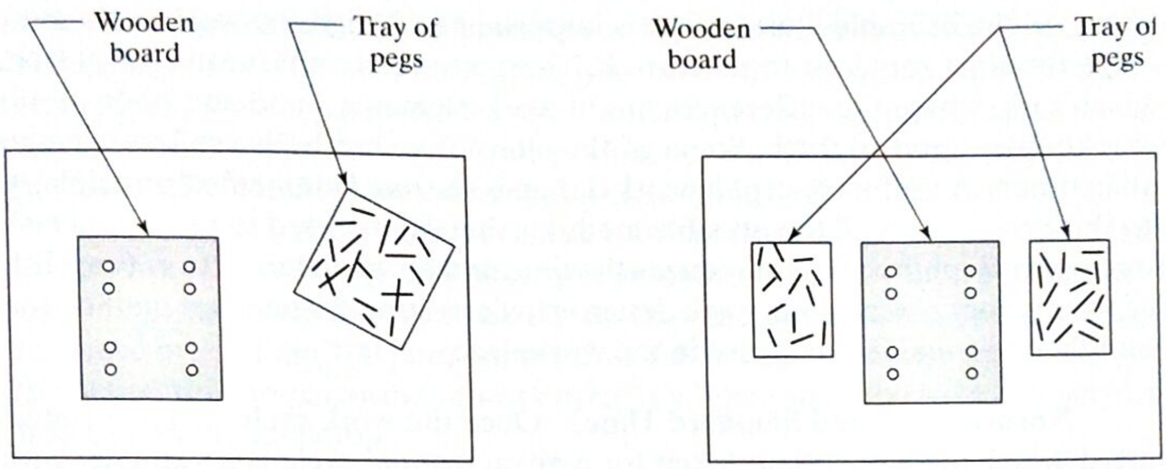

Figure 2.2 Workplace layout for assembly task in Example 2.1: (a) before methods improvement and (b) after methods improvement.

Sequence	Work Element Description	Work Element Time, T_{ek} (min)
1	Worker picks up board with one hand and holds it.	0.08
2	Worker picks peg from tray and inserts it into hole in board.	0.06
3	Worker picks second peg and inserts it into hole in board.	0.06
4	Worker picks third peg and inserts it into hole in board.	0.06
5	Worker picks fourth peg and inserts it into hole in board.	0.06
6	Worker picks fifth peg and inserts it into hole in board.	0.06
7	Worker picks sixth peg and inserts it into hole in board.	0.06
8	Worker picks seventh peg and inserts it into hole in board.	0.06
9	Worker picks eighth peg and inserts it into hole in board.	0.06
10	Worker lays assembled board into tote pan.	0.06
Total work cycle time		0.62

Solution: An opportunity for improvement lies in using a work-holding device to hold and position the board while the worker uses both hands simultaneously to insert the pegs. Two trays filled with pegs will be used, one for each hand. Instead of picking the pegs out of the tray one peg at a time, each hand will grab four pegs in order to minimize the number of times the worker's hands must reach to the trays. The revised workplace layout is shown in Figure 2.2 (b), and the revised sequence of work elements is presented in the table below. The cycle time is reduced from 0.62 min to 0.37 min, a reduction of 40%, which corresponds to an increase in production rate of almost 68%.

Sequence	Work Element Description	Work Element Time, T_{ek} (min)
1	Worker picks up board and positions it in workholder.	0.12
2	Worker picks 4 pegs each with both hands from 2 trays and inserts them into 8 holes in board.	0.15
3	Worker removes board from workholder and places in tote pan.	0.10
Total work cycle time		0.37

■

As the example illustrates, it is important to design the work cycle so as to minimize the time required to perform it. There are many alternative ways to perform a given task, where the differences are in work elements, hand and body motions, tools, workholders, and so forth. Some of the alternative methods are less time-consuming than others. A useful concept in work design is the ***one best method*** principle. According to this principle, of all the possible methods that can be used to perform a task, there is one optimal method that minimizes the time and effort required to accomplish it.[2] One of the primary objectives in work design is to determine the one best method for the task, and then to standardize its use in the workplace.

Normal Time and Standard Time. Once the work cycle and associated method are defined, the actual time taken for a given manual cycle is a variable. Variability is inherent in any repetitive human activity, and this variability is manifested in the time to perform the activity. Reasons for variations in work cycle times include the following:

- Differences in worker performance from one cycle to the next
- Variations in hand and body motions
- Worker blunders and bungles
- Variations in the starting work units
- Inclusion of extra elements that are not performed every cycle
- Differences in the physical and cognitive attributes among workers performing the task
- Variations in the methods used by different workers to perform the task
- The learning curve phenomenon (Chapter 19).

Topping the list is worker ***performance***, which can be defined simply as the pace or relative speed with which the worker does the task. As worker performance increases, the time to accomplish the work cycle decreases. From the employer's viewpoint, it is desirable for the worker to work at a high level of performance. The question is: what is a reasonable performance or pace to expect from a worker in accomplishing a given task? To answer the question, let us introduce the concept of normal performance. ***Normal performance*** (or ***normal pace***) means a pace of working that can be maintained by a properly trained average worker throughout an entire work shift without deleterious short-term or long-term effects on the worker's health or physical well-being. The work shift is usually assumed to be eight hours, during which periodic rest breaks are allowed. Normal performance refers to the pace of the worker while actually working. When a worker works at a normal performance level, we say he or she is working at 100% performance. A faster pace than normal is greater than 100% and a slower pace is less than 100%. A common benchmark of normal performance is walking on level ground at three miles per hour.

The term ***standard performance*** is often used in place of normal performance. They both refer to the same pace while working, but standard performance acknowledges that periodic rest breaks are included in the work shift. For example, a healthy human

[2]The one best method should also satisfy other criteria in addition to minimizing the work cycle time, such as ensuring a safe and convenient workplace for the worker, and producing a work unit of high quality.

can walk at a pace of three miles per hour for an hour or two. However, walking for a solid eight hours without ever stopping for a rest break would be physically wearing. Accordingly, normal performance and standard performance both mean walking three miles per hour during an eight-hour period, but the walker could stop for a rest a few times and take a lunch break during the eight hours.

When a work cycle is performed at 100% performance, the time taken is called the ***normal time*** for the cycle. If worker performance is greater than 100%, then the time required to complete the cycle will be less than the normal time; and when worker performance is less than 100 percent, the time taken will be greater than the normal time. The actual time to perform the work cycle is a function of the worker's performance as indicated in the equation

$$T_c = \frac{T_n}{P_w} \tag{2.2}$$

where T_c = actual cycle time, min; T_n = normal time for the work cycle, min; and P_w = pace or performance of the worker, expressed as a decimal fraction (e.g., 100% = 1.0).

Example 2.2 Normal Performance

A man walks in the early morning for health and fitness. His usual route is 1.85 miles long. The route has minimal elevation changes. A typical time to walk the 1.85 miles is 30 min. Using the benchmark of 3 miles/hr as normal performance, determine (a) how long the route would take at normal performance and (b) the man's performance when he completes the route in 30 min.

Solution: **(a)** At 3 miles/hr, 1.85 miles can be covered in 1.85/3.0 = 0.6167 hr or 37 min.

(b) If the man takes 30 min to complete the walk, then his performance can be determined by dividing the normal time by the actual time, by rearranging equation (2.2). Thus,

$$P_w = 37/30 = 1.233 \text{ or } 123.3\%$$

Alternative Solution: For part (b), we could determine the man's velocity and compare it to the benchmark of 3.0 miles/hr in order to determine his performance. If the man completes 1.85 miles in 30 min, then his walking velocity is 1.85 miles divided by 0.5 hr, which equals 3.7 miles/hr.

$$P_w = 3.7/3.0 = 1.233 \text{ or } 123.3\%$$

■

Workers are allowed periodic rest breaks (e.g., coffee breaks) during their work shift. A typical work shift is eight hours (e.g., 8:00 A.M. to 5:00 P.M. with an hour from noon to 1:00 P.M. for lunch). The shift usually includes a rest break in the morning and another in the afternoon. Unlike the lunch period, these rest breaks are normally included within the eight-hour time of the shift. The employer allows these breaks because it has been found that the overall productivity of the worker during the shift is greater if rest breaks are provided. More work is accomplished by the end of the day and fewer mistakes are made if the worker can take time out periodically from the normal work routine. In addition to the rest breaks, the worker is likely to have other interruptions during the shift, such as equipment breakdowns (if the manual task is somehow dependent on equipment), receiving instructions from the foreman, personal telephone calls, and so on. As a result of all of these factors, the total time actually worked during the shift will be less than the full eight hours, in all likelihood.

To account for these delays and rest breaks, an ***allowance*** is added to the normal time in order to determine an "allowed time" for the worker to perform the task throughout the shift. More commonly known as the ***standard time***, it is defined as follows:

$$T_{std} = T_n(1 + A_{pfd}) \tag{2.3}$$

where T_{std} = standard time, min; T_n = normal time, min; and A_{pfd} = allowance factor, usually expressed as a percentage but used in equation (2.3) as a decimal fraction.[3] The allowance is commonly called the personal time, fatigue, and delay allowance (abbreviated ***PFD allowance***), and it is figured in such a way that, if the worker works at 100 percent performance during the portion of the shift that he or she is working, the amount of work accomplished will be eight hours' worth.

Manual work cycles often include ***irregular work elements***, which are elements performed with a frequency of less than once per cycle. Examples of irregular work elements include periodic changing of tools (e.g., changing a knife blade) and replacing tote pans of parts when the containers become full. In determining a standard time for the cycle, the irregular element times are prorated in the regular cycle time. The following examples illustrate these concepts and definitions.

Example 2.3 Determining Standard Time and Standard Output

The normal time to perform the regular work cycle for a certain manual operation is 3.23 min. In addition, an irregular work element whose normal time is 1.25 min must be performed every 5 cycles. The PFD allowance factor is 15%. Determine (a) the standard time and (b) how many work units are produced if the worker's performance in an 8-hour shift is standard.

Solution: **(a)** The normal time for the work cycle includes the irregular element prorated according to its frequency:

$$T_n = 3.23 + \frac{1.25}{5} = 3.23 + 0.25 = 3.48 \text{ min}$$

The standard time is $T_{std} = T_n(1 + A_{pfd}) = 3.48(1 + 0.15) = 4.00$ min.

(b) The number of work units produced at standard performance in an 8-hour shift is the clock time of the shift divided by the standard time:

$$Q_{std} = \frac{8.0(60)}{4.00} = 120 \text{ work units}$$

■

[3]Allowances, standard times, and the methods by which they are determined are explained more thoroughly in Part III, which discusses time study and work measurement.

Example 2.4 Determining Lost Time Due to the Allowance Factor

Determine the anticipated amount of time lost per 8-hour shift when an allowance factor of 15% is used, as in the previous example.

Solution: Given that $A_{pfd} = 0.15$, the anticipated amount of time lost per 8-hour shift is determined as follows:

$$8.0 \text{ hr} = (\text{actual time worked})(1 + 0.15)$$

$$\text{Actual time worked} = \frac{8.0}{1.15} = 6.956 \text{ hr}$$

$$\text{Time lost} = 8.0 - 6.956 = 1.044 \text{ hr}$$

This is the anticipated daily amount of time lost due to personal time, fatigue, and delays corresponding to a 15% PFD allowance factor. ■

Example 2.5 Production Rate When Worker Performance Exceeds 100%

Now that the standard is set ($T_{std} = 4.00$ min), and given the data from the previous examples, how many work units would be produced if the worker's average performance during an 8-hour shift were 125% and the hours actually worked were exactly 6.956 hr, which corresponds to the 15% allowance factor.

Solution: Based on the normal time $T_n = 3.48$ min, the actual cycle time with a worker performance of 125% is

$$T_c = \frac{3.48}{1.25} = 2.78 \text{ min}$$

Assuming one work unit is produced each cycle, the corresponding daily production rate (symbolized by R_p) is

$$R_p = \frac{6.956(60)}{2.78} = 150 \text{ work units}$$

Note that 150 units = 125% of 120 units at 100% performance. ■

Standard Hours and Worker Efficiency. Two common measures used in industry to assess a worker's productivity are standard hours and worker efficiency. The ***standard hours*** represents the amount of work actually accomplished by the worker during a given period (e.g., shift, week), expressed in terms of time. In its simplest form, it is the quantity of work units produced during the period multiplied by the standard time per work unit; that is,

$$H_{std} = QT_{std} \tag{2.4}$$

where H_{std} = standard hours accomplished, hr; Q = quantity of work units completed during the period, pc; and T_{std} = standard time per work unit, hr/pc. If the time standard

T_{std} is expressed in min/pc, then conversion of units is required to obtain standard hours H_{std}. When a worker works at a performance level greater than 100% and his or her actual time worked during the shift is consistent with or greater than what is provided by the allowance factor, then the number of standard hours accomplished will be greater than the number of hours in the shift.

Worker efficiency is the amount of work accomplished during the shift expressed as a proportion of the shift hours. In equation form,

$$E_w = \frac{H_{std}}{H_{sh}} \tag{2.5}$$

where E_w = worker efficiency, normally expressed as a percentage; H_{std} = number of standard hours of work accomplished during the shift, hr; and H_{sh} = number of shift hours (e.g., 8 hr).

Example 2.6 Standard Hours and Worker Efficiency

For the worker performance of 125% in the previous example (T_{std} = 4.00 min), determine (a) number of standard hours produced and (b) worker efficiency.

Solution: **(a)** H_{std} = 150(4.0 min) = 600 min = 10.0 hr

(b) E_w = (10.0 hr)/(8.0 hr) = 1.25 = 125%

■

In Example 2.5 and 2.6, the worker's efficiency and performance level are equal for two reasons: (1) the number of hours actually worked is exactly consistent with the 15% allowance factor, and (2) the entire work cycle consists exclusively of manual labor and is therefore entirely operator-controlled. In the absence of either or both of these conditions, worker efficiency will not equal worker performance level (except by coincidence, when certain combinations of values offset each other). In reality, the number of hours actually worked by a worker in an 8-hour shift varies each day, depending on the amount of time lost due to personal reasons, rest breaks, and delays. Worker performance and worker efficiency are different if the time lost is different from what is accounted for by the PFD allowance factor, as the following example illustrates.

Example 2.7 Standard Hours and Worker Efficiency as Affected by Hours Actually Worked

Suppose the worker's pace in the task is 125%, but the actual hours worked is 7.42 hr. Determine (a) the number of pieces produced, (b) the number of standard hours accomplished, and (c) the worker's efficiency.

Solution: **(a)** The actual cycle time at 125% performance is 2.78 min, as calculated in Example 2.5. The number of work units produced in 7.42 hr is

$$Q = \frac{7.42(60)}{2.78} = 160 \text{ units}$$

(b) H_{std} = 160(4.0 min) = 640 min = 10.67 hr

(c) E_w = 10.67/8.0 = 1.333 = 133.3%

■

Worker efficiency is commonly used to evaluate workers in industry. In many incentive wage payment plans, the worker's earnings are based on his or her efficiency or the number of standard hours accomplished. Worker efficiency and standard hours are easily computed, because the number of hours in the shift and the standard time are known, and the number of work units produced can be readily counted. The two measures are basically equivalent, because either one can be derived from the other. One might think that worker performance would also be a useful measure; however, it is more difficult to assess because it requires data on the amount of time actually worked by the worker during the shift. This varies from day to day because the interruptions and delays vary from day to day. Some method of continuously observing the worker would be required. Aside from the cost, the worker would likely find such observation objectionable. In addition, the effect of worker performance is reduced when machine time is included in the work cycle, as we see in Section 2.2.

2.2 WORKER–MACHINE SYSTEMS

When a worker operates powered equipment, we refer to the arrangement as a ***worker–machine system***. It is one of the most widely used work systems. Worker–machine systems include combinations of one or more workers and one or more pieces of equipment. The workers and machines are combined to accomplish a desired output. Examples of worker–machine systems include the following:

- A skilled machinist operating an engine lathe in a tool room to fabricate a component (the work unit) for a custom-designed product. The machinist must exercise considerable skill in controlling the feed, speed, and tool position while operating the lathe.
- A construction worker operating a backhoe at a construction site. The worker must continuously operate the machine, using the various levers that control the different hydraulically operated mechanisms.
- A truck driver driving an 18-wheel tractor-trailer on an interstate highway. The driver must constantly be alert while operating the vehicle.
- A factory worker loading and unloading parts at a machine tool. The machine tool operates on semiautomatic cycle to process the parts. At the end of each work cycle, the worker unloads the completed part. Machine processing time is about 3 min. While the machine performs its process, the worker is idle. Loading and unloading the machine takes about 30 sec.
- A crew of workers operating a rolling mill that converts hot steel slabs into flat plates. Each worker has an assigned function. The most important job is the rolling mill operator who must coordinate the gap size (i.e., distance between opposing rolls) and the passing of the slab back and forth between the rolls. Each pass reduces the thickness of the starting slab until the specified thickness has been achieved.
- A secretary using a personal computer with word processor in an office typing pool.
- A clerical worker in a billing center entering data based on checks received by mail from customers into account records on a networked personal computer.
- An industrial engineer creating the design of a plant layout on a computer-aided design (CAD) workstation.

TABLE 2.1 Relative Strengths and Attributes of Humans and Machines

Relative Strengths of Humans	Relative Strengths of Machines
Sense unexpected stimuli	Perform repetitive tasks consistently
Develop new solutions to problems	Store large amounts of data
Cope with abstract problems	Retrieve data from memory reliably
Adapt to change	Perform multiple tasks at the same time
Generalize from observations	Apply high forces and power
Learn from experience	Perform simple computations quickly
Make difficult decisions based on incomplete data	Make routine decisions quickly

Source: [2].

Although the last three examples relate to service and knowledge work (Chapter 6) rather than production and logistics work, they also illustrate the widespread use of worker–machine systems. In these latter examples, the machine is a computer.

In a worker–machine system, the worker and the machine both contribute their own strengths and capabilities to the combination, and the result is synergistic. The relative strengths and attributes of humans and machines are presented in Table 2.1, and the worker–machine system should be designed to exploit these relative strengths.

2.2.1 Types of Worker–Machine Systems

It is instructive to distinguish the various categories and arrangements of worker–machine systems, some of which are suggested by our list of examples. In this section, we discuss the following classifications: (1) types of powered machinery used in the system, (2) numbers of workers and machines in the system, and (3) level of operator attention required to run the machinery.

Types of Powered Machinery. Powered machinery is distinguished from hand tools by the fact that a source of power other than human (or animal) strength is used to operate it. Common power sources are electric, pneumatic, hydraulic, and fossil fuel motors (e.g., gasoline, propane). In most cases, the power source is converted to mechanical energy to process the work unit. Powered machinery can be classified into three categories, summarized in Figure 2.3: (1) portable power tools, (2) mobile powered equipment, and (3) stationary powered machines.

Portable power tools are light enough in weight that they can be carried by the worker from one location to another and manipulated by hand. Examples include portable power drills, rotary saws, chain saws, and electric hedge trimmers. Common power sources are electric, pneumatic, and gasoline.

Mobile powered equipment can be divided into three categories: (1) transportation equipment, (2) transportable and mobile during operation, and (3) transportable and stationary during operation. They are generally heavy pieces of equipment and cannot be classified as power hand tools. Transportation equipment is a large category that includes cars, taxicabs, buses, trucks, trains, airplanes, boats, and ships. This powered machinery is designed to carry materials and/or people. Equipment in category (2), transportable

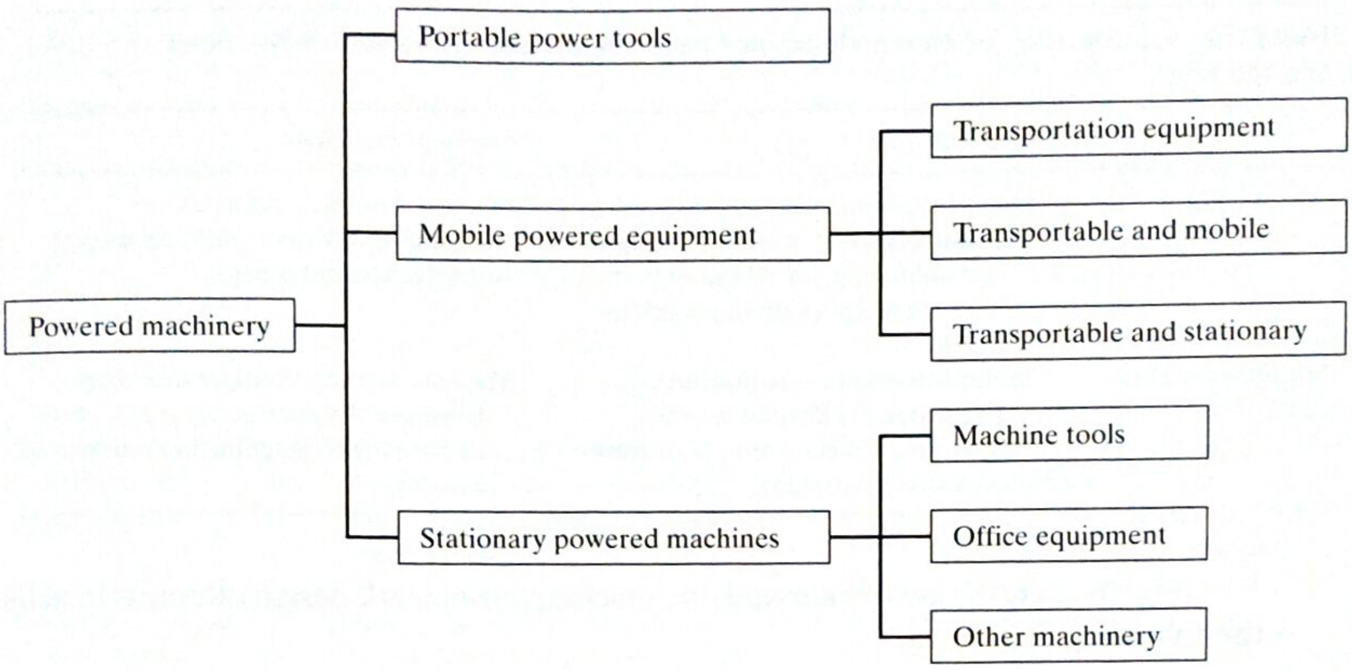

Figure 2.3 Classification of powered machinery in worker–machine systems.

and mobile during operation, consists of equipment that can move under its own power but can also be moved by transportation equipment (e.g., tractor and flatbed). Examples include construction equipment (e.g., bulldozers, backhoes), agricultural and lawn-keeping (e.g., small tractors, lawn mowers), and material-handling equipment (e.g., forklift trucks). The third category, transportable and stationary during operation, is equipment that can be transported by highway truck but it performs its function in a stationary location once it is moved (e.g., electric power generator, large power saws used at construction sites). The typical power sources are fossil fuels.

Stationary powered machines stand on the floor or ground and cannot be moved while they are operating, and they are not normally moved between operations. Electricity is the usual power source. We can classify stationary power tools into the following categories: (1) machine tools, (2) office equipment, and (3) other. A ***machine tool*** is a stationary power-driven machine that shapes or forms parts. Machine tools are normally associated with factory production operations such as machining (e.g., turning, drilling, milling), shearing (e.g., blanking, hole-punching), and squeezing (e.g., forging, extrusion). Office equipment (second category) includes personal computers, photocopiers, telephones, fax machines, design workstations, and other equipment and systems normally found in an office facility. Office work is discussed in Chapter 6. The "other" types of equipment (third category) are a miscellaneous group that includes machinery not fitting into the other two categories. Examples include furnaces, ovens, cash registers, and sewing machines.

Numbers of Workers and Machines. Another means of classifying worker–machine systems is according to whether there are one or more workers and one or more machines. This provides four categories, as indicated in Table 2.2.

TABLE 2.2 Classification of Worker–Machine Systems According to Number of Machines and Workers

	One Machine	Multiple Machines
One worker	One worker–one machine. **Examples:** (1) A worker loading and unloading a machine tool, (2) a truck driver driving a tractor trailer.	One worker–multiple machines **Example:** A worker tending several production machines.
Multiple workers	Multiple workers–one machine. **Examples:** (1) Several workers operating a rolling mill, (2) a crew on a ship or airplane.	Multiple worker–multiple machines. **Example:** An emergency repair crew responding to machine breakdowns in a factory.

For the case of one worker and one machine, good work design attempts to achieve the following objectives:

- Design the controls of the machine to be logical and easy to operate for the worker.
- Design the work sequence so that as much of the worker's task as possible can be accomplished while the machine is operating, thereby minimizing worker idle time.
- Minimize the idle times of both the worker and the machine.
- Design the task and the machine to be safe for the worker. If the task is inherently hazardous to the worker, then an automated work system should be considered.

The same design objectives are applicable when the work system consists of multiple workers and/or multiple machines. An additional objective is to optimize the number of workers or machines in the system according to some appropriate economic objective. For example, if one worker is assigned to attend to multiple machines, how many machines should be assigned to that worker so as to avoid machine idle time?

Level of Operator Attention Required. Another way to distinguish among worker–machine systems is by the level of attention required by the worker(s). In this classification, we have the four categories described in Table 2.3. Full-time attention means that the worker must devote virtually 100% of his or her time to the operation of the equipment during the performance of the task.

2.2.2 Cycle Time Analysis in Worker–Machine Systems

In terms of cycle time analysis, worker–machine systems fall into two categories: (1) systems in which the machine time depends on operator control, and (2) systems in which the machine time is constant and independent of operator control, and the work cycle is repetitive. In the first category, in which machine time depends on operator control, the task can be either (1) repetitive or (2) nonrepetitive. The following examples illustrate repetitive tasks with cycle times that depend on the pace and skill with which the operator applies the powered equipment:

- A typist typing a list of names and telephone numbers on a conventional electric typewriter

TABLE 2.3 Levels of Operator Attention in Worker–Machine Systems

Category	Description	Examples
Full-time attention	Worker is engaged 100% of the time in operating the equipment. The task can be (1) repetitive and cyclical or (2) nonrepetitive.	Worker operating a drop forge hammer (repetitive and cyclical). Worker on an assembly line whose task time equal to available service time (repetitive and cyclical). Truck driver driving an 18-wheeler (nonrepetitive). Worker mowing the lawn (nonrepetitive).
Part-time attention during each work cycle	Worker is engaged less than 100% of the time in operating the equipment. Task is repetitive and cyclical.	Worker loading and/or unloading production machine each cycle. Machine processes work units on mechanized or semiautomatic cycle. Worker is idle during machine cycle.
Periodic attention with regular servicing	Worker must service machine at regular intervals that are greater than one work cycle	Crane operator in steel mill moving molten steel ingots after each heat cycle. The operator must spend most of his time waiting for the next heat. Worker loading and/or unloading an automated production machine every 20 cycles. The machine operates on automatic cycle for the 20 cycles, but its storage capacity is limited to 20 work units.
Periodic attention with random servicing	Worker must service machine at random intervals that average more than one work cycle	Maintenance worker repairing production equipment when it malfunctions at random times. Firefighters responding to alarms that occur at random times.

- A metal trades worker operating a power buffer to buff the surface of a metal part
- A carpenter using a power saw to cut standard lengths of lumber
- A forklift driver moving pallet loads from the truck dock to the storage racks in a warehouse.

In these cases when the work cycle is repetitive but the cycle time is not constant, the analysis methods in Section 2.1.2 can be used.

Examples of worker–machine systems that operate on a nonrepetitive work cycle include the following:

- A trucker driving a tractor-trailer on an interstate highway
- A construction worker operating a backhoe
- A farmer operating a threshing machine to separate seeds from crop
- A carpenter using portable power tools to build a deck on a newly constructed house.

These nonrepetitive work situations do not consist of a regular work cycle that is repeated over and over. The time to accomplish the work depends on the skill and work ethic of the persons performing the tasks. Estimates or historical records based on previous similar jobs are often used to determine how long the work should take to complete.

In this section, we focus attention on the second category of worker–machine system, in which machine time is constant and does not depend on operator control, and the work cycle is repetitive. Two cases are discussed: (1) cycle times with no overlap between worker and machine and (2) worker–machine systems with internal work elements.

Cycle Times with No Overlap Between Worker and Machine. In a worker–machine system, the work elements include one or more actions and/or operations performed by the machine. If there is no overlap in work elements between the worker and the machine, then the normal time for the cycle is simply the sum of their respective normal times:

$$T_n = T_{nw} + T_m \tag{2.6}$$

where T_{nw} = normal time for the worker-controlled portion of the cycle, min; and T_m = machine cycle time (assumed constant).

To determine the standard time for the cycle, a machine allowance is sometimes added to the machine time. If we include such an allowance factor in the standard time calculation, we have

$$T_{std} = T_{nw}(1 + A_{pfd}) + T_m(1 + A_m) \tag{2.7}$$

where T_{nw} = normal time of the worker, min; T_m = constant time for the machine cycle, min; A_m = machine allowance factor, used in the equation as a decimal fraction; and the other terms have the same meaning as before.

A typical value used by companies for the machine allowance factor is $A_m = 30\%$. This tends to help workers achieve higher worker efficiencies, which is especially important if the worker is paid on an incentive basis. Workers might prefer to work on an entirely manual cycle if the machine allowance were not provided. On the other hand, some companies do not see the need to use a machine allowance, in which case $A_m = 0$. An argument for $A_m = 0$ is that the worker is idle during the machine cycle, and so does not have to expend any effort during this portion of the work cycle. Other companies simply set the A_m value to be the same as A_{pfd}. The following examples show how the value of A_m affects the standard time and worker efficiency.

Example 2.8 Effect of Machine Allowance on Standard Time

In the operation of a worker–machine system, the work cycle consists of several manual work elements (operator-controlled) and one machine element performed under semiautomatic control. One workpiece is produced each cycle. The manual work elements total a normal time of 1.0 min and the semiautomatic machine cycle is a constant 2.0 min. The PFD allowance factor A_{pfd} is 15%. Determine the standard time using (a) $A_m = 0$ and (b) $A_m = 30\%$.

Solution: The normal time for the work cycle is the normal time for the worker-controlled elements plus the machine cycle time:

$$T_n = 1.0 + 2.0 = 3.0 \text{ min}$$

(a) With a machine allowance of 0, the standard time is calculated as

$$T_{std} = 1.0(1 + 0.15) + 2.0 = 3.15 \text{ min}$$

(b) With a machine allowance of 30%, the standard time is

$$T_{std} = 1.0(1 + 0.15) + 2.0(1 + 0.30) = 1.15 + 2.60 = 3.75 \text{ min}$$ ■

Example 2.9 Effect of Machine Allowance on Worker Efficiency

Based on the standard times computed in (a) and (b) of the previous example, determine the worker efficiencies for two cases if 150 units are produced in one 8-hour shift.

Solution: **(a)** If T_{std} = 3.15 min, the number of standard hours accomplished is

$$H_{std} = 150(3.15) = 472.5 \text{ min} = 7.875 \text{ hr}$$

$$\text{Worker efficiency } E_w = 7.875/8.0 = 0.984 = 98.4\%$$

(b) If T_{std} = 3.75 min, the number of standard hours accomplished is

$$H_{std} = 150(3.75) = 562.5 \text{ min} = 9.375 \text{ hr}$$

$$\text{Worker efficiency } E_w = 9.375/8.0 = 1.172 = 117.2\%$$ ■

When the work cycle includes a machine cycle and the machine time is a constant, then operator performance has no effect on this machine element. The only way the worker's pace can affect the work cycle time is during those elements that are operator-controlled. The operator may be idle during the machine element, as in Examples 2.8 and 2.9, unless the work sequence can be designed to include operator work elements that are performed while the machine is running.

Worker–Machine Systems with Internal Work Elements. In the operation of a worker–machine system, it is important to distinguish between the operator's work elements that are performed in sequence with the machine's work elements and those that are performed simultaneously with the machine elements. Operator elements that are performed sequentially are called ***external work elements*** while those that are performed simultaneously with the machine cycle are called ***internal work elements***. The distinction is important because it is desirable to construct the work cycle sequence so that as many of the operator elements as possible are performed as internal elements. This tends to minimize the cycle time, as illustrated by the following example.

Example 2.10 Internal Versus External Work Elements in Cycle Time Analysis

The work cycle in a worker–machine system consists of the elements and associated times given in the table below. All of the operator's work elements are external to the machine time. Can some of the worker's elements be made internal to the machine cycle, and if so, what is the expected cycle time for the operation?

Sequence	Work Element Description	Worker Time (min)	Machine Time (min)
1	Worker walks to tote pan containing raw stock	0.13	(idle)
2	Worker picks up raw workpart and transports to machine	0.23	(idle)
3	Worker loads part into machine and engages machine semiautomatic cycle	0.12	(idle)
4	Machine semiautomatic cycle	(idle)	0.75
5	Worker unloads finished part from machine	0.10	(idle)
6	Worker transports finished part and deposits into tote pan	0.15	(idle)
Totals		0.73	0.75

Solution: Since all of the work elements in the cycle are sequential, the total cycle time is the sum of the worker elements and the machine element:

$$T_c = 0.73 + 0.75 = 1.48 \text{ min.}$$

The worker is idle during the entire machine semiautomatic cycle. It should be possible to imbed elements 1, 2, and 6 as internal elements that are performed while the machine is running on a semiautomatic cycle. Using the times from the preceding table, the resulting work cycle can be organized as follows:

Sequence	Work Element Description	Worker Time (min)	Machine Time (min)
1	Worker unloads finished part from machine	0.10	(idle)
2	Worker loads part into machine and engages semiautomatic machine cycle	0.12	(idle)
3	Machine semiautomatic cycle		0.75
4	Worker transports finished part and deposits it into tote pan, walks to tote pan containing raw stock, and picks up raw workpart and transports it to machine. (This element is internal to the machine semiautomatic cycle.)	0.15 + 0.13 + 0.23 = 0.51	
Totals		0.73	0.75

Although the total times for the worker and the machine are the same as before, element 4 in the revised cycle (which consists of elements 1, 2, and 6 from the original work cycle) is performed simultaneously with the machine time, resulting in the following new cycle time:

$$T_c = 0.10 + 0.12 + 0.75 = 0.97 \text{ min}$$

This represents a 34% reduction in cycle time, which translates into a 53% increase in production rate. ■

When internal elements are present in the work cycle, it must then be determined whether the machine cycle time or the sum of the worker's internal elements take longer. To determine the normal time for the cycle,

$$T_n = T_{nw} + \text{Max}\,\{T_{nwi}, T_m\} \tag{2.8}$$

where T_{nw} = normal time for the worker's external elements, min; T_{nwi} = normal time for the worker's internal elements, min; and T_m = machine cycle time. The standard time for the cycle is given by

$$T_{std} = T_{nw}(1 + A_{pfd}) + \text{Max}\ \{T_{nwi}(1 + A_{pfd}), T_m(1 + A_m)\} \tag{2.9}$$

where A_{pfd} and A_m are the worker's allowance factor and the machine allowance factor, respectively. Finally, the actual cycle time depends on the worker's performance level, applied to the normalized times as

$$T_c = \frac{T_{nw}}{P_w} + \text{Max}\left(\frac{T_{nwi}}{P_w}, T_m\right) \tag{2.10}$$

where P_w is the worker performance level during the cycle, expressed as a decimal fraction; and the other symbols mean the same as before. We assume in equation (2.10) that the worker's performance level is the same on the external and internal elements. If these P_w values are different, then the computations must reflect these differences.

2.3 AUTOMATED WORK SYSTEMS

Automation is the technology by which a process or procedure is accomplished without human assistance.[4] It is implemented using a program of instructions combined with a control system that executes the instructions. Power is required to drive the process and to operate the program and control system.

There is not always a clear distinction between worker–machine systems and automated systems, because many worker–machine systems operate with some degree of automation. Let us distinguish between two forms of automation: semiautomated and fully automated. A ***semiautomated machine*** performs a portion of the work cycle under some form of program control, and a human worker tends to the machine for the remainder of the cycle, by loading and unloading it, or performing some other task during each cycle. An example of this category is an automated lathe controlled for most of the work cycle by the part program but requiring a worker to unload the finished part and load the next workpiece at the end of each machine cycle. In these cases, the worker must attend to the machine during every cycle. This type of operation has the same characteristics as a worker–machine system that requires the part-time attention of the worker during each work cycle (Table 2.3). Its cycle time analysis is discussed in Section 2.2.2.

The continuous presence of the operator during the cycle may not always be required. If the automatic machine cycle takes, say, 10 min while the part unloading and loading portion of the work cycle takes only 30 sec, then there may be an opportunity for one worker to tend more than one machine. We analyze this possibility in Section 2.5.

[4]Much of this section on automation is based on Chapters 3 and 13 in [2].

A ***fully automated machine*** is distinguished from its semiautomated cousin by the capacity to operate for extended periods of time with no human attention. By extended periods of time, we mean longer than one work cycle. A worker is not required to be present during each cycle. Instead, the worker may need to tend the machine every tenth cycle, or every hundredth cycle. An example of this type of operation is found in many injection molding plants, where the molding machines run on automatic cycle, but periodically the molded parts at the machine must be collected by a worker. This case is identified in Table 2.3 as periodic attention with regular servicing.

Certain fully automated processes require one or more workers to be present to continuously monitor the operation and make sure that it performs according to the intended specifications. Examples of these kinds of automated processes are found at chemical-processing facilities, oil refineries, and nuclear power plants. The workers do not actively participate in the process except to make occasional adjustments in the equipment settings, to perform periodic maintenance, and to spring into action if something goes wrong.

2.4 DETERMINING WORKER AND MACHINE REQUIREMENTS

One of the problems faced by any organization is determining the appropriate staffing levels. How many workers are required to achieve the organization's work objectives? If too few workers are assigned to perform a given amount of work, then the work cannot be completed on time, and customer service suffers. If too many workers are assigned, then payroll costs are higher than needed, and productivity suffers. Determining the number of workers or worker–machine systems that will be required to accomplish a specified amount of work is the problem we address in this section.[5] The basic approach consists of two steps:

1. Determine the total workload that must be accomplished in a certain period (hour, week, month, year), where ***workload*** is defined as the total hours required to complete a given amount of work or to produce a given number of work units scheduled during the period.
2. Divide the workload by the available time per worker, where ***available time*** is defined as the number of hours in the same period available from one worker or worker–machine system.

Let us consider two general cases: (1) when setup time is not a factor and (2) when setup time must be included in the determination.

2.4.1 When Setup Is Not a Factor

Workload is figured as the quantity of work units to be produced during the period of interest multiplied by the time (hours) required for each work unit. The time required for each work unit is the work cycle time in most cases, so that workload is given by

$$WL = QT_c \tag{2.11}$$

[5]This section is based largely on Section 14.4.1 in [2].

where WL = workload scheduled for a given period, hr of work/period (e.g., hr/wk); Q = quantity to be produced during the period, pc/period (e.g., pc/wk); and T_c = work cycle time required per work unit, hr/pc. Normally, the work cycle time T_c would be the standard time T_{std} for the task, and so the workload is the number of standard hours scheduled during the period.

If the workload includes multiple part or product styles that can all be produced by the same worker or work system during the period of interest, then the following summation is used:

$$WL = \sum_j Q_j T_{cj} \tag{2.12}$$

where Q_j = quantity of part or product style j produced during the period, pc; T_{cj} = cycle time of part or product style j, hr/pc; and the summation includes all of the parts or products to be made during the period. In step (2) the workload is divided by the hours available of one worker in the same time period; that is,

$$w = \frac{WL}{AT} \quad \text{or} \quad n = \frac{WL}{AT} \tag{2.13}$$

where w = number of workers, n = number of workstations (e.g., worker–machine systems); and AT = available time of one worker in the period, hr/period/worker. We can understand the use of these equations with a simple example, and then consider some of the complications.

Example 2.11 Determining Worker Requirements

A total of 800 shafts must be produced in the lathe section of a machine shop during a particular week. Each shaft is identical and requires a standard time T_{std} = 11.5 min (machining time plus worker time). All of the lathes in the department are equivalent in terms of their capability to produce the shaft in the specified cycle time. How many lathes and lathe operators must be devoted to shaft production during the given week, if there are 40 hours of available time on each lathe.

Solution: The workload consists of 800 shafts at 11.5 min per shaft.

$$WL = 800\,(11.5 \text{ min}) = 9200 \text{ min} = 153.33 \text{ hr}$$

The time available per lathe during the week is AT = 40 hr.

$$w = n = \frac{153.33}{40} = 3.83 \text{ lathe operators and } 3.83 \text{ lathes}$$

This calculated value would probably be rounded up to four lathes and operators that are assigned to the production of shafts during the given week. ■

There are several factors present in most work systems that make the computation of the number of workers somewhat more complicated than suggested by Example 2.11. These factors influence either the workload or the amount of time available per worker during the period of interest. There are three principal factors that affect workload during a given period:

- *Worker efficiency*. Workload varies when the worker performs either above or below standard performance for a given manual task.
- *Defect rate*. The output of the work system may not be 100% good quality. Defective units may be produced at a certain fraction defect rate that must be accounted for by increasing the total number of units processed.
- *Learning curve phenomenon*. As the worker becomes more familiar with a repetitive task, the time to accomplish each cycle tends to decrease.

Worker efficiency is defined in Section 2.1.2 and equation (2.5) as the amount of work accomplished during a shift expressed as a proportion of the shift hours. It is the workload actually completed by a worker in a given time period divided by the workload that would be completed at standard performance. An efficiency greater than 1.00 reduces the workload, while an efficiency less than 1.00 increases the workload. Many companies establish their time standards for tasks so that most workers are able to exceed standard performance. In this case, worker efficiency will be greater than 100% on average, and the company should take this into account in determining workloads.

Defect rate is the fraction of parts produced that are defective. A defect rate greater than zero increases the quantity of work units that must be processed in order to yield the desired quantity. If a process is known to produce parts at a certain average scrap rate, then the starting quantity should be increased to compensate for the defective parts that will be made. The relationship between the starting quantity and the final quantity produced is

$$Q = Q_o(1-q) \tag{2.14}$$

where Q = quantity of good units made in the process; Q_o = original or starting quantity; and q = fraction defect rate. Thus, if we want to produce Q good units, we must process a total of Q_o starting units, which is

$$Q_o = \frac{Q}{(1-q)} \tag{2.15}$$

The combined effect of worker efficiency and fraction defect rate is given in the following equation, which amends the workload formula, equation (2.11):

$$WL = \frac{QT_{std}}{E_w(1-q)} \tag{2.16}$$

where E_w = worker efficiency, expressed as a decimal fraction; and q = fraction defect rate.

The learning curve phenomenon is discussed in Chapter 19. As learning occurs in repetitive manual work, worker efficiency increases and the cycle time decreases, so that the workload is gradually reduced as the job progresses. An attempt is made in most companies to take the learning curve into account when determining workloads.

An important factor that affects the available time per worker or per worker–machine system is availability. ***Availability*** is a common measure of reliability for equipment and is defined as the proportion of time the equipment is available to run relative to the total time it could be used. It is the proportion of time that the equipment is not malfunctioning or broken down. Availability is especially applicable for mechanized or automated equipment. As availability decreases, the available time of the equipment is reduced. The available time becomes the actual shift time in the period multiplied by availability. In equation form,

$$AT = H_{sh}A \tag{2.17}$$

where AT = available time, hr/worker; H_{sh} = shift hours during the period, hr.; and A = availability, expressed as a decimal fraction.

Example 2.12 Effect of Worker Efficiency, Defect Rate, and Availability on Worker Requirements

Suppose in Example 2.11 that the anticipated availability of the lathes is 95%. The expected worker efficiency during production = 110%. The fraction defect rate for lathe work of this type is 3%. Other data from Example 2.11 are applicable. How many lathes are required during the 40-hour week, given this additional information?

Solution: The total workload for the 800 parts is equation (2.16):

$$WL = \frac{800(11.5/60)}{(1.10)(1-0.03)} = 143.7 \text{ hr}$$

The available time is affected by the 95% availability:

$$AT = 40(0.95) = 38 \text{ hr/machine}$$

$$n = \frac{143.7}{38} = 3.78 \text{ lathes and lathe operators}$$

This should be rounded up to four lathes, unless the remaining time on the fourth lathe can be used for other production.

■

2.4.2 When Setup Time Is Included

Setup time is associated with batch processing, which is discussed in the following chapter (Section 3.2). Briefly, ***batch processing*** refers to operations in which work units are processed in groups (i.e., batches). In most cases, the equipment must be changed over between batches, and the time lost for the changeover is called the ***setup time***. Setup time is required because the tooling and fixturing must be changed to accommodate the next work unit type, and the machine settings must be adjusted. Time is lost during setup because no work units are produced (except perhaps a few trial units to check out the new setup). Yet setup consumes available time at a machine. In this section, we examine two alternative cases in which setup time must be accounted for: (1) the number of setups is known and (2) the number of setups is unknown.

Number of Setups Is Known. In batch production, we know how many batches must be produced in a given period. Since there is one setup associated with each batch, we therefore know how many setups must be made. Accordingly, the setup workload can be computed as the sum of the setup times for all batches. The following example illustrates this case, as well as some other variations.

Example 2.13 Determining Worker Requirements When Number of Setups Is Known

This is another variation of Example 2.11. A total of 800 shafts must be produced in the lathe section of the machine shop during a particular week. The shafts are of 16 different types, each type being produced in its own batch. Average batch size is 50 parts. Each batch requires a setup and the average setup time is 3.5 hr. The average machine cycle time to produce a shaft T_c is 11.5 min. Assume that the fraction defect rate is 3%, and worker efficiency is 100%. Availability is assumed to be 100% during setup but only 95% during a production run. How many lathes are required during the week?

Solution: In this case we know how many setups are required during the week because we know that 16 batches will be produced. We can determine the following workload for the 16 setups and the workload for 16 production batches:

$$WL = 16(3.5) + \frac{16(50)(11.5/60)}{(0.97)} = 56 + 158.076 = 214.08 \text{ hr}$$

Since machine availability differs between setup and run time, we must figure worker requirements for each separately. For setup, $AT = 40(1.0) = 40$ hr/machine, but for run time, $AT = 40(0.95) = 38$ hr. These two values must be allocated respectively to the two terms of the workload. The number of lathes and operators is calculated as

$$n = \frac{56}{40} + \frac{158.076}{38} = 1.40 + 4.16 = 5.56$$

which would be rounded up to six machines and operators. Note that the rounding up should occur after adding the machine fractions; otherwise there is a risk of overestimating machine requirements.

■

In this example there is a separation of tasks between two or more types of work (in this problem, setup and run are two separate types of work), so we must be careful to use the various factors only where they apply. For example, fraction defect rate does not apply to setup time. Availability is also assumed not to apply to setup (how can the machine break down if it is not running?). Also, worker efficiencies might differ between setup and run. Accordingly, it is appropriate to compute the number of equivalent machines (and/or workers) for setup separately from the number for production.

Number of Setups Is Unknown. In this case, each worker–machine system that will be used to meet production requirements must be set up at the beginning of its respective production run, but we do not know how many machines there will be. Accordingly, we must express the total workload for setup time as a function of the number of machines. This case is illustrated by the following example.

Example 2.14 Including Setup Time When Each Machine Must Be Set Up Once

In another variation of Example 2.11, suppose that a setup is required for each lathe that is used to satisfy the production requirements. The lathe setup for this type of part takes 3.5 hr. Assume that fraction defect rate is 3%, worker efficiency is 100%, and availability is 100%. How many lathes and lathe operators are required during the week?

Solution: The fraction defect rate applies to the production workload but not to the setup workload. Thus workload consists of two terms, as follows:

$$WL = \frac{800(11.5/60)}{(1-0.03)} + 3.5\,n = 158.076 + 3.5\,n$$

For $A = 1.0$,

$$AT = 40(1.0) = 40 \text{ hr of available time per lathe}$$

Dividing WL by AT, we have

$$n = \frac{158.076 + 3.5n}{40} = 3.95 + 0.0875\,n$$

Solving, $n = 4.33$ lathes and lathe operators, which must be rounded up to five lathes and associated workers.

Comment: It is inefficient to devote five lathes and operators for the 40-hour week, because the lathes will not be fully utilized. Given this unfortunate result, it might be preferable to offer overtime to the workers on four of the lathes. How much overtime (represented by OT) above the regular 40 hours will be required?

$$OT = \left(3.5 + \frac{158.076}{4}\right) - 40 = (3.5 + 39.52) - 40 = 3.02 \text{ hr}$$

This is a total of 4 (3.02 hr) = 12.08 hr for the four machine operators. ■

2.5 MACHINE CLUSTERS

When the machine in a worker–machine system does not require the continuous attention of a worker during its machine cycle (i.e., no internal work elements), an opportunity exists to assign more than one machine to the worker. We refer to this kind of work organization as a ***machine cluster***—a collection of two or more machines producing parts or products with identical cycle times and serviced by one worker (the servicing is usually loading and/or unloading parts).[6]

Several conditions must be satisfied in order to organize a collection of machines into a machine cluster: (1) the machine cycle is long relative to the service portion of the cycle that requires the worker's attention; (2) the machine cycle time is the same for all machines; (3) the machines that the worker services are located in close enough proximity to allow time to walk between them; and (4) the work rules of the plant permit a worker to service more than one machine.

[6] This section is based largely on Section 14.4.2 in [2].

to allow time to walk between them; and (4) the work rules of the plant permit a worker to service more than one machine.

Consider a collection of single workstations, all producing the same parts and operating with the same machine cycle time. Each machine operates for a certain portion of the total cycle under its own control T_m (machine cycle), and then it requires servicing by the worker, which takes time T_s. Thus, assuming the worker is always available when servicing is needed so that the machine is never idle, the total cycle time of a machine is $T_c = T_m + T_s$. If more than one machine is assigned to the worker, a certain amount of time will be lost because of walking from one machine to the next, referred to here as the ***repositioning time***, which is represented by T_r. The time required for the operator to service one machine is therefore $T_s + T_r$, and the time to service n machines is $n(T_s + T_r)$. For the system to be perfectly balanced in terms of worker time and machine cycle time,

$$n(T_s + T_r) = T_m + T_s$$

We can determine from this the number of machines that should be assigned to one worker by solving for n:

$$n = \frac{T_m + T_s}{T_s + T_r} \tag{2.18}$$

where n = number of machines; T_m = machine cycle time, min; T_s = worker service time per machine, min; T_r = worker repositioning time between machines, min.

It is likely that the calculated value of n will not be an integer, which means that the worker time in the cycle—that is, $n(T_s + T_r)$—cannot be perfectly balanced with the cycle time T_c of the machines. However, the actual number of machines in the cluster must be an integer, so either the worker or the machines will experience some idle time. The number of machines will either be the integer that is greater than n from equation (2.18) or it will be the integer that is less than n. Let us identify these two integers as n_1 and n_2. We can determine which of the alternatives is preferable by introducing cost factors into the analysis. Let C_L = the labor cost rate and C_m = machine cost rate (certain overhead costs may be applicable to these rates). The decision will be based on the cost per work unit produced by the system.

Case 1: If we use n_1 = maximum integer $\leq n$, then the worker will have idle time and the cycle time of the machine cluster will be the cycle time of the machines $T_c = T_m + T_s$. Assuming 1 work unit is produced by each machine during a cycle, we have the following cost:

$$C_{pc}(n_1) = \left(\frac{C_L}{n_1} + C_m\right)(T_m + T_s) \tag{2.19}$$

where $C_{pc}(n_1)$ = cost per work unit, \$/pc; C_L = labor cost rate, \$/min; C_m = cost rate per machine, \$/min; and $(T_m + T_s)$ is expressed in min.

Case 2: If we use n_2 = minimum integer $> n$, then the machines will have idle time, and the cycle time of the machine cluster will be the time it takes for the worker to service the n_2 machines, which is $n_2(T_s + T_r)$. The corresponding cost per piece is given by

$$C_{pc}(n_2) = (C_L + C_m n_2)(T_s + T_r) \tag{2.20}$$

The selection of n_1 or n_2 is based on whichever case results in the lower value of cost per work unit.

In the absence of cost data needed to make these calculations, the author's view is that it is generally preferable to assign machines to a worker so that the worker has some idle time and the machines are utilized 100%. The reason for this is that the total hourly cost rate of n production machines is usually greater than the labor rate of one worker. Therefore, machine idle time costs more than worker idle time. The corresponding number of machines to assign the worker is therefore given by

$$n_1 = \text{maximum integer } \leq \frac{T_m + T_s}{T_s + T_r} \tag{2.21}$$

Example 2.15 How Many Machines for One Worker?

A machine shop contains many semiautomated lathes that operate on a machining cycle under part program control. A significant number of these machines produce the same part, whose cycle time = 2.75 min. One worker is required to perform unloading and loading of parts at the end of each machining cycle. This process takes 25 sec. Determine how many machines one worker can service if it takes an average of 20 sec to walk between the machines and no machine idle time is allowed.

Solution: Given that $T_m = 2.75$ min, $T_s = 25$ sec $= 0.4167$ min, and $T_w = 20$ sec $= 0.3333$ min, equation (2.21) can be used to obtain n_1:

$$n_1 = \text{maximum integer} \leq \frac{2.75 + 0.4167}{0.4167 + 0.3333} = \frac{3.1667}{0.75} = 4.22 = 4 \text{ machines}$$

Each worker can be assigned four machines. With a machine cycle $T_c = 3.1667$ min, the worker will spend $4(0.4167) = 1.667$ min servicing the machines and $4(0.3333) = 1.333$ min walking between machines, and the worker's idle time during the cycle will be 0.167 min (10 sec). ■

Note the regularity of the worker's schedule in this example. If we imagine the four machines to be laid out on the four corners of a square, the worker services each machine and then proceeds clockwise to the machine in the next corner. Each cycle, servicing, and walking take 3.0 min, with a slack time of 10 sec left over. If this kind of regularity characterizes the operations of a cluster of mechanized or semiautomatic machines, then the preceding analysis can be applied to determine the number of machines to assign to one worker. On the other hand, if servicing is required at random and unpredictable intervals by each machine, then it is likely that there will be periods when several machines require servicing simultaneously, thus overloading the capabilities of the human worker. In addition, at other times during the shift, the worker will have no machines to service and will therefore be idle.

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REVIEW QUESTIONS

2.1 In terms of human participation, what are the three basic categories of work systems?

2.2 What is the general characteristic that is common to nearly all pure manual work?

2.3 What is the one best method principle?

2.4 What is meant by the term *normal performance*?

2.5 What is meant by the term *normal time* for a task?

2.6 What does PFD stand for? What is the purpose of the PFD allowance in determining the standard time for a task?

2.7 What is an irregular work element?

2.8 Define the meaning of worker efficiency.

2.9 What is a worker–machine system?

2.10 What are the three main categories of powered machinery in worker–machine systems?

2.11 Define machine tool.

2.12 Cycle times in worker–machine systems divide into two categories: (1) machine time depends on operator and (2) machine time is constant and repetitive. Give an example of each category.

2.13 What is the difference between an external work element and an internal work element in a worker–machine cycle?

2.14 What are the factors that affect the workload calculation when determining worker requirements?

2.15 What does availability mean?

2.16 What is a machine cluster?

PROBLEMS

Cycle Time Analysis of Manual Work

2.1 If the normal time is 1.30 min for a repetitive task that produces one work unit per cycle, and the company uses a PFD allowance factor of 12%, determine (a) the standard time for the task and (b) how many work units are produced in an 8-hour shift at standard performance.

2.2 The normal time for a repetitive task that produces two work units per cycle is 3.0 min. The plant uses a PFD allowance factor of 15%. Determine (a) the standard time per piece and (b) how many work units are produced in an 8-hour shift at standard performance.

2.3 The normal time to perform a certain manual work cycle is 3.47 min. In addition, an irregular work element whose normal time is 3.70 min must be performed every 10 cycles. One work unit is produced each cycle. The PFD allowance factor is 14%. Determine (a) the standard time per piece and (b) how many work units are produced during an 8-hour shift at 100% performance, and the worker works exactly 7.018 hr, which corresponds to the 14% allowance factor. (c) If the worker's pace is 120% and he works 7.2 hours during the regular shift, how many units are produced?

2.4 The normal time to perform a repetitive manual assembly task is 4.25 min. In addition, an irregular work element whose normal time is 1.75 min must be performed every 8 cycles. Two work units are produced each cycle. The PFD allowance factor is 16%. Determine (a) the standard time per piece and (b) how many work units are produced in an 8-hour shift at standard performance. (c) Determine the anticipated amount of time worked and the amount of time lost per 8-hour shift that corresponds to the PFD allowance factor of 16%.

2.5 The standard time for a manual material-handling work cycle is 2.58 min per piece. The PFD allowance factor used to set the standard was 13%. During a particular 8-hour shift of interest, it is known that the worker lost a total of 53 min due to personal time, rest breaks, and delays. On that same day, the worker completed 214 work units. Determine (a) the number of standard hours accomplished, (b) worker efficiency, and (c) the worker's performance level expressed as a percentage.

2.6 A worker performs a repetitive assembly task at a workbench to assemble products. Each product consists of 25 components. Various hand tools are used in the task. The standard time for the work cycle is 7.45 min, based on using a PFD allowance factor of 15%. If the worker completes 75 product units during an 8-hour shift, determine (a) the number of standard hours accomplished and (b) worker efficiency. (c) If the worker took only one rest break, lasting 13 min, and experienced no other interruptions during the 8 hours of shift time, determine her worker performance.

Cycle Time Analysis in Worker–Machine Systems

2.7 The normal time of the work cycle in a worker–machine system is 5.39 min. The operator-controlled portion of the cycle is 0.84 min. One work unit is produced each cycle. The machine cycle time is constant. (a) Using a PFD allowance factor of 16% and a machine allowance factor of 30%, determine the standard time for the work cycle. (b) If a worker assigned to this task completes 85 units during an 8-hour shift, what is the worker's efficiency? (c) If it is known that a total of 42 min was lost during the 8-hour clock time due to personal needs and delays, what was the worker's performance on the portion of the cycle he controlled?

2.8 A worker is responsible for loading and unloading a production machine. The load/unload elements in the repetitive work cycle have a normal time of only 24 sec, and the machine cycle time is 2.83 min. One part is produced each cycle. Every sixth cycle, the operator must replace the tote pans of parts, which takes 2.40 min (normal time). For setting the standard time, the PFD allowance factor is 15% and the machine allowance factor is 15%. Determine the standard time under the following alternative assumptions: (a) the irregular element is performed as an external element and (b) the irregular element is performed as an internal element. (c) Determine the corresponding standard daily production quantities (8-hour shift) for each of these time standards.

2.9 The work cycle in a worker–machine system consists of (1) external manual work elements with a total normal time of 0.42 min, (2) a machine cycle with a machine time of 1.12 min, and (3) internal manual elements with a total normal time of 1.04 min. (a) Determine the standard time for the cycle, using a PFD allowance factor of 15% and a machine allowance factor of 30%. (b) How many work units are produced daily (8-hour shift) at standard performance?

2.10 Solve the previous problem but assume that the machine allowance factor is 0%.

2.11 The normal time for a work cycle in a worker–machine system is 6.27 min. For setting the standard time, the PFD allowance factor is 12% and the machine allowance factor is 25%. The work cycle includes manual elements totaling a normal time of 5.92 min, all but 0.65 min of which are performed as internal elements. Determine (a) the standard time for the cycle and (b) the daily output at standard performance. (c) During an 8-hour shift, the worker lost 39 min due to personal time, rest breaks, and delays, and she produced 72 pieces. What was the worker's pace on the operator-controlled portion of the shift?

2.12 Solve the previous problem but assume that the machine allowance factor is 0%.

Determining Worker and Work Cell Requirements

2.13 A total of 1000 units of a certain product must be completed by the end of the current week. It is now late Monday afternoon, so only four days (8-hour shifts) are left. The standard time for producing each unit of the product (all manual operations) is 11.65 min. How many workers will be required to complete this production order if it is assumed that worker efficiency will be 115%?

2.14 Future production requirements in the turret lathe department must be satisfied through the acquisition of several new machines and the hiring of new operators, the exact number to be determined. There are three new parts that will be produced. Part A has annual quantities of 20,000 units; part B, 32,000 units; and part C, 47,000 units. Corresponding standard times for these parts are 7.3 min, 4.9 min, and 8.4 min, respectively. The department will operate one 8-hour shift for 250 days/yr. The machines are expected to be 98% reliable, and the anticipated scrap rate is 4%. Worker efficiency is expected to be 100%. How many new turret lathes and operators are required to meet these production requirements?

2.15 A new stamping plant must supply an automotive final assembly plant with stampings, and the number of new stamping presses must be determined. Each press will be operated by one worker. The plant will operate one 8-hour shift per day, five days per week, 50 weeks per year. The plant must produce a total of 20,000,000 stampings annually. However, 400 different stamping designs are required, in batch sizes of 5000 each, so each batch will be produced 10 times per year to minimize build-up of inventory. Each stamping takes 6 sec on average to produce. Scrap rate averages 2% in this type of production. Before each batch, the press must be set up, with a standard time per setup of 3.0 hours. Presses are 95% reliable (availability = 95%) during production and 100% reliable during setup. Worker efficiency is expected to be 100%. How many new stamping presses and operators will be required?

2.16 Solve the previous problem, except the plant will operate two 8-hour shifts instead of one. (a) How much money would be saved if each press has an investment and installation cost of $250,000. (b) If each worker's wage rate is $15.00/hr, how much money would be saved by operating two 8-hour shifts per day rather than one 8-hour shift?

2.17 Specialized processing equipment is required for a new type of integrated circuit to be produced by an electronics manufacturing company. The process is used on silicon wafers. The standard time for this process is 10.6 min per wafer. Scrap rate is 15%. A total of 125,000 wafers will be processed each year. The process will be operated 24 hours per day, 365 days per year. Data provided by the manufacturer of the processing equipment indicate that the availability is 93%. Each machine is operated by one worker, and worker efficiency is 100%. No setups are required for the machine. How many pieces of processing equipment will be needed to satisfy production requirements?

2.18 The standard time to produce a certain part in a worker–machine system is 9.0 min. A rush order has been received to supply 1000 units of the part within five working days (40 hours). How many worker–machine systems must be diverted from other production to satisfy this order? Each machine must be set up at the beginning of production of parts for the order, and the setup time per machine is 5.0 hours. Fraction defect rate is 5%, and worker efficiency is 100%. Availability is expected to be 98% during setup and production. How many machines and machine operators are required during the week?

2.19 A small company that specializes in converting pickup trucks into rear-cabin vehicles has just received a long-term contract and must expand. Heretofore, the conversion jobs were customized and performed in a garage. Now a larger building must be occupied, and the operations must be managed more like a production plant. Three models will be produced: A, B, and C. Annual quantities for the three models are as follows: A, 700; B, 400; and C, 250. Conversion times are as follows: A, 20 hr; B, 30 hr; and C, 40 hr. Defect rates are as follows: A, 11%; B, 7%; and C, 8%. Work teams of three workers each will accomplish the conversions. Each work team will require a space of 350 ft^2 in the plant. Reliability (availability) and worker efficiency of the work teams are expected to be 95% and 90%, respectively. Although the defect rates are given, no truck is permitted to leave the plant with any quality defects. Accordingly, all of the defects must be corrected, and the average time to correct the defect is 25% of the initial conversion time. The same work teams will accomplish this rework. (a) If the plant is run as a one-shift (2000 hr/yr) operation, how many work teams will be required? (b) If the total floor space in the building must include additional space for aisles and offices and the allowance that is added to the working space is 30%, what is the total area of the building?

2.20 It has just been learned that a Boeing 747 transporting garments made in China crashed in the Pacific Ocean during its flight to Los Angeles. Although the crew was saved, all cargo was lost, including 3000 garments that must be delivered in one week. The garment company must produce the order at its Los Angeles plant to satisfy delivery obligations. The number of workers must be determined and workspace must be allocated in the plant for this emergency job. Standard time to produce one garment is 6.50 min. The garments are then 100% inspected at a standard time of 0.75 min per unit. The scrap rate in production is 7%. However, all defective garments can be corrected through rework. Standard time for rework is 5.0 min per unit reworked. It is not necessary to reinspect the garments after rework. Worker efficiency is 120% during production and 100% during inspection and rework. The same production workers do the rework, but inspectors are a different job class. How many workers and how many inspectors are required to produce the required batch of 3000 garments in the regular 40-hour work week?

2.21 In the previous problem, suppose it turns out that only five workers are available to accomplish the production and rework, and because they must work overtime, worker efficiency will be reduced to 110% in production and 90% in rework. If they work 6 days/wk for one week, how many hours per day must they work to produce the 3000 garments?

Machine Clusters

2.22 The CNC grinding section has a large number of machines devoted to grinding of shafts for the automotive industry. The machine cycle takes 3.6 min to grind the shaft. At the end of this cycle, an operator must be present to unload and load parts, which takes 40 sec. (a) Determine how many grinding machines the worker can service if it takes 20 sec to walk between the machines and no machine idle time is allowed. (b) How many seconds during the work cycle is the worker idle? (c) What is the hourly production rate of this machine cluster?

2.23 The screw machine department has a large number of machines devoted to the production of a certain component that is in high demand for the personal computer industry. The semiautomatic cycle for this component is 4.2 min per piece. At the end of the machining cycle, an operator must unload the finished part and load raw stock for the next part. This servicing time takes 21 sec and the walking time between machines is estimated at 24 sec. (a) Determine how many screw machines one worker can service if no idle machine time is allowed. (b) How many seconds during the work cycle is the worker idle? (c) What is the hourly production rate of this machine cluster if one part is produced per machine each cycle?

2.24 A worker is currently responsible for tending two machines in a certain production cell. The service time per machine is 0.35 min and the time to walk between machines is 0.15 min. The machine automatic cycle time is 1.90 min. If the worker's hourly rate is \$12/hr and the hourly rate for each machine is \$18/hr, determine (a) the current hourly rate for the cell, and (b) the current cost per unit of product, given that two units are produced by each machine during each machine cycle. (c) What is the percentage of idle time for the worker? (d) What is the optimum number of machines that should be used in the cell, if minimum cost per unit of product is the decision criterion?

2.25 In a worker–machine cell, the appropriate number of production machines to assign to the worker is to be determined. Let n = the number of machines. Each production machine is identical and has an automatic processing time T_m = 4.0 min to produce one piece. Servicing time T_s = 12 sec for each machine. The full cycle time for each machine in the cell is $T_c = T_s + T_m$. The walk time (repositioning time) for the worker is given by $T_r = 5 + 3n$, where T_r is in seconds. T_r increases with n because the distance between machines increases with more machines. (a) Determine the maximum number of machines in the cell if no machine idle time is allowed. For your answer, compute (b) the cycle time, (c) the worker idle time expressed as a percentage of the cycle time, and (d) the production rate of the machine cluster.

2.26 The injection-molding department contains a large number of molding machines, all of which are automated. They can run continuously for multiple molding cycles without the attention of a human operator by allowing the molded parts to fall into tote pans beneath the machines. However, the tote pans must be periodically emptied by a worker who must attend the machine to perform this task. Each machine can run continuously for approximately 20 min between tote pan changes. A time of 2.0 min is allowed for a worker to tend a given machine. The time to walk between machines increases with the number of machines tended by a worker. In measurements by the time study department, the walking time between two machines in close proximity is about 15 sec. This walking time increases by 15 sec for each new machine added to the worker's tour. Determine (a) how many injection-molding machines one worker can service if no idle machine time is allowed, and (b) how many seconds during the work cycle the worker is idle.