Chapter 3

Work Flow and Batch Processing

Chapter 2 focused on ***unit operations***—single tasks or operations performed at one location and independently of other operations. However, production of a product or delivery of a service usually requires more than one unit operation. Multiple operations are typically needed. They are performed sequentially, usually by multiple workers at multiple workstations. Often, the workstations are located separately, which means that the work units must be moved from one operation to the next in the sequence. In many cases, the most practical way to accomplish the processing is to perform each unit operation on batches of work units. Thus we have the following topics to discuss in this chapter:

- *Sequential operations,* which refers to the series of separate processing steps that are performed on each work unit
- *Work flow,* which is concerned with the physical movement or transportation of work units through the sequence of unit operations (the unit operations might be thought of as interruptions in the work flow)
- *Batch processing,* which consists of the processing of work units in finite quantities or amounts, called *batches*.

The first section of the chapter discusses sequential operations and work flow, while the second section covers batch processing and the economic order quantity model. We then examine the issue of defects in sequential operations and batch processing. The final section in this chapter is concerned with work cells, a possible alternative to batch processing, and worker teams who staff the cell. This chapter is important because sequential operations, work flow, batch processing, work cells, and worker teams are so widely used in production, logistics, and service operations. Applications can also be found in office work and knowledge work.

3.1 SEQUENTIAL OPERATIONS AND WORK FLOW

The term ***sequential operations*** refers to a work system in which multiple processing steps are accomplished in order to complete a work unit, and the processing steps are performed sequentially (rather than simultaneously). The work units may be materials, parts, products, or people. In sequential operations, there are usually limitations on the order in which the operations can be performed, called ***precedence constraints***. Some operations must be completed before others can be started. For example, a hole must be drilled before it can be tapped to cut the threads. The internal components of a product must be assembled to the base part before the cover is attached. Passengers must be checked in and then processed through security at the airport before being allowed to board an aircraft. A surgery patient must be anesthetized before the scalpel is used. There are many examples of sequential operations in production, logistics, service operations, and knowledge work.

Sequential operations usually mean that the work units are processed at different locations. In a manufacturing plant (production work), different locations refer to the locations of the various processing machines and workstations used in the sequence. In a distribution center (logistics work), the various locations include the unloading dock, receiving stations, storage racks, and loading docks through which a product is moved inside the facility before being shipped to the retail store. In a hospital (service work), a surgery patient is first admitted and then moved to a waiting room before arriving in the operating room for the procedure. Because different locations are usually involved in sequential operations, the work units must be transported between the locations. The term ***work flow*** refers to this physical movement of work units in sequential processing. Associated with the physical flow is an information flow to monitor and control the movements of work units.

3.1.1 Work Flow Patterns

The work flow through a sequence of operations can follow different paths. Two basic types of work flow patterns can be distinguished: (1) pure sequential and (2) mixed sequential. In a ***pure sequential pattern***, all work units follow the same exact sequence of workstations and operations. There is no variation in the processing sequence. In a ***mixed sequential pattern***, there are variations in the work flow for different work units. The different work units are processed through different stations. The two types are depicted in Figure 3.1. The diagram is called a ***network diagram***, which is used here to show the flow of work units through a series of operations. (Other uses of the network

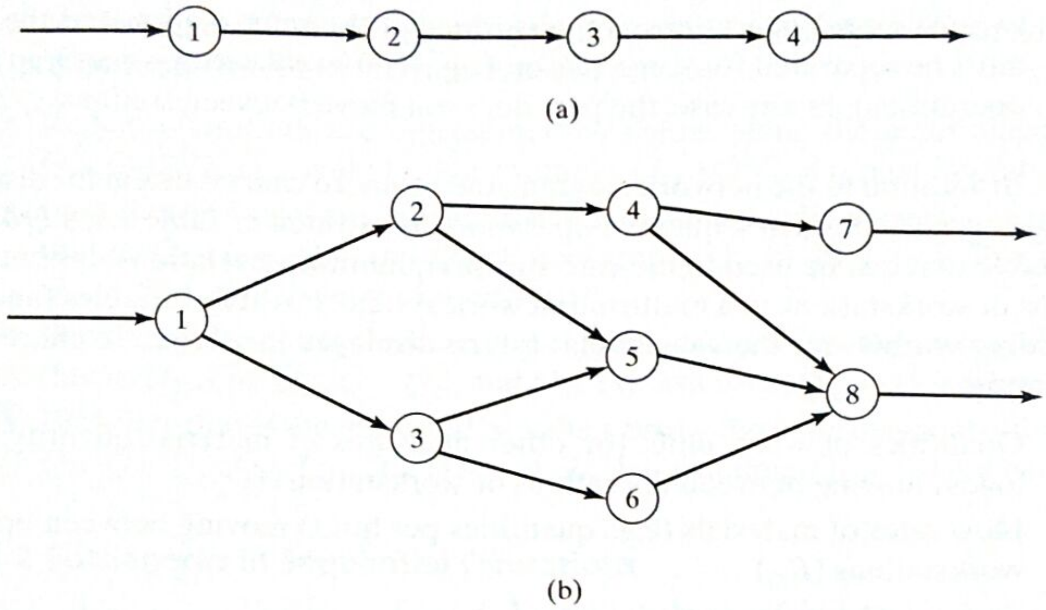


Figure 3.1 Network diagrams representing (a) pure sequential work flow and (b) mixed sequential work flow.

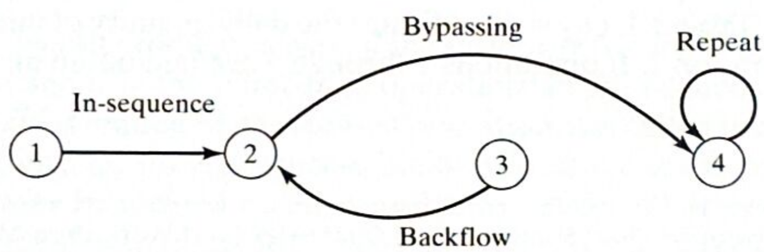


Figure 3.2 Four types of movements in a sequential work flow: in-sequence, bypassing, backflow, and repeat operation.

diagram are identified in Section 9.2.) The nodes (circles) represent operations and the arrows indicate the direction of work flow.

Several types of movements experienced by different work units can be distinguished in a sequential work flow. As illustrated in Figure 3.2, there are four types of moves:

- *In-sequence.* A transport of the work unit from the current operation (workstation) to the neighboring operation immediately downstream. It is a move in the forward direction in the sequence.
- *Bypassing.* A move in the forward direction but beyond the neighboring workstation by two or more stations ahead of the current station.
- *Backflow.* A move of the work unit in the backward direction by one or more stations.
- *Repeat operation.* An operation that is repeated at the same workstation. This might imply that several attempts are required to complete the operation, or that

two (or more) operations are performed at the same station and the operations must be separated for some reason (e.g., a different setup is required for the two operations). In any case, the part does not move between stations.

In addition to the network diagram, the From-To chart is useful for displaying and analyzing work flows in sequential operations. Illustrated in Table 3.1, a ***From-To chart*** is a table that can be used to indicate various quantitative relationships between operations or workstations in a multistation work system. Possible variables (and the corresponding symbols for the values) that can be displayed in a From-To chart include the following:

- Quantities of work units (or other measures of material quantity, e.g., pallet loads) moving between operations or workstations (Q_{ij})
- Flow rates of materials (e.g., quantities per hour) moving between operations or workstations (R_{fij})
- Distances between workstations (L_{ij})
- Combinations of these values (e.g., $R_{fij}L_{ij}$)

The subscripts used in Q_{ij}, R_{fij}, and L_{ij} indicate the "from" and "to" operations involved. For example, Q_{ij} indicates quantities of work units moving from operation i to operation j. In Table 3.1, $Q_{12} = 40$ indicates the daily quantity of units moving from operation 1 to operation 2. If operations 1 through 5 are laid out in an in-line arrangement,

TABLE 3.1 From-To Chart Showing Daily Quantities Q_{ij} of Work Units Moving Between Five Workstations

		To operation j				
		1	2	3	4	5
From operation i	1	—	40		15	
	2		—	30		
	3		10	—	20	
	4				25	50
	5					—

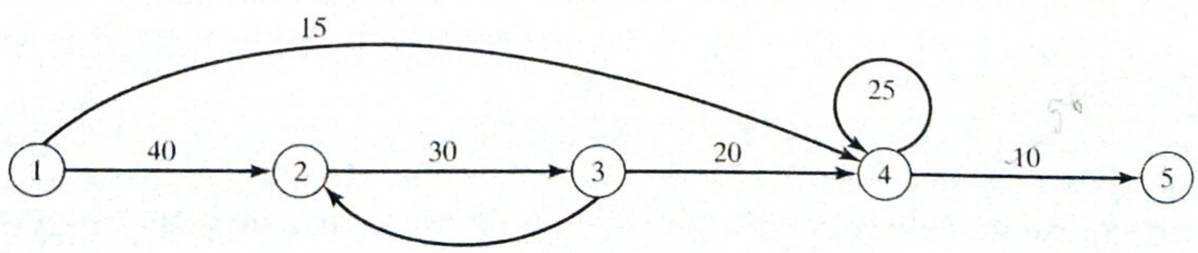


Figure 3.3 Network diagram of the data in the From-To chart of Table 3.1.

as shown in Figure 3.3, then we can make the following interpretations with respect to our previous definitions of the four types of moves:

- Repeat operations are represented by values along the main diagonal—that is, Q_{11}, Q_{22}, Q_{33}, Q_{44}, and Q_{55}. For example, $Q_{44} = 25$ is a repeat operation.
- In-sequence moves are indicated by values immediately above the main diagonal—that is, Q_{12}, Q_{23}, Q_{34}, and Q_{45}. For example $Q_{12} = 40$, $Q_{23} = 30$, $Q_{34} = 20$, and $Q_{45} = 50$ are all in-sequence moves.
- Bypassing moves are indicated by values located above the in-sequence moves—that is, Q_{13}, Q_{14}, Q_{15}, Q_{24}, Q_{25}, and Q_{35}. For example, $Q_{14} = 15$ is a bypassing move.
- Backflow moves are indicated by values below the main diagonal—that is, Q_{21}, Q_{31}, Q_{41}, Q_{51}, Q_{32}, Q_{42}, Q_{52}, Q_{43}, Q_{53}, and Q_{54}. For example, $Q_{32} = 10$ is a backflow move.

3.1.2 Bottlenecks in Sequential Operations

In a work system consisting of a sequence of processing operations, the overall production rate of the system is limited by the slowest operation in the sequence. That is,

$$R_{ps} = \text{Min}\{R_{pi}\} \text{ for } i = 1, 2, \ldots, n \tag{3.1}$$

where R_{ps} = overall production rate of the system, pc/hr; R_{pi} = production rate of operation i, pc/hr; and n = the number of operations in the sequence. Because the overall production rate is limited by the slowest operation, it is called the ***bottleneck*** operation.

Ultimately, the slowest process limits the output of the other operations in the sequence. It may be technologically possible to run the other operations faster, at least those that are upstream from the bottleneck, but this would only cause an accumulation of parts in front of the bottleneck. Accumulating work-in-process inventory before the bottleneck station makes no sense, except on a temporary basis. In the long run, the upstream operations must produce at a rate that is no greater than the bottleneck operation. The upstream operations are said to be blocked. ***Blocking*** means that the production rate(s) of one or more upstream operations are limited by the rate of a downstream operation.

The downstream operations can work no faster than the rate at which the bottleneck feeds work units to them. The operations downstream from the bottleneck are said to be starved for work. ***Starving*** means that the production rate(s) of one or more downstream operations are limited by the rate of an upstream operation (e.g., the bottleneck).

The reasons why one workstation is the slowest are usually due to (1) technological factors, (2) work allocation decisions, and (3) ergonomic limitations. ***Technological factors*** include limits on the speed of the equipment in the workstation—for example, the upper limit on the rotational speed of the motor that drives the machine at the workstation. Also included in this category are equipment breakdowns representing reliability problems. ***Work allocation decisions*** refer to the ways in which the total work content in the sequence is divided among the workstations. For instance, should the drilling operation included in the sequence be performed at the milling station, or should it be performed at a separate drilling station? Work allocation decisions are often influenced by technological factors. For example, the drilling operation cannot be performed at the milling station because that machine does not have a feed capability for drilling.

Ergonomic limitations are the physical (and mental) restrictions of the human worker at the workstation. How much time should the worker be allowed to manually load and unload a work unit into the machine? We cannot expect the worker to accomplish loading and unloading at a pace so fast that it leads to physiological injury.

3.2 BATCH PROCESSING

Work units are often processed in batches. We briefly discussed batch processing in the context of setup time in Section 2.4.2. ***Batch processing*** consists of the processing of work units—materials, products, information, or people, depending on the nature of the processes—in finite quantities or amounts. Batch processing is common in many production, logistics, and service operations. In low and medium quantity production, it is common to process parts in batches. Passengers who travel by airplane are transported in batches. Freight is moved in batch loads by truck or railway train. Teachers grade reports and exams one at a time in batches. Personal laundry is washed as a batch in a washing machine.

Batch processing is accomplished in either of two ways: (1) ***sequential batch processing***, in which the members of the batch are processed one after the other; and (2) ***simultaneous batch processing***, in which the members of the batch are processed all at the same time. Both types of processing are represented in our preceding list of examples. Table 3.2 presents more examples illustrating the two categories.

3.2.1 The Pros and Cons of Batch Processing

Batch processing is discontinuous because there are interruptions between the batches. The interruptions represent times when the equipment is not being productive, which adversely affects productivity. In production, the machine tool must be changed over for the next part style; we referred to this interruption as the setup time in Chapter 2. In air travel, the airplane must remain at the terminal to discharge passengers, be cleaned and refueled, and load passengers for the next flight. In book publishing, the plates on the printing presses must be changed for the next book.

When viewed as an operation sequence, delays occur between processing steps because multiple batches are competing for the same equipment. Queues of batches

TABLE 3.2 Examples of Sequential and Simultaneous Batch Processing

Sequential Batch Processing	Simultaneous Batch Processing
Production machining operations. Other examples include sheet metal stamping, injection molding, casting, welding, and powder-metal pressing.	Production electroplating operations. Other examples include many chemical batch processes and powder-metal sintering.
Batch assembly	Passenger air travel
Book publishing	Cargo transportation
Payroll checks	Entertainment in movie theaters
Grading of student papers	Laundry

form in front of workstations, resulting in long lead-times to complete the work units and the accumulation of large quantities or amounts of work units in the sequential processing system. In production this accumulation of inventory is called ***work-in-process*** (WIP). Neither long lead-times nor high work-in-process are desirable. Yet these are typical characteristics of batch processing.

Despite the disadvantages cited above, batch production is nevertheless widely used for the following reasons:

- *Work unit differences.* There are differences in work units between batches, and it is necessary to make changes in the methods, tooling, and equipment to accommodate the differences.
- *Equipment limitations.* The size capacity of the equipment restricts the amount of material or quantity of work units that can be processed at one time (e.g., the equipment capacity imposes an upper limit on the batch size).
- *Material limitations.* The material in the operation must be processed as a unit, and that unit will be later divided into multiple work units (e.g., the processing of silicon wafers into individual integrated circuit chips).

Batch processing is widely used in production operations.[1] It is probably the most common form of production. In ***batch production***, a batch of one type of part (or product) is completed, and then the work system is changed over to produce a batch of a different type of part, and then another, and so on. The changeover takes time, because the physical setup for the second product is different from the first. Tooling has to be changed, equipment settings must be adjusted, and workers need to familiarize themselves with the new part or product. This setup time is lost production time, which is a disadvantage of batch production. Thus, a work system used for batch production experiences a sequence of setups followed by production runs, as illustrated in Figure 3.4.

While the work system is producing, its production rate is greater than the demand rate for the current product type. This has two effects. First, it means that the same work system can be shared among multiple products, which has economic benefits in terms of equipment investment. Second, it means that the units in a batch of items must be held in inventory for extended periods of time, while demand gradually reduces the stock level down to the point at which another production run will be made. This is the typical ***make-to-stock*** situation, in which items are manufactured to replenish inventory

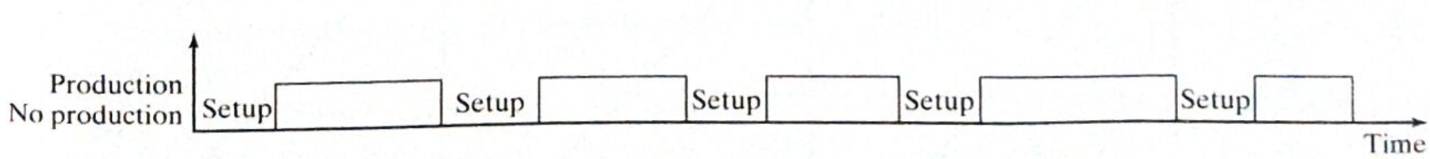


Figure 3.4 The alternating cycles of setup and production run experienced by a work system engaged in batch production.

[1]The discussion that follows is based on Section 26.5 in [3].

that has been gradually depleted by demand. An important question arises in make-to-stock situations and in batch production: How many units should be produced in a given batch? The answer involves achieving a balance between inventory costs and setup costs. Holding items in inventory is an expense in the form of storage costs and investment interest. And each time the work system must be changed over, the resulting downtime is also an expense. From the viewpoint of items that are produced in batches and carried in inventory, the sudden increase and gradual depletion causes the inventory level over time to have the sawtooth appearance shown in Figure 3.5.

3.2.2 Economic Order Quantity Model

A total cost equation can be derived for the sum of carrying cost and setup cost for the inventory model in Figure 3.5. The figure assumes that demand rate is constant, so that inventory is gradually depleted over time and then quickly replenished to some maximum level determined by the order quantity. Because of the triangular shape of inventory cycle, the average inventory level is one-half the maximum level Q in our figure, and this average is multiplied by the inventory carrying cost per item. The annual setup cost is determined as the number of setups per year multiplied by the cost per setup. The total annual inventory cost is therefore given by

$$TIC = \frac{C_h Q}{2} + \frac{C_{su} D_a}{Q} \tag{3.2}$$

where TIC = total annual inventory cost (holding cost plus ordering cost), \$/yr; Q = order quantity, pc/order; C_h = inventory carrying or holding cost, \$/pc/yr; C_{su} = setup cost and/or ordering cost for an order, \$/setup or \$/order; and D_a = annual demand for the item, pc/yr. In the second term on the right-hand side of the equation, the ratio D_a/Q is

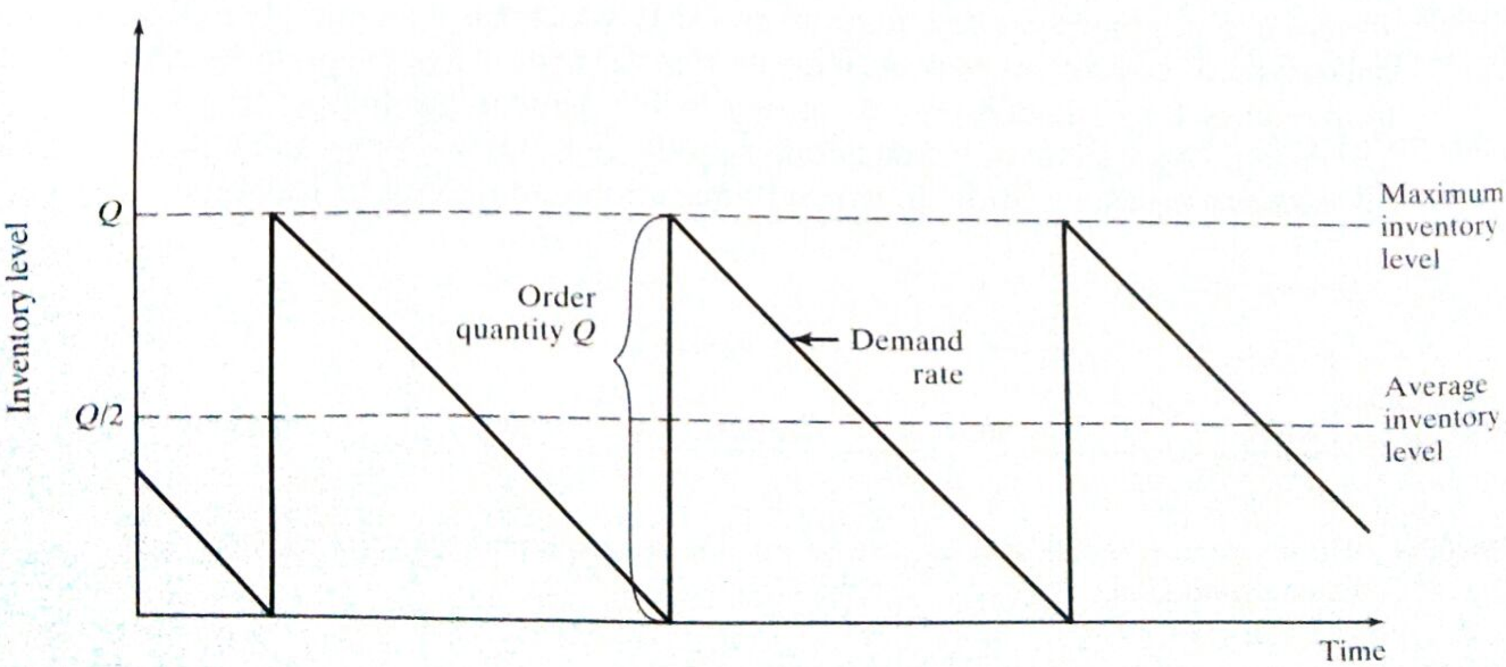


Figure 3.5 Model of inventory level over time in the typical make-to-stock situation.

the number of orders or batches produced per year; it therefore gives the number of setups per year.

The holding cost C_h consists of two main components, investment cost and storage cost. Both are related to the time that the inventory spends in the warehouse or factory. The investment cost results from the money the company must invest in inventory before it is sold to customers. This inventory investment cost can be calculated as the interest rate paid by the company, i (expressed as a fraction), multiplied by the value of the inventory.

Storage cost occurs because the inventory takes up space that must be paid for. The amount of the cost is generally related to the size of the part and how much space it occupies. As an approximation, it can be related to the value or cost of the item stored. For our purposes, this is the most convenient method of valuating the storage cost of an item. By this method, the storage cost equals the cost of the inventory multiplied by the storage rate, s. The term s is the storage cost as a fraction of the value of the item in inventory.

Combining interest rate and storage rate into one factor, we have $h = i + s$, where h is the holding cost rate. Like i and s, it is a fraction that is multiplied by the cost of the item to evaluate the cost of holding the items in inventory. Accordingly, holding cost can be expressed as

$$C_h = h\, C_{pc} \tag{3.3}$$

where C_h = holding (carrying) cost, \$/pc/yr; C_{pc} = unit cost of the item, \$/pc; and h = holding cost rate, rate/yr.

Setup cost includes the cost of idle production equipment during the changeover time between batches. The costs of labor performing the setup changes might also be added in. Thus,

$$C_{su} = T_{su} C_{dt} \tag{3.4}$$

where C_{su} = setup cost, \$/setup or \$/order; T_{su} = setup or changeover time between batches, hr/setup or hr/order; and C_{dt} = cost rate of machine downtime during the changeover, \$/hr. In cases where parts are ordered from an outside vendor, the price quoted by the vendor usually includes a setup cost, either directly or in the form of quantity discounts. C_{su} should also include the internal costs of placing the order to the vendor.

Equation (3.2) excludes the actual annual cost of part production. If this cost is included, then annual total cost is given by the following equation:

$$TC = D_a C_{pc} + \frac{C_h Q}{2} + \frac{C_{su} D_a}{Q} \tag{3.5}$$

where $D_a C_{pc}$ = annual demand (pc/yr) multiplied by cost per item (\$/pc).

If the derivative is taken with respect to Q in either equation (3.2) or (3.5), the economic order quantity (EOQ) formula is obtained by setting the derivative equal to zero and solving for Q. This batch size minimizes the sum of carrying costs and setup costs:

$$Q = EOQ = \sqrt{\frac{2D_aC_{su}}{C_h}} \tag{3.6}$$

where EOQ = economic order quantity (number of parts to be produced per batch), pc/batch or pc/order; and the other terms have been defined previously.

Example 3.1 Economic Order Quantity Formula

The annual demand for a certain item made-to-stock is 15,000 pc/yr. One unit of the item costs $20.00 and the holding cost rate is 18%/yr. Setup time to produce a batch is 5 hr. The cost of equipment downtime plus labor is $150/hr. Determine the economic order quantity (EOQ) and the total inventory cost for this case.

Solution: Setup cost $C_{su} = 5 \times \$150 = \$750$. Holding cost per unit $= 0.18 \times \$20.00 = \$3.60$. Using these values and the annual demand rate in the EOQ formula, we have

$$EOQ = \sqrt{\frac{2(15000)(750)}{3.60}} = 2500 \text{ units}$$

Total inventory cost is given by the TIC equation:

$$TIC = 0.5(3.60)(2500) + 750(15{,}000/2500) = \$9000$$

Including the actual production costs in the annual total and using equation (3.5), we have:

$$TC = 15{,}000(20) + 9000 = \$309{,}000$$

■

The EOQ formula has been widely used for determining so-called optimum batch sizes in production. More sophisticated forms of equations (3.2) and (3.5) have appeared in the literature—for example, models that take production rate into account to yield alternative EOQ equations [7]. Equation (3.6) is the most general form and is quite adequate for most real-life situations. The difficulty in applying the EOQ formula is in obtaining accurate values of the parameters in the equation—namely, (1) setup cost and (2) inventory carrying costs. These cost factors are usually difficult to evaluate; yet they have an important impact on the calculated economic batch size.

There is no disputing the mathematical accuracy of the EOQ equation. Given specific values of annual demand (D_a), setup cost (C_{su}), and carrying cost (C_h), equation (3.6) computes the lowest cost batch size to whatever level of precision the user desires. The trouble is that the user may be lulled into a false sense of security by the knowledge that no matter how much it costs to change the setup, the EOQ formula always calculates the optimum batch size for that setup cost. For many years in U.S. industry, this belief tended to encourage long production runs by manufacturing managers. The thought process went something like this: "If the setup cost increases, we just increase the batch size, because the EOQ formula always tells us the optimum production quantity."

Users of the EOQ equation must not lose sight of the total inventory cost equation, equation (3.2), from which EOQ is derived. Examining the TIC equation, a cost conscious production manager would quickly conclude that total inventory cost can be reduced by decreasing the values of holding cost (C_h) and setup cost (C_{su}). The production manager may not be able to exert much influence on holding cost, because it is determined largely by prevailing interest rates. However, methods can be developed to reduce setup cost by reducing the time required to accomplish the changeover of a production machine. Reducing setup times is an important focus in lean production, and we review the approaches for achieving the reductions in Section 20.2.2.

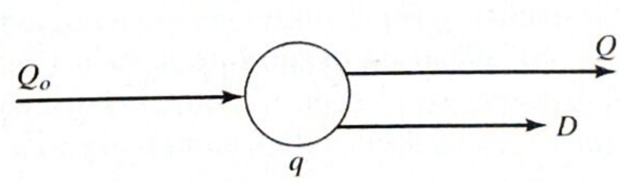
3.3 DEFECTS IN SEQUENTIAL OPERATIONS AND BATCH PROCESSING

In a sequence of operations, defective units may be produced in any or all of the operations. The defect rate must be considered in determining the quantity of good units produced. This is the issue we consider in this section.[2] Figure 3.6 depicts a unit operation in which incoming work units are processed to yield good products and defects. The starting quantity or batch size of raw material to be processed is Q_o, the fraction defect rate produced by the operation is q, yielding good units of quantity Q and defects numbering D. We previously encountered the fraction defect rate q in our discussion of workloads in Chapter 2 (Section 2.4.1). The relationships among the variables in a unit operation are defined as follows:

$$Q = Q_o(1 - q) \tag{3.7}$$

and

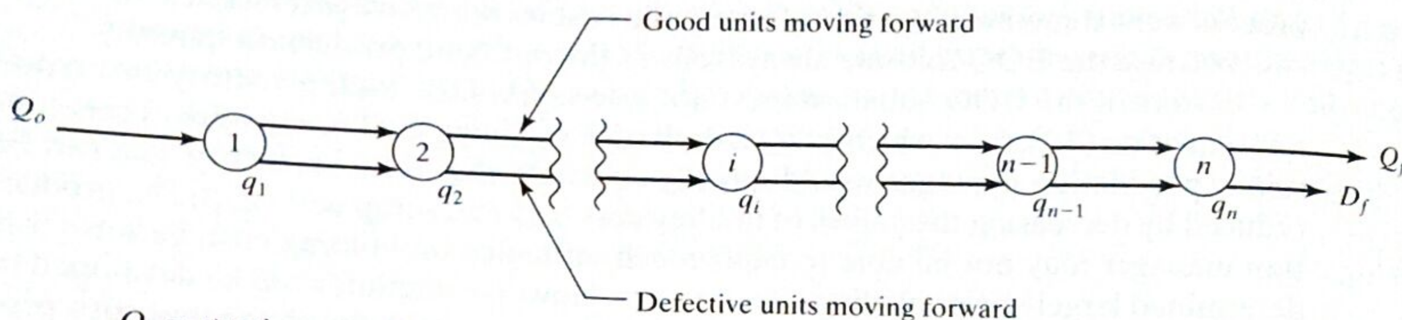
$$D = Q_o q \tag{3.8}$$



Q_o = starting quantity,
q = fraction defect rate,
Q = quantity of good units produced, and
D = number of defects produced.

Figure 3.6 The unit operation in which incoming work units are processed to yield good products and defects.

[2] This section is based on Section 22.5 in [3].



Q_o = starting quantity, Q_f = quantity of good units produced, and
q_i = fraction defect rate in operation i, D_f = number of defects produced.

Figure 3.7 A sequence of unit operations where each operation has a certain fraction defect rate.

A sequence of unit operations is portrayed in Figure 3.7. Each operation or workstation has a certain fraction defect rate q_i, so the final quantity of defect-free units exiting the sequence is given by

$$Q_f = Q_o(1 - q_1)(1 - q_2)\dots(1 - q_i)\dots(1 - q_n) \tag{3.9}$$

where Q_f = final quantity of good units produced by the sequence of n operations and Q_o = the starting quantity. The ratio of good units produced to starting units in a sequence of operations is called the ***yield***.

$$Y = \frac{Q_f}{Q_o} = (1 - q_1)(1 - q_2)\dots(1 - q_i)\dots(1 - q_n) \tag{3.10}$$

where Y = yield, usually expressed as a percentage. The yield metric can be applied to a sequence of operations or to an individual process in the sequence. The number of defects in the final batch is given by

$$D_f = Q_o\{1 - (1 - q_1)(1 - q_2)\dots(1 - q_i)\dots(1 - q_n)\} \tag{3.11}$$

where D_f = number of defects in the final batch. If all q_i are equal, then the two equations reduce to

$$Q_f = Q_o(1 - q)^n \tag{3.12}$$

and

$$D_f = Q_o\{1 - (1 - q)^n\} \tag{3.13}$$

where q = fraction defect rate of each operation in the sequence.

Example 3.2 The Compounding Effect of Defect Rate in Sequential Operations

A starting batch of 1000 work units is processed through 10 operations, each of which has a fraction defect rate of 5%. Determine (a) how many good parts and defects are produced by the first operation, (b) how many good parts and defects are in the final batch, and (c) the yield of the first operation and the yield of the operation sequence.

Solution **(a)** For the first operation,

$$Q = 1000(1 - 0.05) = 950 \text{ good units}$$

and

$$D = 1000(0.05) = 50 \text{ defects}$$

(b) For the 10 sequential operations,

$$Q_f = 1000(1 - 0.05)^{10} = 1000(0.95)^{10} = 1000(0.5987) = 599 \text{ good units}$$

and

$$D_f = 1000(1 - 0.5987) = 1000(0.4013) = 401 \text{ defects}$$

(c) The yield of the first process is $Y_1 = 950/1000 = 95\%$. The yield of the process sequence is $Y = 0.5987 = 59.87\%$. ■

The binomial expansion can be used to determine the allocation of defects associated with each operation or workstation i. Given that q_i equals probability of a defect being produced in operation i, let p_i equal the probability of a good unit being produced in the sequence; thus $p_i + q_i = 1$. Expanding this for n operations, we have

$$\prod_{i=1}^{n} (p_i + q_i) = 1 \tag{3.14}$$

To illustrate, consider the case of two operations in sequence ($n = 2$). The binomial expansion yields the expression

$$(p_1 + q_1)(p_2 + q_2) = p_1p_2 + p_1q_2 + p_2q_1 + q_1q_2$$

where p_1p_2 = proportion of defect-free parts; p_1q_2 = proportion of parts that have no defects from operation 1 but a defect from operation 2; p_2q_1 = proportion of parts that have no defects from operation 2 but a defect from operation 1; and q_1q_2 = proportion of parts that have both types of defect.

As the number of operations in the sequence increases, the number of terms in the binomial expansion increases exponentially in proportion to 2^n, where n equals the number of operations. Thus for 10 operations in sequence, the number of terms is 1024, all but one representing various combinations of processing defects. The one term representing the proportion of good units is the yield, given by equation (3.10).

3.4 WORK CELLS AND WORKER TEAMS

A ***work cell*** is a group of workstations dedicated to the processing of a range of work units within a given type. The processing is typically performed as a sequence of operations. In production, where work cells are often employed, the work units are parts, and the range of parts is called a ***part family***. The members of the part family possess similarities that permit them to be processed by the work cell. The processing of part families is associated with an approach to manufacturing called ***group technology***, in which similar parts are identified and grouped together to take advantage of their similarities in design and production.

Work cells can often be used to mitigate some of the disadvantages of batch processing. Instead of processing each of the various part types in batches, the work units are processed individually and continuously, without the need for time-consuming changeovers between part types. This is made possible by (1) the similarity of parts within a part family and (2) the adaptability and flexibility of the workers and equipment in the cell that can accommodate the moderate differences among part family members. In a work cell, the operations are integrated to facilitate the flow of work from one workstation to the next, so that lead time and work-in-process are minimized.

3.4.1 Work Cell Layouts and Material Handling

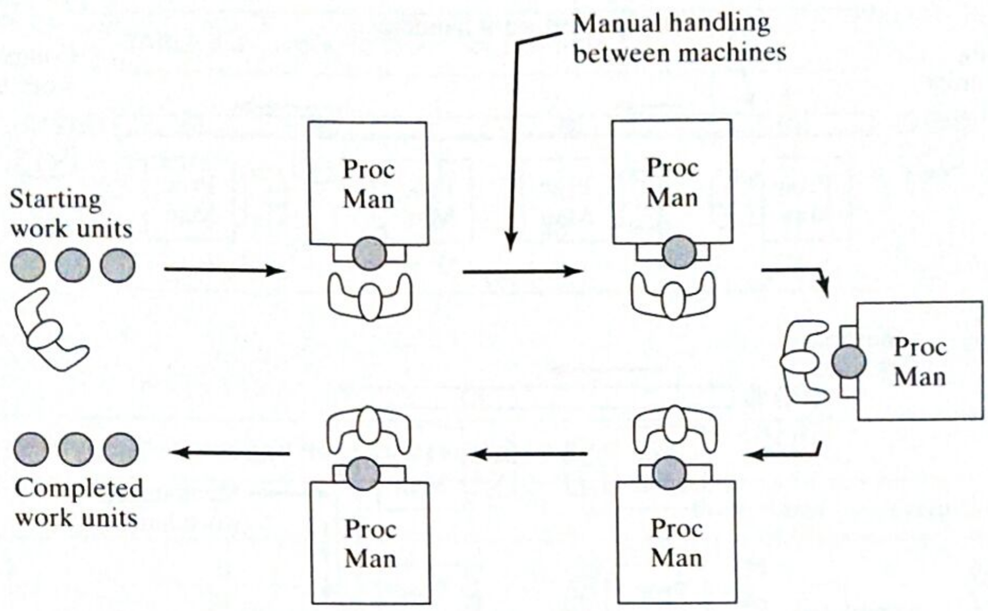
Because the range of parts or products in a work cell is limited, the processing (or assembly) of work units consists of operations that are similar but not identical. Thus, although the layout of the cell is fixed, the operations and their sequence are not. We are dealing with a mixed sequential work flow system (Section 3.1.1). The workstations in the cell are usually arranged to facilitate the flow of work from one operation to the next. In some cases, the stations are connected by a mechanized material-handling system. In other cases the work is carried from station to station by hand.

Work cells can be distinguished according to the following factors: (1) number of workstations in the cell, (2) material-handling method, and (3) layout of the cell. They can also be distinguished by the way in which the workers are organized into worker teams. We discuss worker teams in Section 3.4.3.

The number of workstations in a cell can range from two to about a dozen. There are no hard limits on the upper end of the range. However, one of the advantages of a work cell is that it promotes teamwork and a sense of mission among its workers, and this advantage tends to be diminished if the cell becomes too large. If the number of workstations is very large (e.g., several dozen to several hundred), then the work is more likely to be organized as a manual assembly line, discussed in Chapter 4.

The material-handling method in a work cell can be manual or mechanized. Manual material handling consists of the workers in a cell moving the work units between stations. This is appropriate when one worker performs all of the operations to complete a given work unit, so it is logical for the worker to carry the units through the sequence of stations, stopping at those stations where processing is required. Manual handling can also be used when workers are assigned to specific workstations. Either the station operators themselves are responsible for moving the work units forward, or designated material-handling workers are assigned to move the units between stations. Manual work cells are often organized into a U-shaped layout, as shown in Figure 3.8. This arrangement has been found to promote teamwork among the workers. It also allows for variations in operation sequence among different part or product styles.

Mechanized handling is usually achieved by means of a powered conveyor, such as a belt conveyor. A variety of layouts are possible in work cells with mechanized handling, including in-line, U-shaped, loop, and rectangular, as shown in Figure 3.9. In an in-line layout, the workstations are arranged in a straight line, as in Figure 3.9 (a). This layout type is appropriate when all work units are processed in the same basic operation



Proc = processing operation (e.g., mill, drill), Man = manual operator, arrows indicate predominant work flow.

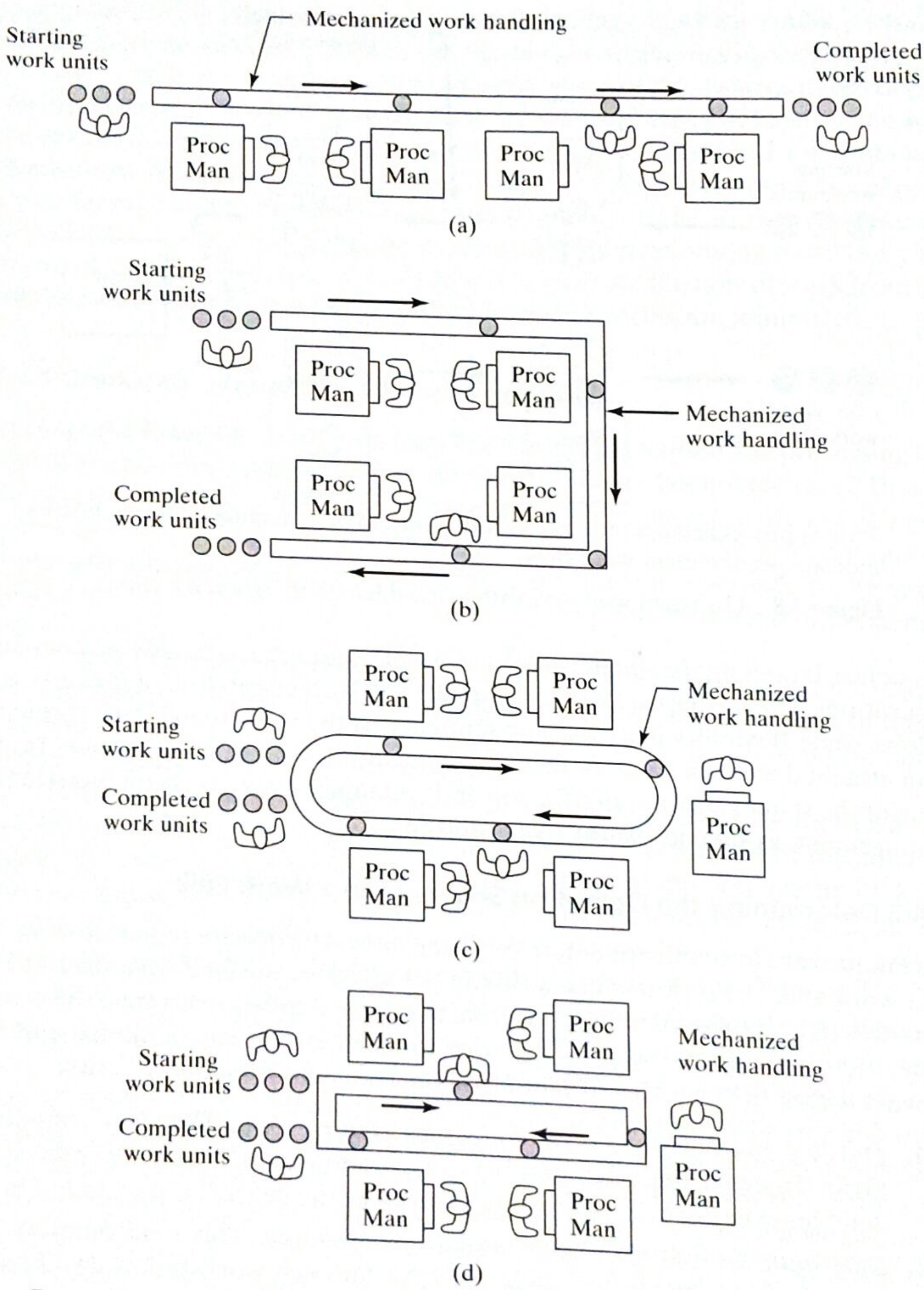
Figure 3.8 U-shaped work cell with manual handling between stations.

sequence. It does not facilitate variations in work sequence as readily as other layout configurations. The U-shaped layout, Figure 3.9 (b), is an adaptation of the in-line type that allows some flexibility in processing sequence. If the work units move through the system attached to work carriers, then some means of returning the carriers to the beginning of the sequence is required. Loop and rectangular layouts accommodate this return requirement, as seen in Figure 3.9 (c) and (d).

3.4.2 Determining the Operation Sequence in a Work Cell

Techniques are available for determining the most appropriate sequence of workstations in a work cell. Let us introduce a simple yet effective method described in Hollier [4] that uses data contained in From-To charts and is intended to arrange the stations in an order that maximizes the proportion of forward moves (in-sequence and bypassing moves) within the cell. The Hollier algorithm can be outlined as follows:

1. *Develop the From-To chart from part routing data.* The data contained in the From-To chart indicates numbers of part moves between the workstations (or machines) in the cell. Moves into and out of the cell are not included in the chart.
2. *Determine the From-To ratio for each workstation.* This is accomplished by summing up all of the "From" and "To" trips for each workstation. The From sum for a station is determined by adding the entries in the corresponding row, and the To sum is determined by adding the entries in the corresponding column. For each station, the From-To ratio is calculated by taking the From sum for each station and dividing by the respective To sum.
3. *Arrange workstations in order of decreasing From-To ratio.* Stations with high From-To ratios distribute work to other stations in the cell but receive work from few of them. Conversely, stations with low From-To ratios receive more work than



Proc = processing (e.g., mill, drill), Man = manual operator, arrows indicate predominant work flow.

Figure 3.9 Alternative layouts in work cells with mechanized material handling: (a) in-line, (b) U-shaped, (c) loop, and (d) rectangular.

TABLE 3.3 From-To Chart for Example 3.3

To:	1	2	3	4
From: 1	0	5	0	25
2	30	0	0	15
3	10	40	0	0
4	10	0	0	0

TABLE 3.4 From-To Sums and Ratios for Example 3.3

To:	1	2	3	4	From Sums	From-To Ratios
From: 1	0	5	0	25	**30**	**0.60**
2	30	0	0	15	**45**	**1.0**
3	10	40	0	0	**50**	∞
4	10	0	0	0	**10**	**0.25**
To Sums	**50**	**45**	**0**	**40**	**135**	

they distribute. Therefore, stations are arranged in order of descending From-To ratio; that is, stations with high ratios are placed at the beginning of the work flow, and stations with low ratios are placed at the end of the work flow. In case of a tie, the workstation with the higher From value is placed ahead of the station with a lower value.

Example 3.3 Work Cell Station Sequence

Four workstations, 1, 2, 3, and 4, have been assigned to a work cell. An analysis of 50 parts processed in these stations has been summarized in the From-To chart of Table 3.3. Additional information is that 50 parts enter the cell at station 3, 20 parts leave after processing at station 1, and 30 parts leave after station 4. Determine a logical workstation arrangement using the Hollier algorithm.

Solution: Table 3.3 is repeated in Table 3.4 along with the From-To sums. The From-To ratios are given in the last column on the right. Arranging the stations in order of descending From-To ratio, the cell is sequenced as follows:

$$3 \rightarrow 2 \rightarrow 1 \rightarrow 4$$

■

It is helpful to use a network diagram (Figure 3.10) to conceptualize the work flow in the cell. The work flow consists of mostly in-sequence moves; however, there is some bypassing and backflow of parts that must be considered in the design of any material-handling system that might be used in the cell. A powered conveyor would be appropriate for the forward flow between machines, with manual handling for the back flow.

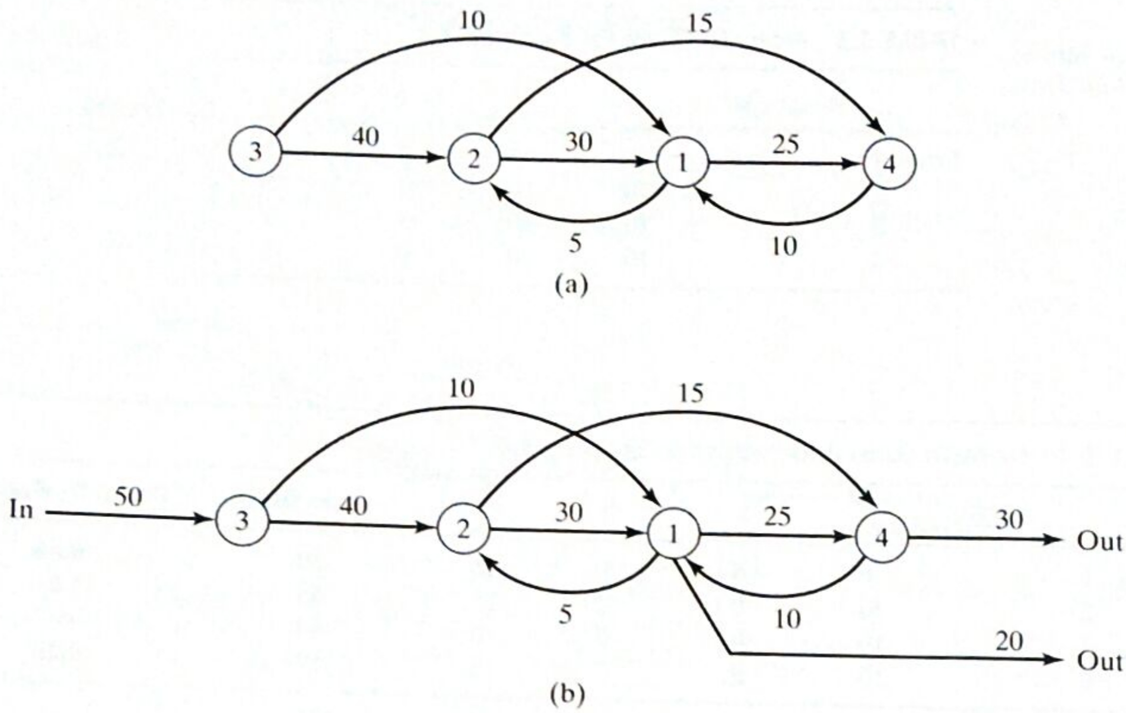


Figure 3.10 Network diagram for the work cell station sequence in Example 3.3: (a) internal work flow given in Table 3.3 and (b) work flow including work units into and out of the cell.

Several performance measures can be used to compare alternative solutions to the machine sequencing problem. The measures are based on the types of moves defined in Section 3.1:

1. *Percentage of in-sequence moves*, computed by adding all of the values representing in-sequence moves and dividing by the total number of moves.
2. *Percentage of bypassing moves*, found by adding all of the values representing bypassing moves and dividing by the total number of moves.
3. *Percentage of backflow moves*, determined by summing all of the values representing backflow moves and dividing by the total number of moves.
4. *Percentage of repeated operations*, which is the sum of all repeated operations divided by the total number of moves.

It is desirable for the layout arrangement to have high proportions of in-sequence and bypassing moves since these both represent forward work flow (in-sequence moves are more desirable than bypassing moves). The layout should minimize the percentage of backflow moves. The percentage of repeated operations will have the same value for all solutions.

Example 3.4 Performance Measures for Example 3.3

Compute (a) the percentage of in-sequence moves, (b) the percentage of bypassing moves, and (c) the percentage of backflow moves for the solution in Example 3.3.

Solution: From Figure 3.10, the total number of moves is 135 (totaling either the From sums or the To sums).

(a) The number of in-sequence moves = 40 + 30 + 25 = 95; percentage of in-sequence moves = 95/135 = 0.704 = 70.4%.

(b) The number of bypassing moves = 10 + 15 = 25; percentage of bypassing moves = 25/135 = 0.185 = 18.5%.

(c) The number of backflow moves = 5 + 10 = 15; percentage of backflow moves = 15/135 = 0.111 = 11.1%.

There are no repeated operations, so all of the part moves between workstations are accounted for by the three measures in (a), (b), and (c). ■

3.4.3 Worker Teams

Worker teams are closely associated with the operation of work cells. A ***worker team*** is a group of employees who work together to achieve common objectives. In the case of a work cell, the common objectives of the team are to (1) meet the production or service schedule, (2) achieve high quality in the goods or services provided by the cell, and (3) make the operation of the cell as efficient as possible. These objectives are achieved by means of ***teamwork***, in which the collective skills and efforts of the team members exceed the sum of their individual skills and efforts. Teamwork provides a synergistic effect that would not be realized by each member working independently.

Production Work Teams. Our primary interest is in production work teams, which are generally limited in size to between five and 15 workers, and the team has a defined level of authority for operating the work cell (or other organizational unit) for which it is responsible. Production work teams represent an attempt to instill a sense of teamwork in a production department, office, or other work unit. Accordingly, the membership of the team consists of the regular workers in the unit. The purpose of organizing them as a team is to improve the morale and efficiency of the work unit. Work teams can be organized and operated in various ways, the differences being in the level of autonomy given to them. At one end of the spectrum are ***work-unit teams*** that have little autonomy and are basically a unit in the traditional hierarchical structure of the organization. They operate with a foreman or manager who supervises the team members. At the other extreme are ***self-managed work teams*** that enjoy significant autonomy. They not only perform the work of the unit, they also plan and manage it. Self-managed work teams manifest a high level of worker involvement and empowerment. Team leaders are elected by the membership, and the position is often rotated among the members.

An evolutionary process often occurs between the two forms, with work-unit teams gradually transforming themselves into self-managed teams over the course of several years under the guidance and encouragement of management. The final form of the self-managed work team is one in which the regular management and administrative duties in a traditional organization are assumed by the team leadership, at least within their own working units. The function of company management evolves from commanding the work units under the former hierarchical structure to coordinating their activities in the new worker team organization.

One of the important keys to success for production work teams is ***cross-training***, in which workers become trained in more than one job in the work cell. Although each individual brings unique knowledge, skills, and abilities to the team's activities, having more than one team member know each job mitigates problems of absences and allows for job rotations to increase work variety and employee satisfaction. Workers are often rewarded in proportion to their versatility in acquiring multiple task skills.

Other Types of Worker Teams. There are several other types of worker teams, each suited to different objectives that the sponsoring organization is attempting to achieve. These objectives may be temporary and short term (e.g., solving a problem or completing a project) or continuous and long term (e.g., production work teams). Here we discuss three principal categories, classified according to function and/or objective: (1) project teams, (2) cross-functional teams, and (3) improvement teams.

Project teams are organized for the purpose of expeditiously completing a given project. They are commonly associated with construction projects (e.g., buildings, bridges, roads), but other project areas include new product design, research, and software development. Like production work teams, the team membership consists of the workers responsible for doing the work. However, whereas production is continuous and ongoing, projects are completed one at a time and have a predictable life cycle. We discuss project teams in Chapter 7.

Cross-functional teams are distinguished by the fact that their members are drawn from different functional departments in the organization. Upper management is responsible for identifying the problem area to be addressed and selecting the appropriate team members who are qualified to solve it. The purpose of organizing a cross-functional team is to bring a diversity of knowledge and backgrounds together and to overcome functional boundaries. Examples of cross-functional teams include (1) ***concurrent engineering teams***, which are involved in the development and design of a new product; (2) ***task forces***, which are constituted to deal with an urgent problem or immediate commercial opportunity confronting the organization; and (3) ***crisis management teams***, which are a form of task force intended to cope with a particular crisis or disaster faced by the organization, such as the loss of key personnel (e.g., the unexpected death of the chief executive officer), floods and hurricanes, terrorist attacks, and liability lawsuits.

Improvement teams are organized to improve the operations of a department or process. The focus of the improvement may be on product quality, productivity and process efficiency, job design and ergonomics, safety, or some other aspect of the department. Improvement teams are usually temporary; they are instituted to address a particular problem area (e.g., product quality), and once that problem is solved, the team is disbanded. We discuss improvement teams in the context of lean production and Six Sigma quality programs in Chapters 20 and 21.

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REVIEW QUESTIONS

3.1 What does sequential operations mean?

3.2 What is a precedence constraint in sequential operations?

3.3 What is the difference between pure sequential work flow and mixed sequential work flow?

3.4 Name and define the four types of part moves between workstations in sequential operations.

3.5 What is a From-To chart?

3.6 What is a bottleneck in sequential operations?

3.7 What do the terms *starving* and *blocking* mean in terms of sequential operations?

3.8 What does the term *batch processing* mean?

3.9 What are some of the disadvantages of batch processing?

3.10 Given the disadvantages of batch production, what are the reasons why it is so widely used in industry?

3.11 What are the two cost terms in the economic order quantity model?

3.12 Write the equation that describes the relationship between the starting quantity of work units Q_o, the completed quantity Q, and the fraction defect rate q of the operation processing the work units.

3.13 What is a work cell?

3.14 What is a worker team?

3.15 Define teamwork.

3.16 What is the difference between a work-unit team and a self-managed work team?

3.17 What is cross-training and what is its value in a worker team?

3.18 Name some examples of cross-functional teams.

PROBLEMS

Workflow Structures

3.1 Four parts (A, B, C, and D) are processed through a sequence of four operations (1, 2, 3, and 4). Not all parts are processed in all operations. Part A, which has weekly quantities of 70 units, is processed through operations 1, 2, and 3 in that order. Part B, which has weekly quantities of 90 units, is processed through operations 2, 4, and 1 in that order. Part C, which has weekly quantities of 65 units, is processed through operations 3, 2, and 4 in that order. Finally, part D, which has weekly quantities of 100 units, is processed through operations

2, 1, and 4 in that order. (a) Draw the network diagram and (b) prepare the From-To table for this work system.

3.2 Five parts (A, B, C, D, and E) are processed through a sequence of five operations (1, 2, 3, 4, and 5). Not all parts are processed in all operations. Part A, which has daily quantities of 50 units, is processed through operations 1, 3, 5, and 1 in that order. Part B, which has daily quantities of 70 units, is processed through operations 2, 4, and 5 in that order. Part C, which has daily quantities of 25 units, is processed through operations 3, 2, and 4 in that order. Part D, which has daily quantities of 10 units, is processed through operations 1, 2, 4, and 5 in that order. Finally, part E, which has daily quantities of 15 units, is processed through operations 3, 1, and 2 in that order. (a) Draw the network diagram and (b) prepare the From-To table for this work system.

Bottleneck Operations

3.3 A factory produces cardboard boxes. The production sequence consists of three operations: (1) cutting, (2) indenting, and (3) printing. There are three automated machines in the factory, one for each operation. The machines are 100% reliable and the scrap rate in each operation is zero. In the cutting operation, large rolls of cardboard are fed into the cutting machine, which cuts the cardboard into blanks. Each large roll contains enough material for 4000 blanks. Production time is 0.03 min/blank during a production run, but it takes 25 min to change rolls and cutting dies between runs. In the indenting operation, indentation lines are pressed into printed blanks that allow the blanks to later be bent into boxes. Indenting is performed at an average time of 2.5 sec/blank. Batches from the previous cutting operation are subdivided into two smaller batches with different indenting lines, so that starting batch size in indenting is 2000 blanks. The time needed to change dies between batches on the indenting machine is 30 min. In printing, the blanks are printed with labels for a particular customer. Starting batch size in printing is 2000 blanks (these are the same batches as in indenting). The production rate is 30 blanks/min. Between batches, changeover of the printing plates is required, which takes 40 min. What is the maximum possible output of this factory during a 40-hour week, in printed and indented blanks/week. Assumptions: (1) steady state operation and (2) there is work-in-process between operations 1 and 2 and between 2 and 3, so that blocking and starving of operations is negligible.

3.4 Solve the previous problem but assume that the reliability of the cutting machine is 80% (availability or uptime proportion is 80%), the reliability of the indenting machine is 95%, and the reliability of the printing machine is 85%. These reliability factors apply only when the machines are producing, not during setup or changeovers.

3.5 A factory produces one product, with 1 unit of raw material required for each unit of product. Two processes are required to produce the product: process 1, which feeds into process 2. A total of five identical machines are available in the plant that can be set up to perform either process. Once set up, each machine will be dedicated to perform that process. For each machine that is set up for process 1, production rate is 12 units/hr. For each machine that is set up for process 2, production rate is 18 units/hr. Both processes produce 100% good units (fraction defect rate = 0). A work-in-process buffer is provided between the two processes to avoid starving and blocking of machines. The factory operates 40 hr/week. (a) In order to maximize factory production, how many machines should be set up for process 1 and how many for process 2? (b) What is the factory's maximum possible weekly production rate of good product units?

3.6 A factory is dedicated to the production of one product, with 1 unit of raw material required for each unit of product. Two processes are required to produce the product: process 1, which feeds into process 2. A total of eight identical machines are available in the plant that can be set up to perform either process. Once set up, each machine will be dedicated to that process. For each machine that is set up for process 1, the production rate is 10 units/hr. For each machine that is set up for process 2, the production rate is 6 units/hr. Both processes produce 100% good units (fraction defect rate = 0). A work-in-process buffer is provided between the two processes to avoid starving and blocking of machines. The factory operates 40 hr/week. (a) In order to maximize factory production, how many machines should be set up for process 1 and how many for process 2? (b) What is the factory's maximum possible weekly production rate of good product units?

3.7 There are 20 automatic turning machines in the lathe department. Batches of parts are machined in the department. Each batch consists of setup and run. Batch size is 100 parts. The standard time to set up a machine for each batch is 5.0 hr. Four setup workers perform the setups. They each work 40 hr/week. Once a machine is set up, it runs automatically, with no worker attention until the batch is completed. Cycle time to machine each part is 9.0 min; thus it takes 15 hr of run time to produce a batch. Assume all machines are perfectly reliable. (a) What is the production output of the lathe department in 40 hr of operation per week? (b) How many machines are idle (not in use or being set up between production runs) on average at any moment?

Batch Processing and Economic Order Quantities

3.8 The annual demand for a certain item is 22,500 pc/yr. One unit of the product costs $35.00, and the holding cost rate is 15%/yr. Setup time to produce a batch is 3.25 hr. The cost of equipment downtime during setup plus associated labor is $200/hr. Determine the economic order quantity and the total inventory cost for this case.

3.9 A stamping plant supplies sheet metal parts to a final assembly plant in the automotive industry. Annual demand for a typical part is 150,000 pc. Average cost per piece is $20; holding cost is 25%; changeover (setup) time for the presses is 5 hr; and cost of downtime for changing over a press is $200/hr. Compute the economic batch size and the total annual inventory cost for the data.

3.10 Demand for a certain product is 25,000 units/yr. Unit cost is $10.00. Holding cost rate is 30%/yr. Changeover (setup) time between products is 10.0 hr, and downtime cost during changeover is $150/hr. Determine (a) economic order quantity, (b) total inventory costs, and (c) total inventory cost per year as a proportion of total production costs.

3.11 Last year, the annual demand for a certain piece of merchandise that is inventoried at a department store warehouse was 13,688 units. The annual demand is expected to increase 10% in the next year. One unit of the product costs $8.75, and the selling price is $19.95. The holding cost rate is 15%/yr. The cost to place an order for the merchandise is figured at $65. Determine the economic order quantity and the total inventory cost for this case.

3.12 A part is produced in batches containing 3000 pc in each batch. Annual demand is 60,000 pc, and piece cost is $5.00. The setup time to run a batch is 3.0 hr, the cost of downtime on the affected equipment is figured at $200/hr, and the annual holding cost rate is 30%. What would the annual savings be if the product were produced in the economic order quantity?

3.13 A certain machine tool is used to produce several components for one assembled product. To keep in-process inventories low, a batch size of 100 units is produced for each component.

Demand for the product is 3000 units/yr. Production downtime costs an estimated \$150/hr. All parts produced on the machine tool are approximately \$9.00/unit. The holding cost rate is 30%/yr. In how many minutes must the changeover between batches be accomplished so that 100 units is the economic order quantity?

3.14 The annual demand for a certain part is 10,000 units. At present the setup time on the machine tool that makes this part is 5.0 hr. The cost of downtime on this machine is \$200/hr. Annual holding cost per part is \$1.50. Determine (a) EOQ and (b) total inventory costs for this data. Also, determine (c) EOQ and (d) total inventory costs if the changeover time could be reduced to 6 min.

3.15 A variety of assembled products is made in batches on a manual assembly line. Every time a different product is produced, the line must be changed over, which causes lost production time. The assembled product of interest here has an annual demand of 12,000 units. The changeover time to set up the line for this product is 6.0 hr. The company figures that the hourly rate for lost production time on the line due to changeovers is \$500/hr. Annual holding cost for the product is \$7.00/product. The product is currently made in batches of 1000 units for shipment each month to the wholesale distributor. (a) Determine the total annual inventory cost for this product in batch sizes of 1000 units. (b) Determine the economic batch quantity for this product. (c) How often would shipments be made using this EOQ? (d) How much would the company save in annual inventory costs, if it produced batches equal to the EOQ rather than 1000 units?

Fraction Defect Rate

3.16 A starting batch of 5000 work units is processed through 8 sequential operations, each of which has a fraction defect rate of 3%. (a) How many good parts and (b) how many defects are in the final batch? (c) What is the yield of the operation sequence?

3.17 A starting batch of 10,000 parts is processed through 6 sequential operations. Operations 1 and 2 each have a fraction defect rate of 4%, operations 3, 4, and 5 each have a fraction defect rate of 6%, and operation 6 has a fraction defect rate of 10%. (a) How many good parts and (b) how many defects are in the final batch? (c) What is the yield of the operation sequence?

3.18 A total of 1000 good units must be produced by a sequence of 10 operations, each of which has fraction defect rate of 6%. (a) How many units must be in the starting batch in order to produce this required quantity? (b) What is the yield of the operation sequence?

3.19 A starting batch of 20,000 work units is processed through 7 sequential operations. Operations 1, 2, and 3 each have a fraction defect rate of 5%, and operations 4, 5, and 6 each have a fraction defect rate of 4%. The fraction defect rate of operation 7 is unknown. If a final batch contains a total of 5328 defects, determine the fraction defect rate of operation 7.

3.20 Three sequential operations are required for a certain automotive component. The defect rates are 4% for operation 1, 5% for operation 2, and 10% for operation 3. Operations 2 and 3 can be performed on units that are already defective. Assume that 25,000 starting parts are processed through the sequence. (a) How many units are expected to be defect-free? (b) How many units are expected to have exactly one defect? (c) How many units are expected to have all three defects?

3.21 Solve Problem 3.3 but assume that there is a 10% scrap rate in printing (operation 3).

3.22 A starting batch of 10,000 workparts is processed through three sequential operations: 1 then 2 then 3. Operation 1 sometimes produces parts with defect type 1 at a rate of 5%;

operation 2 sometimes produces parts with defect type 2 at a rate of 8%; and operation 3 sometimes produces parts with defect type 3 at a rate of 10%. Assume that the defects occur randomly and that all 10,000 parts are processed through all three operations. (a) How many are expected to be defect free? (b) How many are expected to have all three defects? (c) How many are expected to have exactly one defect?

3.23 A factory is dedicated to the production of one product. One unit of raw material is required for each unit of product. Two processes are required to produce the product: process 1, which feeds into process 2. A total of eight identical machines are available in the plant that can be set up to perform either process. Once set up, each machine will be dedicated to the performance of that process. For each machine set up, the production rate is 10 units/hr for process 1, production rate = 6 units/hr for process 2. Process 1 produces only good units, but process 2 has a scrap rate of 20%. A work-in-process buffer is allowed between the two processes so that process 2 will not be starved for work. The factory operates 40 hr/wk. (a) In order to maximize factory production, how many machines should be set up for process 1 and for process 2? (b) What is the factory's maximum possible weekly production rate of good product units? (c) How many starting units of raw material are needed each week to attain this production rate?

3.24 Two sheet metal parts, A and B, are produced separately, each requiring two press-working operations. Part A is routed through operations 1 and 2, and part B is routed through operations 3 and 4. The two parts are then joined in a welding step (operation 5), and the assembly is routed to an electroplating operation (operation 6). The six operations have the following fraction defect rates: $q_1 = 0.05$, $q_2 = 0.15$, $q_3 = 0.10$, $q_4 = 0.20$, $q_5 = 0.13$, $q_6 = 0.08$. If the desired final quantity of assemblies is 100,000 units, how many starting units of parts A and B will be required? There is no inspection or separation of defective units until after the final process, so defective units and good units are processed together through all production processes.

3.25 Two subassemblies, A and B, are processed separately, each requiring two finishing operations. A is routed through operations 1 and 2, and B is routed through operations 3 and 4. The two subassemblies are then joined in an assembly operation (operation 5). The five operations have the following fraction defect rates: $q_1 = 0.03$, $q_2 = 0.08$, $q_3 = 0.05$, $q_4 = 0.09$, $q_5 = 0.01$. If the desired final quantity of completed assemblies is 10,000 units, how many starting units of A and B will be required? There is no inspection or separation of defective units until after the final operation, so defective units and good units are processed together through all processing and assembly steps.

Work Cells and Worker Teams

3.26 For Problem 3.1, (a) use the Hollier algorithm to determine the most logical in-line sequence of workstations in the work system, and (b) compute the percentages of in-sequence, backflow, and bypassing moves for the sequence.

3.27 For Problem 3.2, (a) use the Hollier method to find the most logical in-line sequence of workstations in the work system, and (b) compute the percentages of in-sequence, backflow, and bypassing moves for the sequence.

3.28 Four workstations (1, 2, 3, and 4) used to produce a family of similar parts are to be arranged into an in-line layout. The daily flow of parts between workstations is as follows: 10 parts from stations 1 to 2, 40 parts from stations 1 to 4, 50 parts from stations 3 to 1, 20 parts from stations 3 to 4, and 50 parts from stations 4 to 2. (a) Use the Hollier algorithm to determine the most logical sequence of stations in the work system. (b) Draw the network diagram for the system. (c) Compute the percentages of in-sequence, bypassing, and backflow moves for the sequence.

3.29 Four workstations (1, 2, 3, and 4) are used to produce similar parts. The stations are to be arranged into a work cell with an in-line layout. The daily flow of parts between workstations is as follows: 15 parts from stations 2 to 4, 60 parts from stations 3 to 2, 35 parts from stations 2 to 1, 20 parts from stations 4 to 3, and 30 parts from stations 4 to 2. (a) Use the Hollier algorithm to determine the most logical sequence of stations in the work system. (b) Draw the network diagram for the system. (c) Compute the percentages of in-sequence, bypassing, and backflow moves for the sequence.

3.30 Five workstations (1, 2, 3, 4, and 5) that produce about 10 similar parts must be arranged into an in-line layout. The daily flow of parts between workstations is as follows: 20 parts from stations 1 to 2, 30 parts from stations 1 to 3, 25 parts from stations 3 to 4, 20 parts from stations 5 to 4, 10 parts from 5 to 2, and 35 parts from stations 4 to 2. (a) Use the Hollier algorithm to determine the most logical sequence of stations in the work system. (b) Draw the network diagram for the system. (c) Compute the percentages of in-sequence, bypassing, and backflow moves for the sequence.

3.31 Five workstations (1, 2, 3, 4, and 5) that produce about 10 similar parts must be arranged into an in-line layout. The daily flow of parts between workstations is as follows: 40 parts from stations 5 to 2, 35 parts from stations 5 to 3, 20 parts from stations 3 to 1, 25 parts from stations 1 to 4, 60 parts from 3 to 2, 15 parts from stations 2 to 5, and 30 parts from stations 4 to 2. (a) Use the Hollier algorithm to determine the most logical sequence of stations in the work system. (b) Draw the network diagram for the system. (c) Compute the percentages of in-sequence, bypassing, and backflow moves for the sequence.

3.32 A team approach is to be used in an assembly cell; each team will consist of w workers, all working together to assemble the same product. The total work content time per product is T_{wc} and so the cycle time T_c to complete a unit is ideally T_{wc} divided by w. However, congestion occurs as the number of workers in the cell increases; the workers get in each other's way, and this degrades the cycle time. Thus a better model of cycle time is $T_c = T_{wc}/w + wF_cT_{wc}$, where T_c = production cycle time, min; F_c = the congestion factor (a constant of proportionality); and other terms are defined above. If T_{wc} = 45 min and F_c = 0.02, and it is desired to maximize the production rate of the cell, determine (a) the optimum number of workers w and (b) the corresponding production rate. The number of workers must be an integer.