Capacity and Facilities Design

John Carl D'Annibale/AP Images

LEARNING OBJECTIVES

After reading this chapter, you will be able to:

- Evaluate different strategies for capacity expansion, and explain the concepts of economies of scale, best operating level, and capacity cushion.
- Describe the advantages and disadvantages of basic types of layouts in both manufacturing and service settings.
- Visualize work flow and utilize algorithmic problem solving to design product and process layouts.
- Create and evaluate hybrid layouts and hybrid solutions to problems.

Making Capacity Decisions

The semiconductor industry is a high tech, high volume, expensive fabrication environment. The major players, Intel, Global Foundries (see photo), Samsung, and TSMC, are centered in the United States, South Korea, and Taiwan. Less sophisticated, lower cost foundries and specialty fabs are more common in Japan and Europe. *Fabless* companies who design semiconductors and contract out their manufacturing (e.g., Qualcomm, Nvidia, IBM) are mainly U.S. companies. Technology advances in chip design can make products obsolete in six months to two years.

While there are many places to manufacture different kinds of chips, from low–cost, general-purpose foundries to specialty and captive fabs, there is a limit to how many wafers (and chips) the industry can produce each day. For advanced products, the cost of outfitting new, state-of-the-art fabs can be prohibitive: TSMC's new foundry in Taiwan cost $9.3 billion and Samsung's new Austin foundry cost $13 billion. For less advanced products, expanding existing facilities can be challenging because equipment (new or used) can be difficult to find. As a result, capacity tends to remain relatively stable.

Demand, however, does not. Large consumer electronics companies such as Apple or Qualcomm consume huge portions of available -capacity at the leading foundries. A shift by either of those players from one foundry to another could seriously impact capacity elsewhere in the industry. In addition, any change in the new product introduction cycle design, say from 24 months to 18 months, could cause severe capacity shortages in multiple foundries.

Demand patterns in the electronics industry vary by type of product. For example, while demand for computer products is decreasing and -demand for consumer electronics has stabilized, demand for sensors and other IoT (i.e., Internet of Things) devices is increasing rapidly. Sensors use simpler technology; smartphones and computers use the most advanced technology. So demand currently favors older fabs, but companies are hesitant to build new foundries based on older technology. To complicate the decision, the lead time for getting a new foundry online is two to three years.

China, the world's largest manufacturer and assembler of electronics products, imports 91% of its semiconductor needs. The Chinese government is investing $150 billion into developing its domestic semiconductor industry over the next ten years. We'll see what kind of capacity they build and how that affects the rest of the industry.

Making capacity decisions into an uncertain future is difficult. In this chapter, we discuss issues with capacity planning and facility-related decisions on size, location, and layout. These decisions can have a long-term effect on the profitability of a firm, especially in the electronics industry.

Sources: E. Sperling, "Manufacturing Constraint Fears Grow," *Semiconductor Engineering*, December 18, 2014; D. Lammers, "Fabs in the Internet of Things Era," *NanoChip*, Vol. 8, Issue 2, pp. 20–23; ITA, "Semiconductors and Semiconductor Manufacturing Equipment Top Markets Report," Washington, DC: International Trade Administration, July 2015.

Capacity Planning

Capacity is the maximum capability to produce. Capacity planning takes place at several levels of detail. We discuss long-term capacity planning in this chapter, intermediate-term capacity planning in Chapter 14, and short-term capacity planning in Chapters 15 and 16.

Capacity The maximum capability to produce.

Long-term **capacity planning** is a strategic decision that establishes a firm's overall level of resources. It extends over a time horizon long enough to obtain those resources—usually a year or more for building or expanding facilities or acquiring new businesses. Capacity decisions affect product lead times, customer responsiveness, operating costs, and a firm's ability to compete. Inadequate capacity can lose customers and limit growth. Excess capacity can drain a company's resources and prevent investments in more lucrative ventures. *When* to increase capacity and *how much* to increase it are critical decisions.

Capacity planning Establishes the overall level of productive resources for a firm.

Figure 7.1 *a*, *b*, and ***c*** show three basic strategies for the timing of capacity expansion in relation to a steady growth in demand.

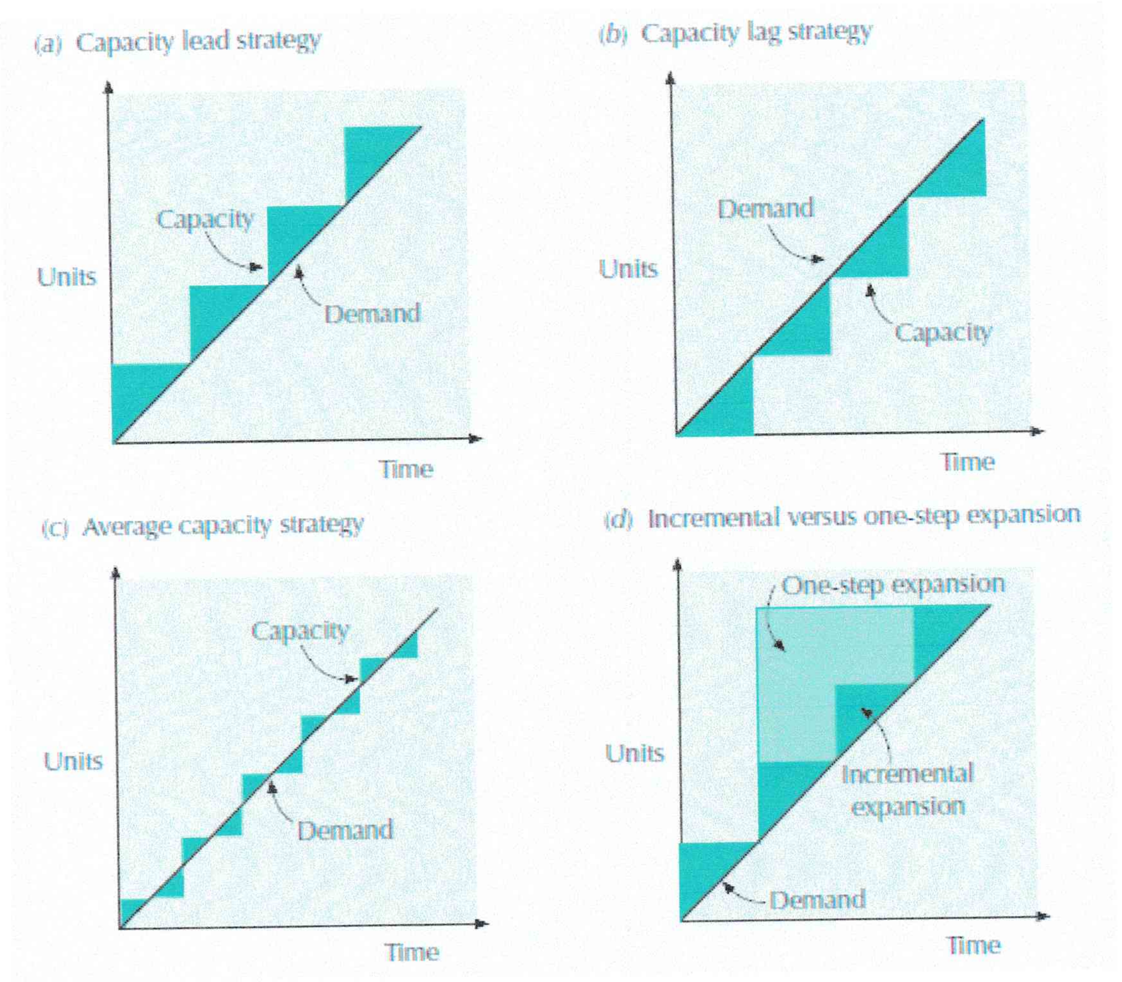


FIGURE 7.1 **Capacity Expansion Strategies**

1. ***Capacity lead strategy***. Capacity is expanded in anticipation of demand growth. This aggressive strategy is used to lure customers from competitors who are capacity constrained or to gain a foothold in a rapidly expanding market. It also allows companies to respond to unexpected surges in demand and to provide superior levels of service during peak demand periods.
2. ***Average capacity strategy***. Capacity is expanded to coincide with average expected demand. This is a moderate strategy in which managers are certain they will be able to sell at least some portion of expanded output, and endure some periods of unmet demand. Approximately half of the time capacity leads demand, and half of the time capacity lags demand.
3. ***Capacity lag strategy***. Capacity is increased after an increase in demand has been documented. This conservative strategy produces a higher return on investment but may lose customers in the process. It is used in industries with standard products and cost-based or weak competition. The strategy assumes that lost customers will return from competitors after capacity has expanded.

Consider higher education's strategy in preparing for a tripling of the state's college-bound population in the next decade. An established university, guaranteed applicants even in lean years, may follow a capacity lag strategy. A young university might lead capacity expansion in hopes of capturing students not admitted to the more established universities. A community college may choose the average capacity strategy to fulfill its mission of educating the state's youth but with little risk.

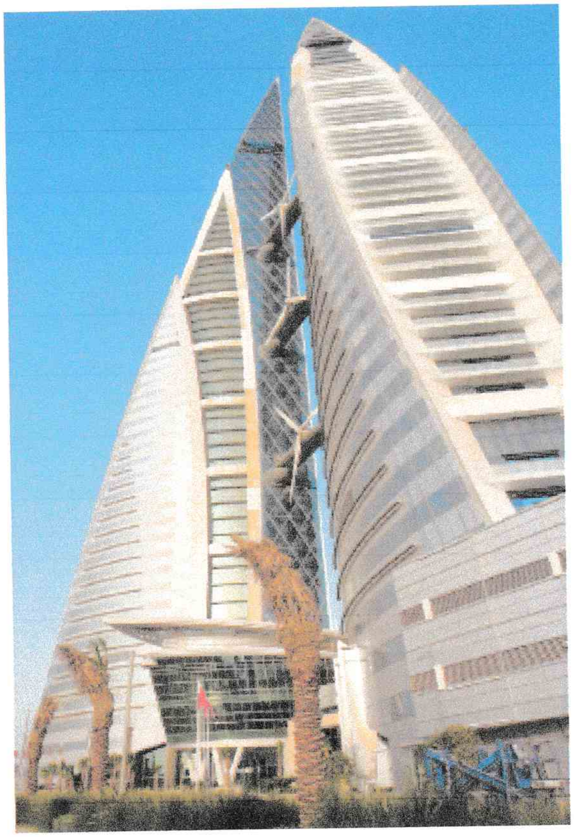
How much to increase capacity depends on (1) the volume and certainty of anticipated *demand;* (2) *strategic objectives* in terms of growth, customer service, and competition; and (3) the *costs* of expansion and operation.

Capacity can be increased incrementally or in one large step, as shown in **Figure 7.1d**. Incremental expansion is less risky but more costly. An attractive alternative to expanding capacity is *outsourcing*, in which suppliers absorb the risk of demand uncertainty.

The **best operating level** for a facility is the percent of capacity utilization that minimizes average unit cost. Rarely is the best operating level at 100% of capacity—at higher levels of utilization, productivity slows and things start to go wrong. Average capacity utilization differs by industry. An industry with an 80% average utilization would have a 20% **capacity cushion** for unexpected surges in demand or temporary work stoppages. Large-capacity cushions are common in industries in which demand is highly variable, resource flexibility is low, and customer service is important. Utilities, for example, maintain a 20% capacity cushion. Capital-intensive industries with less flexibility and higher costs maintain cushions under 10%. Airlines maintain a negative cushion by overbooking flights. Best operating level can also refer to the most economic size of a facility.

Best operating level The percent of capacity utilization that minimizes unit costs.

Capacity cushion A percent of capacity held in reserve for unexpected occurrences



Orhan Cam/Shutterstock

The 50-story Bahrain World Trade Center is powered by three huge wind turbines that connect twin sail-shaped towers. The shape of the towers funnels and accelerates the wind toward the -turbines. Wind was chosen as a clean energy -alternative, instead of solar, because of the intense heat in Manama, Bahrain. Green buildings of many different types are gaining popularity worldwide.

Figure 7.2 shows the best operating level—in this case, the number of rooms for a hotel—as the point at which the *economies of scale* have reached their peak and the **diseconomies of scale** have not yet begun.

Diseconomies of scale When higher levels of output cost more per unit to produce.

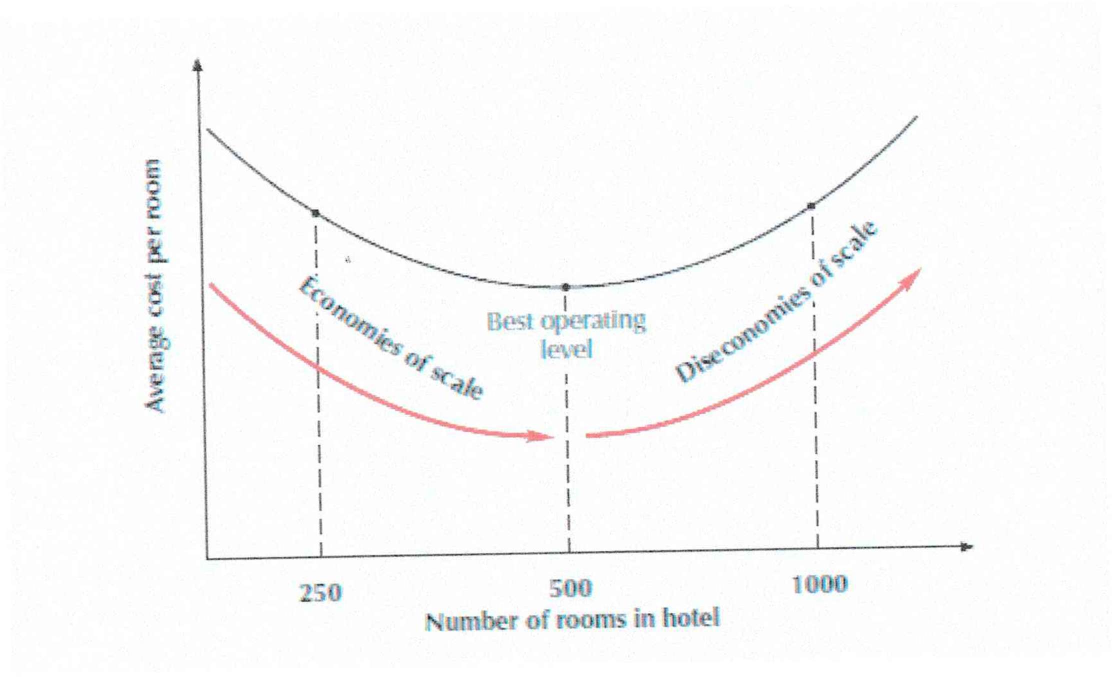


FIGURE 7.2 **Best Operating Level for a Hotel**

Economies of scale occur when it costs less per unit to produce or operate at high levels of output. This holds true when:

- Fixed costs can be spread over a larger number of units,
- Production or operating costs do not increase linearly with output levels,
- Quantity discounts are available for material purchases, and
- Operating efficiency increases as workers gain experience.

Economies of scale When it costs less per unit to produce high levels of output.

The electronics industry provides a good case example of economies of scale. The average cost per chip placement for printed circuit-board assembly is 32 cents in factories with a volume of 25 million placements, 15 cents in factories with 200 million placements, and only 10 cents in factories with 800 million placements.[1]

Capacity decisions provide a framework for further facility decisions, such as where to locate a new facility and how to arrange the flow of work in the facility. Facility location is discussed in the supplement to this chapter. The remainder of the chapter presents various alternatives for laying out a facility.

Along the Supply Chain

Is There Really a Starbucks at Every Corner?

Starbucks may seem to spring up overnight at seemingly random locations, but be assured, where to locate a new store (and what menu items to offer there) is the result of careful analysis. There's even an app for that.

Atlas is the market planning and store development application built by Starbucks. Basically a big data analytics tool layered onto a geographic information system (GIS), Atlas allows Starbucks to visualize a range of variables that lead to success in existing locations and then identify sites with similar data patterns for new store locations. For example, a city map showing current Starbucks locations can be layered with demographic information, daily traffic volume, availability of parking or public transportation, and locations (or soon-to-be locations) of other stores, offices, and eating establishments. These same factors can then be used to identify new potential sites. Once chosen, a workflow screen appears to guide the process of securing approval for the new site at corporate, filing the proper permits, and launching the store.

Menus, décor, and layout can differ by location as well. A map of purchasing patterns for wine and beer, for example, can determine the hours a Starbucks is open and what food and drink are offered. For Starbucks, location is all about the data.

1. Look at the Starbucks locations in your area. What similarities do those locations provide? Are there other stores or restaurants that seem to be paired with Starbucks?
2. What differences have you noticed in the layout of Starbucks sites recently? Do they vary by type of customer or location? What kind of activities do the layouts encourage?
3. Have you noticed any differences in the size of Starbucks by location? Why does the company choose to open multiple small stores in close proximity?

Source: Jeff Vance, "Big data secrets from Airbnb, Starbucks and Sonic," Computerworld (February 17, 2015); Paul Ausick, "Starbucks Closing 4 Teavanna Stores," 24/7 Wall St. (January 22, 2016).

Facilities

Facilities make a difference. They can provide a competitive edge by enabling and leveraging the latest process concepts. For example, Tesla, featured in the "Along the Supply Chain" box, is building an exemplary facility showcasing green design. Green buildings, such as the Bahrain World Trade Center shown previously, can save energy costs and increase worker productivity. Facility design has an impact on both quality and productivity. Facilities affect how efficiently workers can do their jobs, how much and how fast goods can be produced, how difficult it is to automate a system, and how responsive the system can be to changes in product or service design, product mix, or demand volume. Facilities must be planned, located, and laid out.

Facility layouts are more flexible than ever before. Factories that once positioned shipping and receiving departments at one end of the building now construct T-shaped buildings so that deliveries can be made directly to points of use within the factory. Stores sport portable kiosks for customer inquiry and checkout at various locations throughout the facility. Classrooms incorporate desks on wheels to be repositioned for different teaching styles and student interaction. Effective layouts can have many different objectives.

Facility layout The arrangement of areas within a facility.

Objectives of Facility Layout

Facility layout refers to the arrangement of activities, processes, departments, workstations, storage areas, aisles, and common areas within an existing or proposed facility. The basic objective of the layout decision is to ensure a smooth flow of work, material, people, and information through the system. Effective layouts also do the following:

- Minimize movement and material handling costs;
- Utilize space efficiently;
- Utilize labor efficiently;
- Eliminate bottlenecks;
- Facilitate communication and interaction between workers, between workers and their supervisors, and between workers and customers;
- Reduce manufacturing cycle time and customer service time;
- Eliminate wasted or redundant movement;
- Facilitate the entry, exit, and placement of material, products, and people;
- Incorporate safety and security measures;
- Promote product and service quality;
- Encourage proper maintenance activities;
- Provide a visual control of activities;
- Provide flexibility to adapt to changing conditions;
- Increase capacity.

Along the Supply Chain

Tesla's Gigafactory Produces Energy As Well As Batteries

Tesla's gigafactory is the biggest lithium-ion battery factory in the world. When completed, its 13 million sq ft footprint will rival the largest building in the world. At full production, the factory will produce half a million batteries per day, and require 100 megawatts of energy to operate. And yet, the factory, run by solar panels, a 85-turbine wind farm, and geothermal energy, will itself generate 20% more power than it can use. The excess power will provide electricity to nearby Reno, Nevada. The location of the factory, as shown in the photo, was carefully calculated to provide maximum sun exposure (5+ hours per day), abundant land, and access to geothermal and wind energy. Elon Musk built the factory to reduce the cost of batteries for its Tesla electric car, and to provide homes, businesses, and industry with their own "Powerpacks."

1. What are the advantages and disadvantages of building one enormous factory instead of multiple normal-sized factories in more diverse locations?
2. Panasonic makes batteries for the current line of Tesla cars and is expected to continue as a supplier. Why would Elon Musk build the new factory instead of Panasonic?
3. Less than 1% of LEED certified buildings are manufacturing and distribution centers, and yet these types of facilities are the biggest users of energy and materials. Why do you think this is the case?

The Washington Post/Getty Images, Inc.

Source: Katie Fehrenbacher, "Tesla is Already Making Grid Batteries at the Gigafactory," Fortune, (November 3, 2015); Max Chaffin, "Elon Musk Powers Up: Inside Tesla's $5 Billion Gigafactory," Fast Company (December/January 2016).

Basic Layouts

Layouts can take many different forms. In the next section, we discuss three basic layout types: process, product, and fixed-position. Later in the chapter, we discuss three hybrid layouts: cellular layouts, flexible manufacturing systems, and mixed-model assembly lines.

Process Layouts

Process layout, also known as *functional layouts*, group similar activities together in departments or work centers according to the process or function they perform. For example, in a machine shop, all drills would be located in one work center, lathes in another work center, and milling machines in still another work center. In a department store, women's clothes, men's clothes, children's clothes, cosmetics, and shoes are located in separate departments. A process layout is characteristic of service shops, job shops, or batch production, i.e., intermittent operations that serve different customers with different needs. The volume of each customer's order is low, and the sequence of operations required to complete a customer's order can vary considerably.

Process layouts Group similar activities together according to the process or function they perform.

The equipment in a process layout is general purpose, and the workers are skilled at operating the equipment in their particular department. The advantage of this layout is flexibility. The disadvantage is inefficiency. Jobs or customers do not flow through the system in an orderly manner, backtracking is common, movement from department to department can take a considerable amount of time, and queues tend to develop. In addition, each new arrival may require that an operation be set up differently for its particular processing requirements. Although workers can operate a number of machines or perform a number of different tasks in a single department, their workload often fluctuates—from queues of jobs or customers waiting to be processed to idle time between jobs or customers. Figures 7.3 and 7.4 show schematic diagrams of process layouts in services and manufacturing.

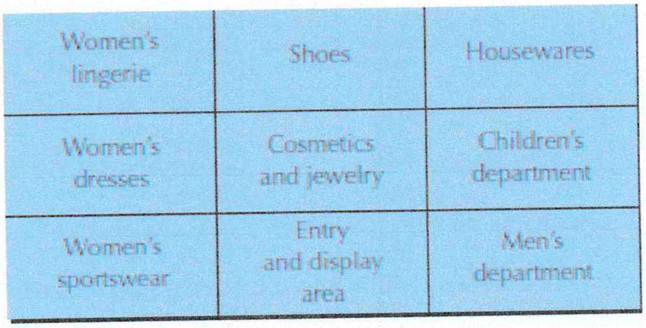


FIGURE 7.3 **A Process Layout in Services**

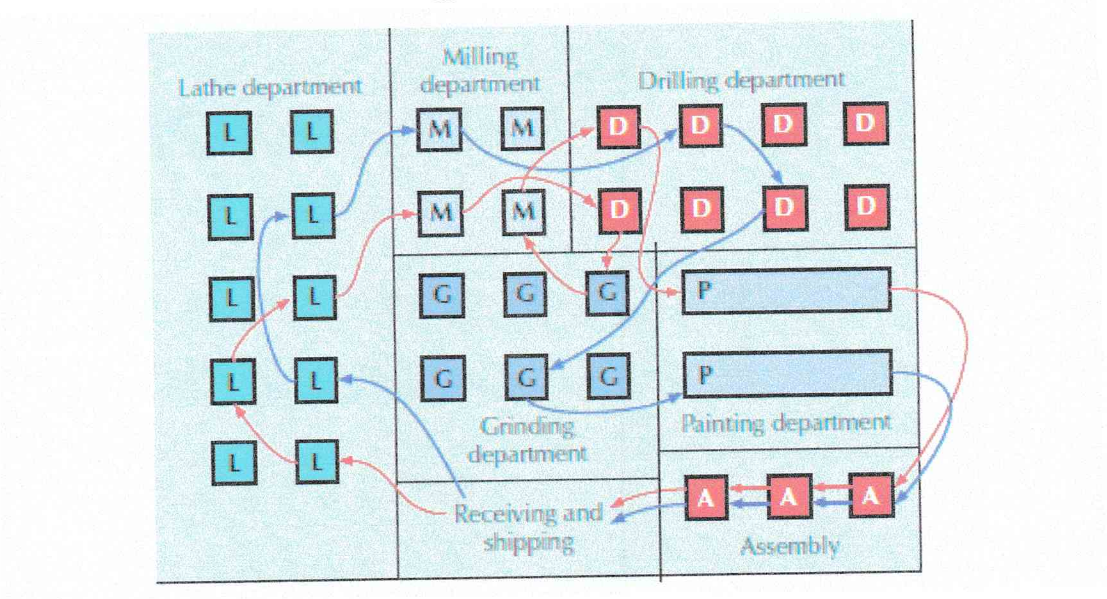


FIGURE 7.4 **A Process Layout in Manufacturing**

Material storage and movement are directly affected by the type of layout. Storage space in a process layout is large to accommodate the large amount of in-process inventory.

The factory may look like a warehouse, with work centers strewn between storage aisles. In-process inventory is high because material moves from work center to work center in batches waiting to be processed. Finished goods inventory, on the other hand, is low because the goods are being made for a particular customer and are shipped out to that customer on completion.

Process layouts in manufacturing firms require flexible material handling equipment (such as forklifts, carts or AGVs) that can follow multiple paths, move in any direction, and carry large loads of in-process goods. A *forklift* moving pallets of material from work center to work center needs wide aisles to accommodate heavy loads and two-way movement. Scheduling of forklifts is typically controlled by radio dispatch and varies from day to day and hour to hour. Routes have to be determined and priorities given to different loads competing for pickup.

Process layouts in service firms require large aisles for customers to move back and forth and ample display space to accommodate different customer preferences.

The major layout concern for a process layout is where to locate the departments or machine centers in relation to each other. Although each job or customer potentially has a different route through the facility, some paths will be more common than others. Past information on customer orders and projections of customer orders can be used to develop patterns of flow through the shop.

Product Layouts

Product layouts, better known as *assembly lines*, arrange activities in a line according to the sequence of operations that need to be performed to assemble a particular product. Each product has its own "line" specifically designed to meet its requirements. The flow of work is orderly and efficient, moving from one workstation to another down the assembly line until a finished product comes off the end of the line, as shown in the photo below.

Since the line is set up for one type of product or service, special machines can be purchased to match a product's specific processing requirements. Product layouts are suitable for mass production or repetitive operations in which demand is stable and volume is high. The product or service is a standard one made for a general market, not for a particular customer. Because of the high level of demand, product layouts are more automated than process layouts, and the role of the worker is different. Workers perform narrowly defined assembly tasks that do not demand as high a wage rate as those of the more versatile workers in a process layout.

Bloomberg/Getty Images, Inc.

In this Porsche AG factory in Leipzig, Germany SUV chassis are moving down a paced assembly line with robots performing welding and other production tasks. The product layout is so named because the order of operations is standardized according to how a particular product is put together. Today's factories are increasingly automated, clean and orderly.

Product layouts Arrange activities in a line according to the sequence of operations for a particular product or service.

The advantage of the product layout is its efficiency and ease of use. The disadvantage is its inflexibility. Significant changes in product design may require that a new assembly line be built and new equipment be purchased. This is what happened to U.S. automakers when demand shifted to smaller cars. The factories that could efficiently produce six-cylinder engines could not be adapted to produce four-cylinder engines. A similar inflexibility occurs when demand volume slows. The fixed cost of a product layout (mostly for equipment) allocated over fewer units can send the price of a product soaring.

The major concern in a product layout is balancing the assembly line so that no one workstation becomes a bottleneck and holds up the flow of work through the line. **Figure 7.5** shows the product flow in a product layout. Contrast this with the flow of products through the process layout shown in Figure 7.4.

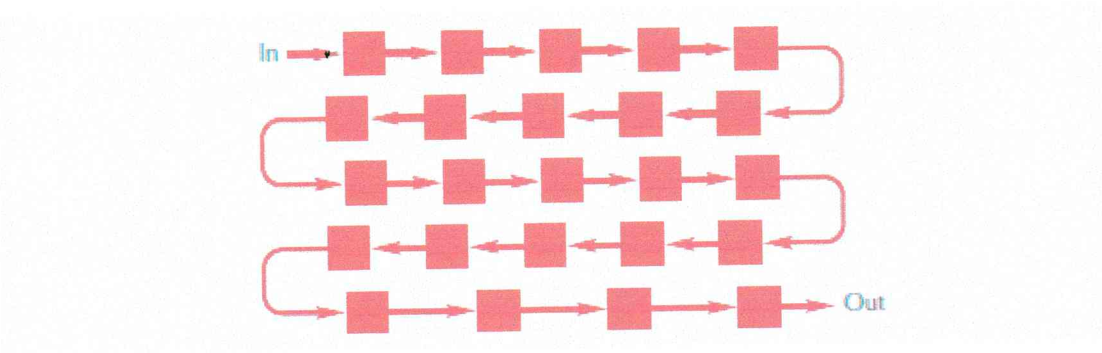


FIGURE 7.5 **A Product Layout**

A product layout needs material moved in one direction along the assembly line and always in the same pattern. Conveyors are the most common material handling equipment for product layouts. Conveyors can be *paced* (automatically set to control the speed of work) or *unpaced* (stopped and started by the workers according to their pace). Assembly work can be performed *online* (i.e., on the conveyor) or *offline* (at a workstation serviced by the conveyor).

Along the Supply Chain

Stihl's Manufacturing Complex

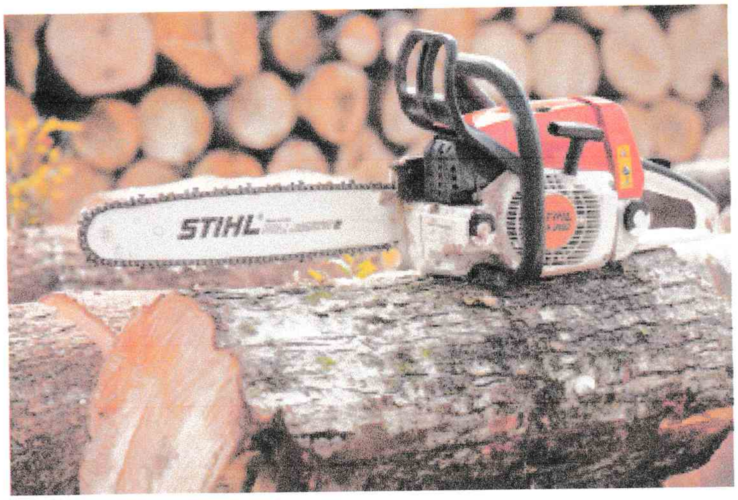
Stihl, Inc., a venerable 100-year-old German engineering and manufacturing firm, has a 150-acre manufacturing complex in Virginia Beach, VA, consisting of six factories, 2 million square feet of production space, and several supporting buildings (e.g., offices, warehouses, and testing facilities). The complex employs over 1900 people and produces 275 different models of handheld outdoor power equipment, such as chain saws (see photo), trimmers, blowers, and shredders. Stihl also manufactures its own engines on site, as well as machined and plastic parts for its products. In addition, Stihl designs and builds much of its own production and testing equipment, including machine vision robots. This degree of vertical integration is unusual today.

The newest building on site is a 60,000-square-foot guide bar factory that sports fully automated stamping, welding, riveting, painting, and packaging processes. In another building, seven chain saw assembly lines (or cells) produce more than 35 different models, while 15 power tool assembly lines build more than 100 models. The two sections of assembly are separated by a kanban supermarket of key components that feed the lines (we discuss kanbans in Chapter 16). Workstations along the assembly line are ergonomically designed and electric fastening tools employ smart-arm technology.

The assembly lines are flexible and assembly line workers are cross-trained on a variety of lines, so that work can be quickly reconfigured to reflect seasonal demand for products. Demand is higher for trimmers during the spring and summer, and blowers in the fall; demand for chain saws peaks during hurricane season from summer through fall. Production takes placein the off season prior to demand peaks.

The variety of chain saws assembled range from a 9-pound tool for homeowners to a professional lumberjack's tool with a 25" guide bar that can fell and buck large-diameter trees. Product options for power-landscaping tools include engine displacements, driveshafts, filter systems, fuel tanks, mufflers, cutting heads, and attachments. One of the trimmer assembly lines, for instance, runs three shifts and handles over 500 product variations, including advanced engine technology (i.e., 2-cycle, 4-cycle, and hybrid engines) requiring different emissions testing. Stihl has 137 test cells where every product coming off the assembly line is run-in for quality checks. Finally, since 45% of manufacturing output is sent overseas, warning labels, instruction manuals, and packaging are added in more than a dozen languages.

The Stihl complex is heavily invested in lean production. In addition to the kanban supermarket, the plant uses 5S, kaizen, visual control, value-stream mapping, and andon boards that display production rates, takt time, safety records, and quality ratings for specific assembly lines. Continuous improvement methodologies are used by teams of workers and engineers to streamline both manual and automated processes. For example, in the plastics factory, one operator can run 27 different injection molding machines at a time. With over 150 robots across factories at the site, many of the improvement projects address machine vision or the collaborative work of humans and machines. Employees that make suggestions for process improvement can get paid up to 25 percent of the first-year's cost savings.



© Kevin Brine - Editorial / Alamy Stock Photo

Consistent with German tradition, the Virginia Beach complex also includes an apprenticeship program that trains workers in robotics, tool and die making, polymer technology, CNC machining, quality assurance, and plant maintenance.

1. Explore the Stihl corporate website and other online resources. How does Stihl fare in various product markets? What is their positioning strategy, i.e., on what do they compete? (see Chapter 1)
2. Make a list of the ways in which Stihl controls the inputs to its manufacturing processes. Why do you think Stihl is so invested in vertical integration?
3. For what reasons might Stihl have built this large manufacturing complex in the United States? Comment on both the size and location. Where else in the world are Stihl products manufactured?
4. There are several different types of production processes exhibited in the Stihl manufacturing complex. What kinds of items are produced in batch production? When does mass production take place? How are hybrid layouts used?

Sources: Austin Weber, "STIHL Stays a Cut Above the Competition," *Assembly Magazine* (October 3, 2014); Bill Bregar, "Stihl cuts through the competition," *Plastics News* (February 10, 2015).

Aisles are narrow because material is moved only one way, it is not moved very far, and the conveyor is an integral part of the assembly process, usually with workstations on either side. Scheduling of the conveyors, once they are installed, is simple—the only variable is how fast they should operate.

Storage space along an assembly line is quite small because in-process inventory is consumed in the assembly of the product as it moves down the assembly line. Finished goods, however, may require a separate warehouse for storage before they are shipped to dealers or stores to be sold.

Product and process layouts look different, use different material handling methods, and have different layout concerns. Table 7.1 summarizes the differences between product and process layouts.

TABLE 7.1 A Comparison of Product and Process Layouts

Internet Exercises

	PRODUCT LAYOUT	PROCESS LAYOUT
1. Description	Sequential arrangement of activities	Functional grouping of activities
2. Type of process	Continuous, mass production, mainly assembly	Intermittent, job shop, batch production, mainly fabrication
3. Product	Standardized, made to stock	Varied, made to order
4. Demand	Stable	Fluctuating
5. Volume	High	Low
6. Equipment	Special purpose	General purpose
7. Workers	Limited skills	Varied skills
8. Inventory	Low in-process, high finished goods	High in-process, low finished goods
9. Storage space	Small	Large
10. Material handling	Fixed path (conveyor)	Variable path (forklift)
11. Aisles	Narrow	Wide
12. Scheduling	Part of balancing	Dynamic
13. Layout decision	Line balancing	Machine location
14. Goal	Equalize work at each station	Minimize material handling cost
15. Advantage	Efficiency	Flexibility

Fixed-Position Layouts

Fixed-position layouts are typical of projects in which the product produced is too fragile, bulky, or heavy to move. Ships, houses, and aircraft are examples. In this layout, the product remains stationary for the entire manufacturing cycle. Equipment, workers, materials, and other resources are brought to the production site. Equipment utilization is low because it is often less costly to leave equipment idle at a location where it will be needed again in a few days, than to move it back and forth. Frequently, the equipment is leased or subcontracted because it is used for limited periods of time. The workers called to the work site are highly skilled at performing the special tasks they are requested to do. For instance, pipefitters may be needed at one stage of production, and electricians or plumbers at another. The wage rate for these workers is much higher than minimum wage. Thus, if we were to look at the cost breakdown for fixed-position layouts, the fixed cost would be relatively low (equipment may not be owned by the company), whereas the variable costs would be high (due to high labor rates and the cost of leasing and moving equipment).

Fixed-position layouts Are used for projects in which the product cannot be moved.

Aircraft production generally takes place in a fixed-position layout due to the size and complexity of assembly. Shown here is a Boeing 787 Dreamliner being outfitted.

Kevin P. Casey/Bloomberg/Getty Images, Inc.

Fixed-position layouts are specialized to individual projects and thus are beyond the scope of this book. Projects are covered in more detail in the next chapter. In the sections that follow, we examine some quantitative approaches for designing product and process layouts.

Designing Process Layouts

In designing a process layout, we want to minimize movement or material handling cost, which is a function of the amount of material moved times the distance it is moved. This implies that departments that incur the most interdepartment movement should be located closest to each other, and those that do not interact should be located further away. Two techniques used to design process layouts, block diagramming and relationship diagramming, are based on logic and the visual representation of data.

Block Diagramming

We begin with data on historical or predicted movement of material between departments in the existing or proposed facility. This information is typically provided in the form of a from/to chart, or *load summary chart*. The chart gives the average number of **unit load** transported between the departments over a given period of time. A unit load can be a single unit, a pallet of material, a bin of material, or a crate of material—however material is normally moved from location to location. In automobile manufacturing, a single car represents a unit load. For a ball-bearing producer, a unit load might consist of a bin of 100 or 1000 ball bearings, depending on their size.

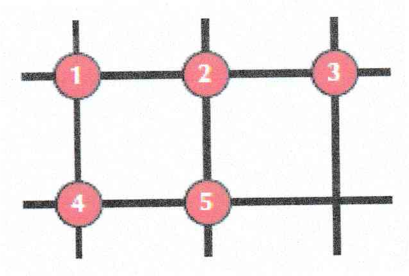
Unit load The quantity in which material is normally moved.

The next step in designing the layout is to calculate the *composite movements* between departments and rank them from most movement to least movement. Composite movement, represented by a two-headed arrow, refers to the back-and-forth movement between each pair of departments.

Finally, trial layouts are placed on a grid that graphically represents the relative distances between departments in the form of uniform blocks. The objective is to assign each department to a block on the grid so that *nonadjacent loads* are minimized. The term *nonadjacent* is defined as a distance farther than the next block, either horizontally, vertically, or diagonally. The trial layouts are scored on the basis of the number of nonadjacent loads. Ideally, the optimal layout would have zero nonadjacent loads. In practice, this is rarely possible, and the process of trying different layout configurations to reduce the number of nonadjacent loads continues until an acceptable layout is found.

EXAMPLE 7.1 | Process Layout

Barko, Inc., makes *bark scalpers*, processing equipment that strips the bark off trees and turns it into nuggets or mulch for gardens. The facility that makes bark scalpers is a small-job shop that employs 50 workers and is arranged into five departments: (1) bar stock cutting, (2) sheet metal, (3) machining, (4) painting, and (5) assembly. The average number of loads transported between the five departments per month is given in the accompanying load summary chart. The current layout of the facility is shown schematically on the 2 × 3 grid. Notice that there is quite a bit of flexibility in the facility, as indicated by the six possible locations (i.e., intersections) available for five departments. In addition, the forklift used in the facility is very flexible, allowing horizontal, vertical, and diagonal movement of material.



LOAD SUMMARY CHART

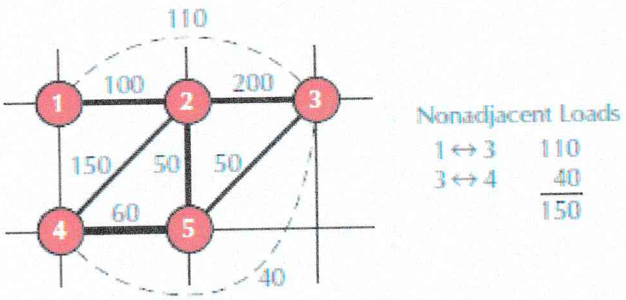
	DEPARTMENT				
FROM/TO DEPARTMENT	1	2	3	4	5
1	—	100	50		
2		—	200	50	
3	60		—	40	50
4		100		—	60
5		50			—

Barko management anticipates that a new bark scalper plant will soon be necessary and would like to know if a similar layout should be used or if a better layout can be designed. You are asked to evaluate the current layout in terms of nonadjacent loads, and if needed, propose a new layout on a 2 × 3 grid that will minimize the number of nonadjacent loads.

Solution: In order to evaluate the current layout, we need to calculate the composite, or back-and-forth, movements between departments. For example, the composite movement between department 1 and department 3 is the sum of 50 loads moved from 1 to 3, plus 60 loads moved from 3 to 1, or 110 loads of material. If we continue to calculate composite movements and rank them from highest to lowest, the following list results:

COMPOSITE	MOVEMENTS	COMPOSITE	MOVEMENTS
2 ↔ 3	200 loads	3 ↔ 5	50 loads
2 ↔ 4	150 loads	2 ↔ 5	50 loads
1 ↔ 3	110 loads	3 ↔ 4	40 loads
1 ↔ 2	100 loads	1 ↔ 4	0 loads
4 ↔ 5	60 loads	1 ↔ 5	0 loads

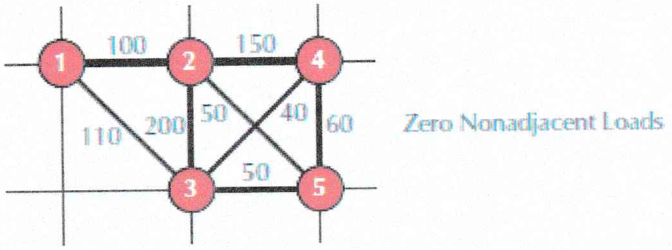
Next, we evaluate the “goodness” of the layout by scoring it.id 1.



Grid 1

The adjacent moves are marked with a solid line and the nonadjacent moves are shown with a curved dashed line to highlight the fact that material is moved farther than we would like, that is, across more than one square. Following our composite movement list, 2 ↔ 3 and 2 ↔ 4 are adjacent moves, but 1 ↔ 3 is not. Our nonadjacent score starts with 110 loads of material from 1 ↔ 3. Continuing down our list, all moves are adjacent and are marked with solid lines until 3 ↔ 4. Movement 3 ↔ 4 is nonadjacent, so we designate it as such and add 40 loads to our nonadjacent score. The remaining movements have zero loads. Thus, our score for this layout is 110 + 40 = 150 nonadjacent loads.

To improve the layout, we note that departments 3 and 4 should be located adjacent to department 2, and that departments 4 and 5 may be located away from department 1 without adding to the score of nonadjacent loads. Let's put departments 4 and 5 on one end of the grid and department 1 on the other and then fill in departments 2 and 3 in the middle. The revised solution is shown in Grid 2. The only nonadjacent moves are between departments 1 and 4, and 1 and 5. Since no loads of material are moved along those paths, the score for this layout is zero.

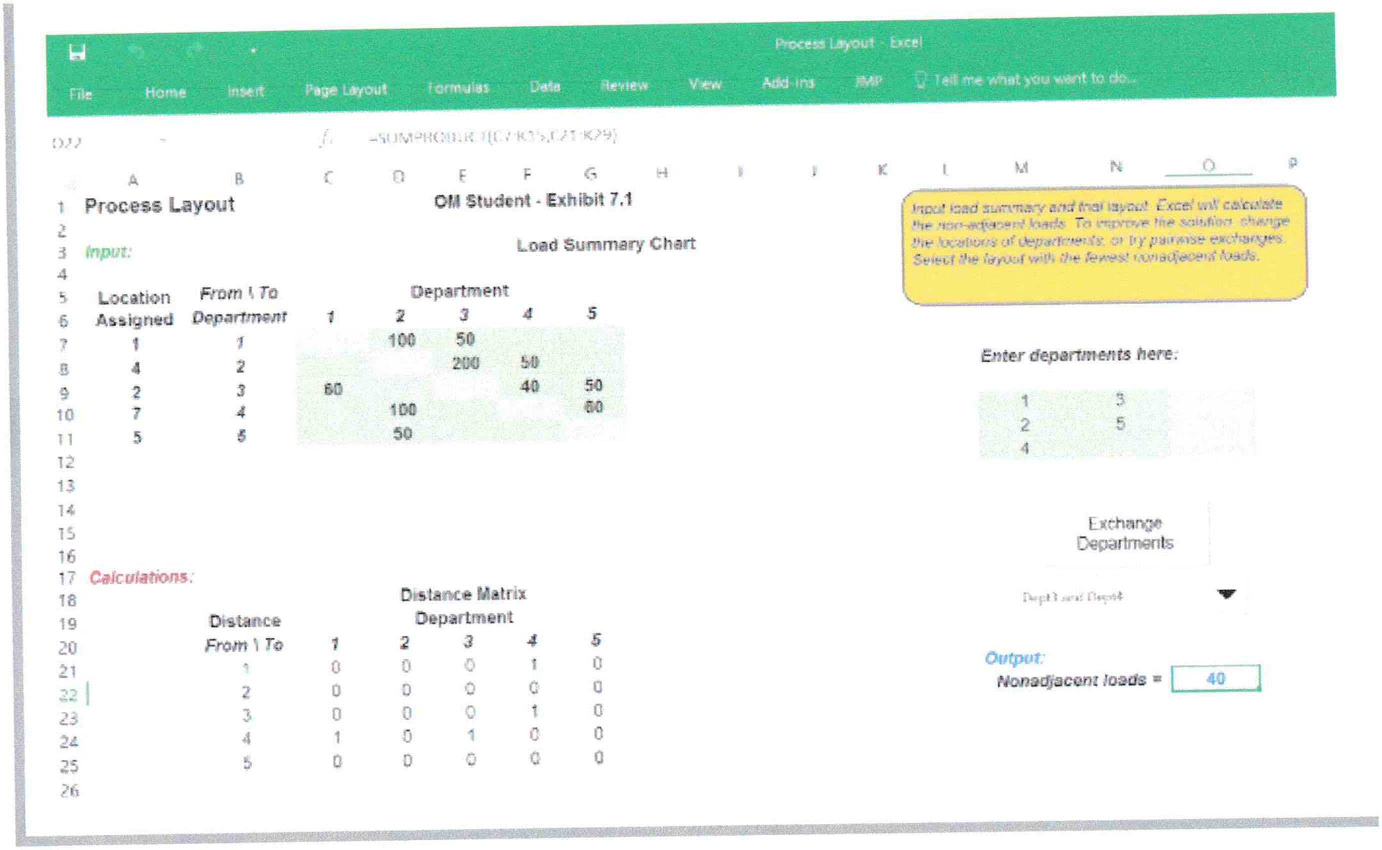


Grid 2

The Excel setup for this problem is shown in **Exhibit 7.1**.

EXHIBIT 7.1

Excel File



=SUMPRODUCT(C7:K15,C21:K29)

Process Layout

OM Student - Exhibit 7.1

Input:

Load Summary Chart

Location Assigned	*From \ To Department*	1	2	3	4	5
1	1		100	50		
4	2			200	50	
2	3	60			40	50
7	4		100			60
5	5		50			

Input load summary and final layout. Excel will calculate the non-adjacent loads. To improve the solution, change the locations of departments, or try pairwise exchanges. Select the layout with the fewest nonadjacent loads.

Enter departments here:

1	3
2	5
4	

Output:

Nonadjacent loads = 40

Calculations:

Distance Matrix

Distance *From \ To*	1	2	3	4	5
1	0	0	0	1	0
2	0	0	0	0	0
3	0	0	0	1	0
4	1	0	1	0	0
5	0	0	0	0	0

The layout solution in Grid 2 represents the relative position of each department. The next step in the layout design is to add information about the space required for each department. Recommendations for workspace around machines can be requested from equipment vendors or found in safety regulations or operating manuals. In some cases, vendors provide templates of equipment layouts, with work areas included. Workspace allocations for workers can be specified as part of job design, recommended by professional groups, or agreed on through union negotiations. A **block diagram** can be created by "blocking in" the work areas around the departments on the grid. The *final block diagram* adjusts the block diagram for the desired or proposed shape of the building. Standard building shapes include rectangles, L shapes, T shapes, and U shapes.

Block diagram A type of schematic layout diagram that includes space requirements.

Figure 7.6a shows an initial block diagram for Example 7.1, and **Figure 7.6b** shows a final block diagram. Notice that the space requirements vary considerably from department to department, but the relative location of departments has been retained from the grid.

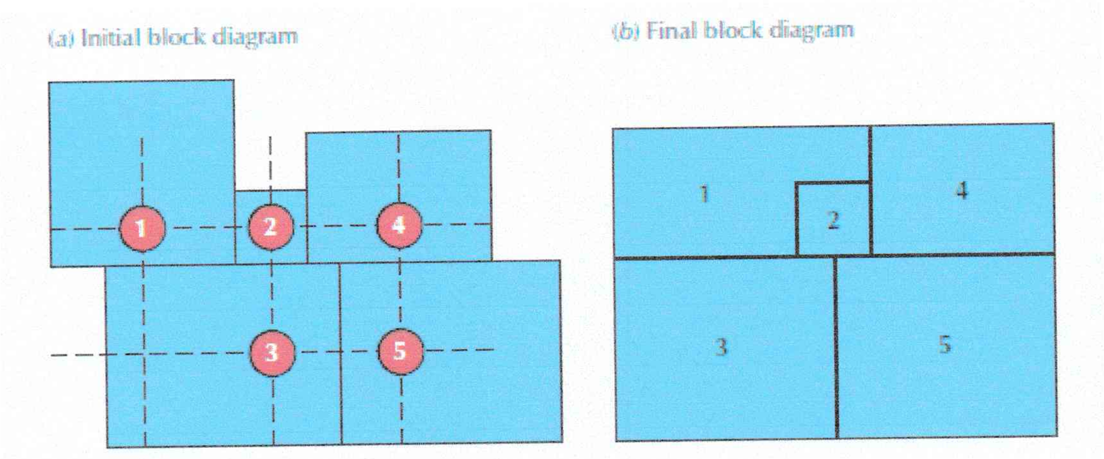


FIGURE 7.6 **Block Diagrams**

Relationship Diagramming

The preceding solution procedure is appropriate for designing process layouts when quantitative data are available. However, in situations for which quantitative data are difficult to obtain or do not adequately address the layout problem, the load summary chart can be replaced with subjective input from analysts or managers. Richard Muther developed a format for displaying manager preferences for departmental locations, known as **Muther's grid**.[2] The preference information is coded into six categories associated with the five vowels, *A*, *E*, *I*, *O*, and *U*, plus the letter *X*. As shown in **Figure 7.7**, the vowels match the first letter of the closeness rating for locating two departments next to each other. The diamond-shaped grid is read similarly to mileage charts on a road map. For example, reading down the highlighted row in **Figure 7.7**, it is *okay* if the offices are located next to production, *absolutely necessary* that the stockroom be located next to production, *important* that shipping and receiving be located next to production, *especially important* that the locker room be located next to production, and *absolutely necessary* that the toolroom be located next to production.

Muther's grid A format for displaying manager preferences for department locations.

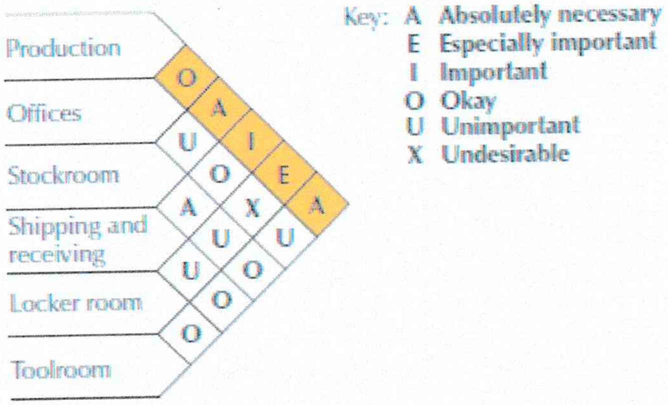


FIGURE 7.7 Muther's Grid

The information from Muther's grid can be used to construct a **relationship diagram** that evaluates existing or proposed layouts. Consider the relationship diagram shown in **Figure 7.8*a***. A schematic diagram of the six departments from Figure 7.7 is given in a 2 × 3 grid. Lines of different thicknesses are drawn from department to department. The thickest lines (three, four, or five strands) identify the closeness ratings with the highest prioritythat is, for which departments it is *important*, *especially important*, or *absolutely necessary* that they be located next to each other. The priority diminishes with line thickness. *Undesirable* closeness ratings are marked with a zigzagged line. Visually, the best solution would show short heavy lines and no zigzagged lines (undesirable locations are noted only if they are adjacent). Thin lines (one or two strands, representing *unimportant* or *okay*) can be of any length and for that reason are sometimes eliminated from the analysis. An alternative form of relationship diagramming uses colors instead of line thickness to visualize closeness ratings.

Relationship diagram A schematic diagram that uses weighted lines to denote location preference.

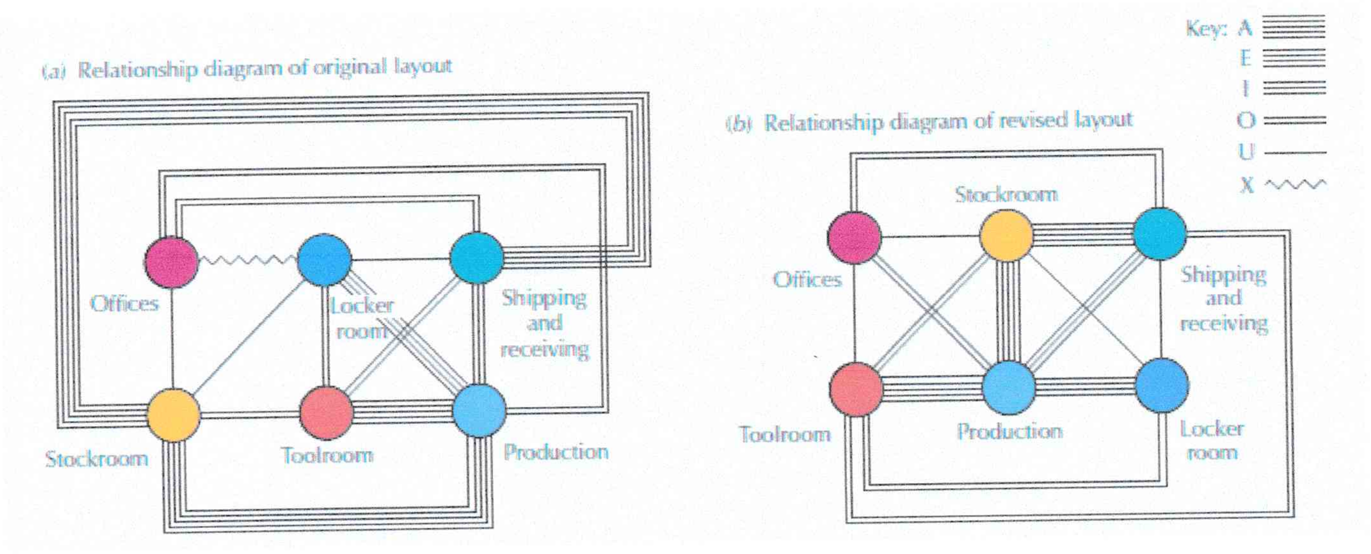


FIGURE 7.8 **Relationship Diagrams**

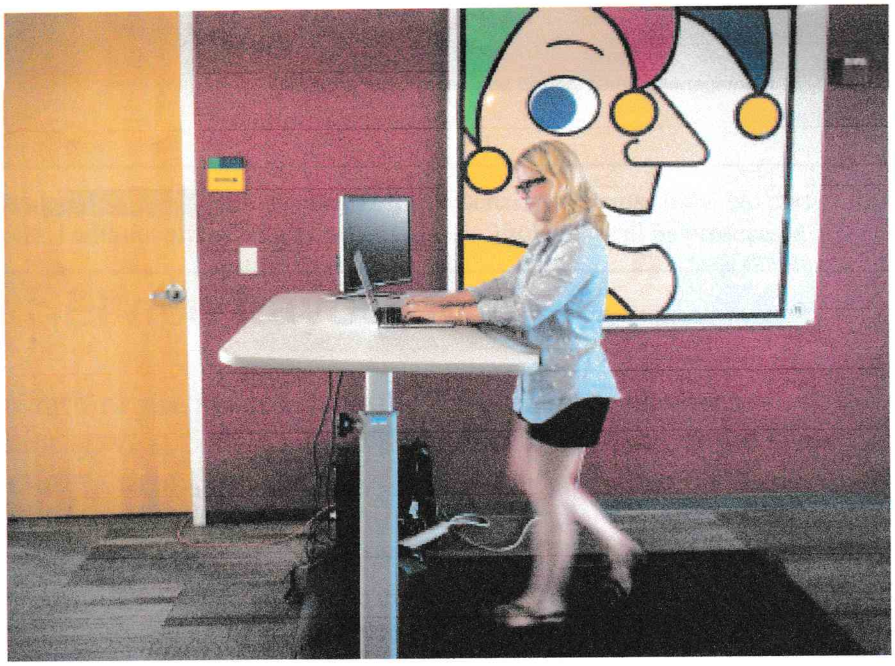
From Figure 7.8*a*, it is obvious that production and shipping and receiving are located too far from the stockroom and that the offices and locker room are located too close to one another. **Figure 7.8*b*** shows a revised layout and evaluates the layout with a relationship diagram. The revised layout appears to satisfy the preferences expressed in Muther's grid. The heavy lines are short and within the perimeter of the grid. The lengthy lines are thin, and there are no zigzagged lines (X's are shown only if the departments are adjacent).

Computerized Layout Solutions

The diagrams just discussed help formulate ideas for the arrangement of departments in a process layout, but they can be cumbersome for large problems. Fortunately, several computer packages are available for designing process layouts. The best known are CRAFT (Computerized Relative Allocation of Facilities Technique) and CORELAP (Computerized Relationship Layout Planning). CRAFT takes a load summary chart and block diagram as input and then makes pairwise exchanges of departments until no improvements in cost or nonadjacency score can be found. The output is a revised block diagram after each iteration for a rectangular-shaped building, which may or may not be optimal. CRAFT is sensitive to the initial block diagram used; that is, different block diagrams as inputs will result in different layouts as outputs. For this reason, CRAFT is often used to improve on existing layouts or to enhance the best manual attempts at designing a layout.

CORELAP uses nonquantitative input and relationship diagramming to produce a feasible layout for up to 45 departments and different building shapes. It attempts to create an acceptable layout from the beginning by locating department pairs with A ratings first, then those with E ratings, and so on.

Simulation software for layout analysis such as PROMODEL and EXTEND provide visual feedback and allow the user to quickly test a variety of scenarios. Three-D modeling and CAD-integrated layout analysis are available in VisFactory and similar software.



The Washington Post/Getty Images, Inc.

Trends in office layouts include flexibility, shared spaces, and ergonomic desks, like the one here at Motley Fool's headquarters, that can transition from sitting to standing and may even include a treadmill.

Along the Supply Chain

Inviting Retail Layouts

In contrast to manufacturing layouts, retail layouts need to be inviting to the customer. The invitation begins at the threshold, the first 5 to 15 feet of space at the entry to a facility. This is where customers get their first impression of the store and its merchandize, and where they "decompress" or transition to the retail environment. No need to put displays, signage, or product here; customers will walk right by them.

Research shows that 90% of customers turn right upon entering a store. Knowing that, retailers typically have a display wall or area to the right of store entry; subsequent displays lead customers along walking paths through the store usually in a circular pattern from front to back and then up to the front again. The path is not always as long or as obvious as the one IKEA leads its customers down, but a customer journey is indeed mapped out by the placement of aisles, displays, signage, and other visual cues.

The purpose of a retail layout is not efficiency, but rather maximum exposure to products. In fact, retail stores often create "speed bumps" to slow the customer's pace through the store and encourage impulse purchases. And saving space is not usually the top goal in retail layouts. Shopping anthropologist Paco Underhill found that narrow or crowded aisles discourage shoppers who fear the "butt-brush effect" of close proximity to other customers. Who knew?

1. Compare your grocery store layout to another type of retail store. What differences do you find in the "walking path"?
2. Think about how layouts can affect human behavior. Give an example from your own experience.

Source: Gus Lubin, "This Heat Map reveals the secret to IKEA's Store Design," *Business Insider* (January 21, 2014); Humayun Khan, "How to Create Retail Store Interiors That Get People to Purchase Your Products," https://www.shopify.com/blog/12927757, posted March 19, 2014 (accessed January 23, 2016).

Service layouts are also concerned with the allocation of space to departments, the location of special displays, the efficiency of checkout procedures, and protection from pilferage. Space allocation is determined by evaluating the sales per square foot of a product or product line versus the willingness of a vendor to pay for product placement. Queuing analysis, discussed in Chapter 5, is a quantitative technique for improving waiting lines that often form at checkouts.

Industry-specific recommendations are available for layout and display decisions. Computerized applications, such as SLIM (Store Labor and Inventory Management) and COSMOS (Computerized Optimization and Simulation Modeling for Operating Supermarkets), consider shelf space, demand rates, profitability, and stockout probabilities in layout design.

Finally, services may have both a *back office* (invisible to the customer) and a *front office* (in full view of the customer) component. Back offices may be organized for employee efficiency, functionality or well-being, while front office layouts must be aesthetically pleasing to the customer as well as functional. For that reason, service layouts are often considered part of the service design process.

Designing Product Layouts

A product layout arranges machines or workers in a line according to the operations that need to be performed to assemble a particular product. From this description, it would seem the layout could be determined simply by following the order of assembly as contained in the bill of material for the product. To some extent, this is true. Precedence requirements, specifying which operations must precede others, which can be done concurrently and which must wait until later, are an important input to the product layout decision. But there are other factors that make the decision more complicated.

Product layouts or assembly lines are used for high-volume production. To attain the required output rate as efficiently as possible, jobs are broken down into their smallest indivisible portions, called *work elements*. Work elements are so small that they cannot be performed by more than one worker or at more than one workstation. But it is common for one worker to perform several work elements as the product passes through his or her workstation. Part of the layout decision is concerned with grouping these work elements into workstations so products flow through the assembly line smoothly. A *workstation* is any area along the assembly line that requires at least one worker or one machine. If each workstation on the assembly line takes the same amount of time to perform the work elements that have been assigned, then products will move successively from workstation to workstation with no need for a product to wait or a worker to be idle. The process of equalizing the amount of work at each workstation is called **line balancing**.

Line balancing Tries to equalize the amount of work at each workstation.

Line Balancing

Assembly-line balancing operates under two constraints: precedence requirements and cycle time restrictions.

Precedence requirements are physical restrictions on the *order* in which operations are performed on the assembly line. For example, we would not ask a worker to package a product before all the components were attached, even if he or she had the time to do so before passing the product to the next worker on the line. To facilitate line balancing, precedence requirements are often expressed in the form of a precedence diagram. The *precedence diagram* is a network, with work elements represented by circles or nodes and precedence relationships represented by directed line segments connecting the nodes. We will construct a precedence diagram later in Example 7.2.

Precedence requirements Physical restrictions on the order in which operations are performed.

Cycle time, the other restriction on line balancing, refers to the maximum amount of time the product is allowed to spend at each workstation if the targeted production rate is to be reached. *Desired cycle time* is calculated by dividing the time available for production by the number of units scheduled to be produced:

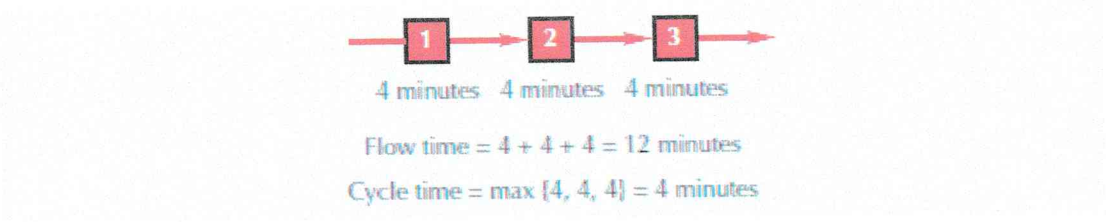
Cycle time The maximum amount of time a product is allowed to spend at each workstation.

$$C_d = \frac{\text{production time available}}{\text{desired units of output}}$$

Suppose a company wanted to produce 120 units in an 8-hour day. The cycle time necessary to achieve the production quota is

$$\begin{aligned} C_d &= \frac{(8 \text{ hours} \times 60 \text{ minutes / hour})}{(120 \text{ units})} \\ &= \frac{480}{120} = 4 \text{ minutes} \end{aligned}$$

Cycle time can also be viewed as the time between completed items rolling off the assembly line. Consider the three-station assembly line shown here.



It takes 12 minutes (i.e., 4 + 4 + 4) for each item to pass completely through all three stations of the assembly line. The time required to complete an item is referred to as its *flow time*. However, the assembly line does not work on only one item at a time. When fully operational, the line will be processing three items at a time, one at each workstation, in various stages of assembly. Every 4 minutes a new item enters the line at workstation 1, an item is passed from workstation 1 to workstation 2, another item is passed from workstation 2 to workstation 3, and a completed item leaves the assembly line. Thus, a completed item rolls off the assembly line every 4 minutes. This 4-minute interval is the actual cycle time of the line.

The *actual cycle time*, C_a, is the maximum workstation time on the line. It differs from the desired cycle time when the production quota does not match the maximum output attainable by the system. Sometimes the production quota cannot be achieved because the time required for one work element is too large. To correct the situation, the quota can be revised downward or parallel stations can be set up for the bottleneck element.

Line balancing is basically a trial-and-error process. We group elements into workstations recognizing time and precedence constraints. For simple problems, we can evaluate all feasible groupings of elements. For more complicated problems, we need to know when to stop trying different workstation configurations. The *efficiency* of the line can provide one type of guideline; the *theoretical minimum number of workstations* provides another. The formulas for efficiency, *E*, and minimum number of workstations, *N*, are

$$E = \frac{\sum_{i=1}^{j} t_i}{nC_a}; \quad N = \frac{\sum_{i=1}^{j} t_i}{C_d};$$

where

t_i = completion time for element i
j = number of work elements
n = actual number of work stations
C_a = actual cycle time
C_d = desired cycle time

The total idle time of the line, called **balance delay**, is calculated as (1 – efficiency). Efficiency and balance delay are usually expressed as percentages. In practice, it may be difficult to attain the theoretical number of workstations or 100% efficiency.

Balance delay The total idle time of the line.

The line balancing process can be summarized as follows:

1. Draw and label a precedence diagram.
2. Calculate the desired cycle time required for the line.
3. Calculate the theoretical minimum number of workstations.
4. Group elements into workstations, recognizing cycle time and precedence constraints.
5. Calculate the efficiency of the line.
6. Determine if the theoretical minimum number of workstations or an acceptable efficiency level has been reached. If not, go back to step 4.

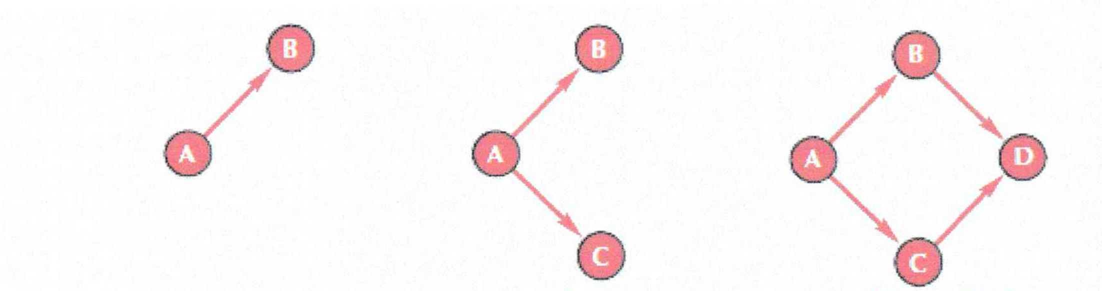
EXAMPLE 7.2 | Line Balancing

Real Fruit Snack Strips are made from a mixture of dried fruit, food coloring, preservatives, and glucose. The mixture is pressed out into a thin sheet, imprinted with various shapes, rolled, and packaged. The precedence and time requirements for each step in the assembly process are given below. To meet demand, Real Fruit needs to produce 6000 fruit strips every 40-hour week. Design an assembly line with the fewest number of workstations that will achieve the production quota without violating precedence constraints.

WORK ELEMENT		PRECEDENCE	TIME (MIN)
A	Press out sheet of fruit	—	0.1
B	Cut into strips	A	0.2
C	Outline fun shapes	A	0.4
D	Roll up and package	B, C	0.3

Solution

First, we draw the precedence diagram as follows.

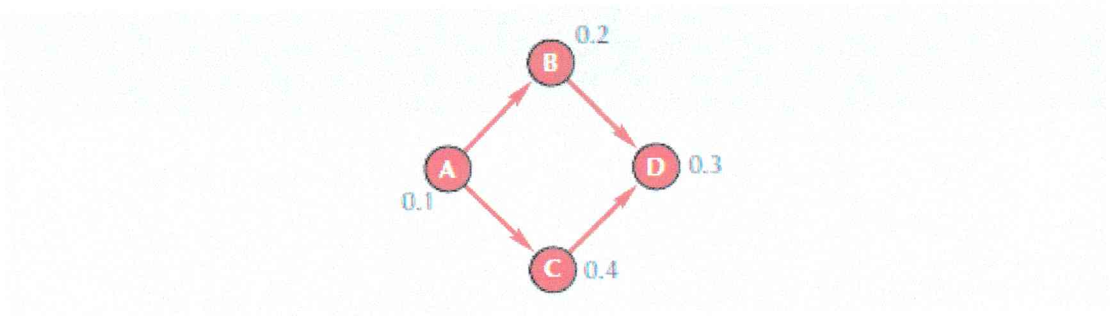


A precedes B. A precedes C. B and C precede D.

The precedence diagram is completed by adding the time requirements beside each node. Next, we calculate the desired cycle time and the theoretical minimum number of workstations:

$$C_d = \frac{40 \text{ hours} \times 60 \text{ minutes / hour}}{6000 \text{ units}} = \frac{2400}{6000} = 0.4 \text{ minutes}$$

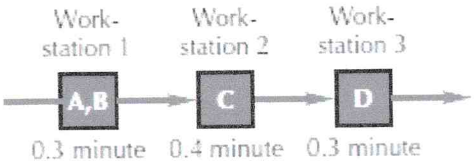
$$N = \frac{0.1+0.2+0.3+0.4}{0.4} = \frac{1.0}{0.4} = 2.5 \approx 3 \text{ workstations (round up)}$$



To balance the line, we must group elements into workstations so that the sum of the element times at each workstation is less than or equal to the desired cycle time of 0.4 minutes. Examining the precedence diagram, we begin with A since it is the only element that does not have a precedence. We assign A to workstation 1. B and C are now available for assignment. Cycle time is exceeded with A and C in the same workstation, so we assign B to workstation 1 and place C in a second workstation. No other element can be added to workstation 2, due to cycle time constraints. That leaves D for assignment to a third workstation. Elements grouped into workstations are circled on the precedence diagram and placed into workstations shown on the assembly line diagram.

WORKSTATION	ELEMENT	REMAINING TIME	REMAINING ELEMENTS
1	A	0.3	B, C
	B	0.1	C, D
2	C	0.0	D
3	D	0.1	none

Assembly-line diagram:



Since the theoretical minimum number of workstations was three, we know we have balanced the line as efficiently as possible. The assembly line has an efficiency of

$$E = \frac{0.1 + 0.2 + 0.3 + 0.4}{3\,(0.4)} = \frac{1.0}{1.2} = 0.833 = 83.3\%$$

Computerized Line Balancing

Line balancing by hand becomes unwieldy as the problems grow in size. Fortunately, there are software packages that will balance large lines quickly. IBM's COMSOAL (Computer Method for Sequencing Operations for Assembly Lines) and GE's ASYBL (Assembly Line Configuration Program) can assign hundreds of work elements to workstations on an assembly line. These programs, and most that are commercially available, do not guarantee optimal solutions. They use various *heuristics*, or rules, to balance the line at an acceptable level of efficiency. Five common heuristics are: longest operation time, shortest operation time, most number of following tasks, least number of following tasks, and ranked positional weight. Positional weights are calculated by summing the processing times of those tasks that follow an element. These heuristics specify the *order* in which work elements are considered for allocation to workstations. Elements are assigned to workstations in the order given until the cycle time is reached or until all tasks have been assigned. The most number of following tasks heuristic was used in Example 7.2.

Hybrid Layouts

Hybrid layouts modify and/or combine some aspects of product and process layouts. We discuss three hybrid layouts: cellular layouts, flexible manufacturing systems, and mixed-model assembly lines.

Cellular Layouts

Cellular layouts attempt to combine the flexibility of a process layout with the efficiency of a product layout. Based on the concept of group technology (GT), dissimilar machines or activities are grouped into work centers, called *cells*, to process families of parts or customers with similar requirements. (**Figure 7.10** shows a family of parts with similar shapes and a family of related grocery items.) The cells are arranged in relation to each other so that material movement is minimized. Large machines that cannot be split among cells are located near to the cells that use them, that is, at their *point of use*.

Cellular layouts Group dissimilar machines into work centers (called cells) that process families of parts with similar shapes or processing requirements.

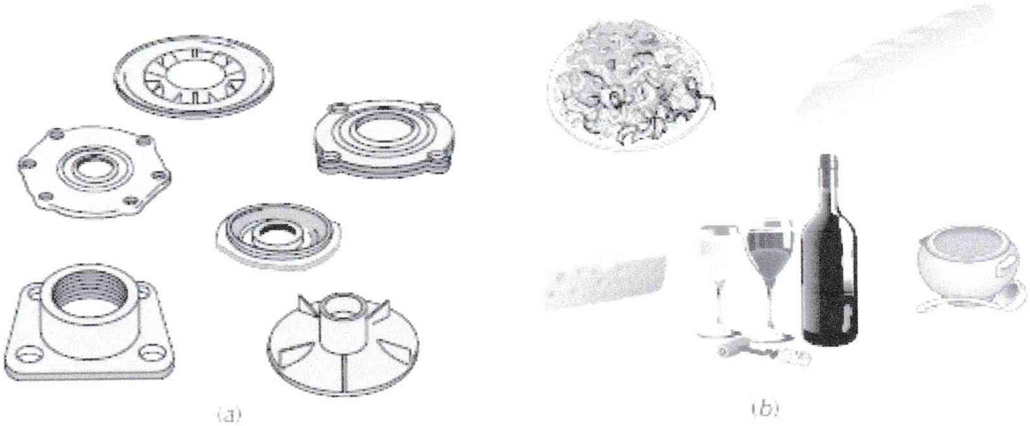
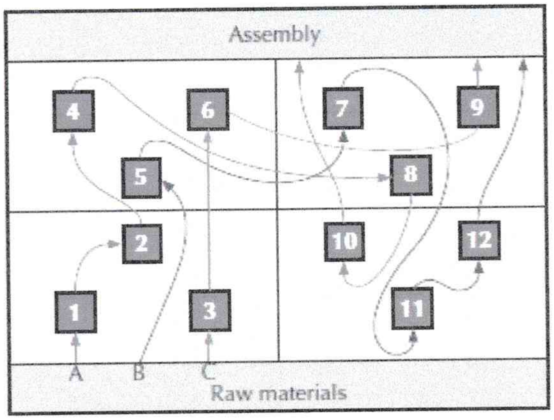


FIGURE 7.10 **Group Technology: (*a*) A family of similar parts; (*b*) A family of related grocery items.**

Source: Adapted from Mikell P. Groover, *Automation, Production Systems, and Computer Integrated Manufacturing* © 1987. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.

The layout of machines *within* each cell resembles a small assembly line. Thus, line-balancing procedures, with some adjustment, can be used to arrange the machines within the cell. The layout *between* cells is a process layout. Therefore, computer programs such as CRAFT can be used to locate cells and any leftover equipment in the facility.

Consider the process layout in Figure 7.11. Machines are grouped by function into four distinct departments. Component parts manufactured in the process layout section of the factory are later assembled into a finished product on the assembly line. The parts follow different flow paths through the shop. Three representative routings, for parts A, B, and C, are shown in the figure. Notice the distance that each part must travel before completion and the irregularity of the part routings. A considerable amount of "paperwork" is needed to direct the flow of each individual part and to confirm that the right operation has been performed. Workers are skilled at operating the types of machines within a single department and typically can operate more than one machine at a time.

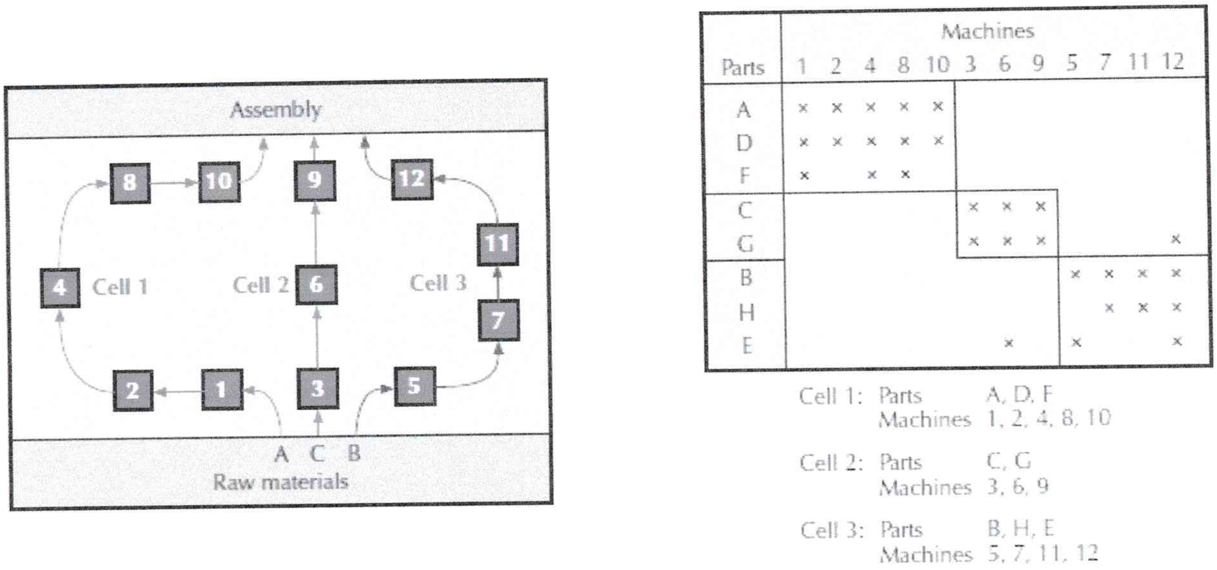


Parts	Machines 1	2	3	4	5	6	7	8	9	10	11	12
A	×	×		×				×		×		
B					×		×				×	×
C			×			×			×			
D	×	×		×				×		×		
E					×	×						×
F	×			×				×				
G			×			×			×			×
H							×				×	×

FIGURE 7.11 **Original Process Layout with Routing Matrix**

Figure 7.11 gives the complete part routing matrix for the eight parts processed through the facility. In its current form, there is no apparent pattern to the routings. **Production flow analysis (PFA)** is a group technology technique that reorders part routing matrices to identify families of parts with similar processing requirements. The reordering process can be as simple as using the "Data Sort" command in Excel for the most common machines, or as sophisticated as pattern-recognition algorithms from the field of artificial intelligence. **Figure 7.12** shows the results of reordering. Now the part families and cell formations are clear. Cell 1, consisting of machines 1, 2, 4, 8, and 10, will process parts A, D, and F; Cell 2, consisting of machines 3, 6, and 9, will process products C and G; and Cell 3, consisting of machines 5, 7, 11, and 12, will process parts B, H, and E. A complete cellular layout showing the three cells feeding a final assembly line is also given in Figure 7.12. The representative part flows for parts A, B, and C are much more direct than those in the process layout. There is no backtracking or crisscrossing of routes, and the parts travel a shorter distance to be processed. Notice that parts G and E cannot be completely processed within cells 2 and 3, to which they have been assigned. However, the two cells are located in such a fashion that the transfer of parts between the cells does not involve much extra movement.

Production flow analysis Reorders part routing matrices to identify families of parts with similar processing requirements.



Parts	1	2	4	8	10	3	6	9	5	7	11	12
A	×	×	×	×	×							
D	×	×	×	×	×							
F	×		×	×								
C						×	×	×				
G						×	×	×				×
B									×	×	×	×
H										×	×	×
E							×		×			×

Cell 1:	Parts	A, D, F
	Machines	1, 2, 4, 8, 10
Cell 2:	Parts	C, G
	Machines	3, 6, 9
Cell 3:	Parts	B, H, E
	Machines	5, 7, 11, 12

FIGURE 7.12 **Revised Cellular Layout with Reordered Routing Matrix**

The U shape of cells 1 and 3 is a popular arrangement for manufacturing cells because it facilitates the rotation of workers among several machines. Workers in a cellular layout typically operate more than one machine, as was true in the process layout. However, workers who are assigned to each cell must now be multifunctional—that is, skilled at operating many different kinds of machines, not just one type, as in the process layout. In addition, workers are assigned a *path* to follow among the machines that they operate, which may or may not coincide with the path the product follows through the cell. **Figure 7.13** shows a U-shaped manufacturing cell including worker paths.

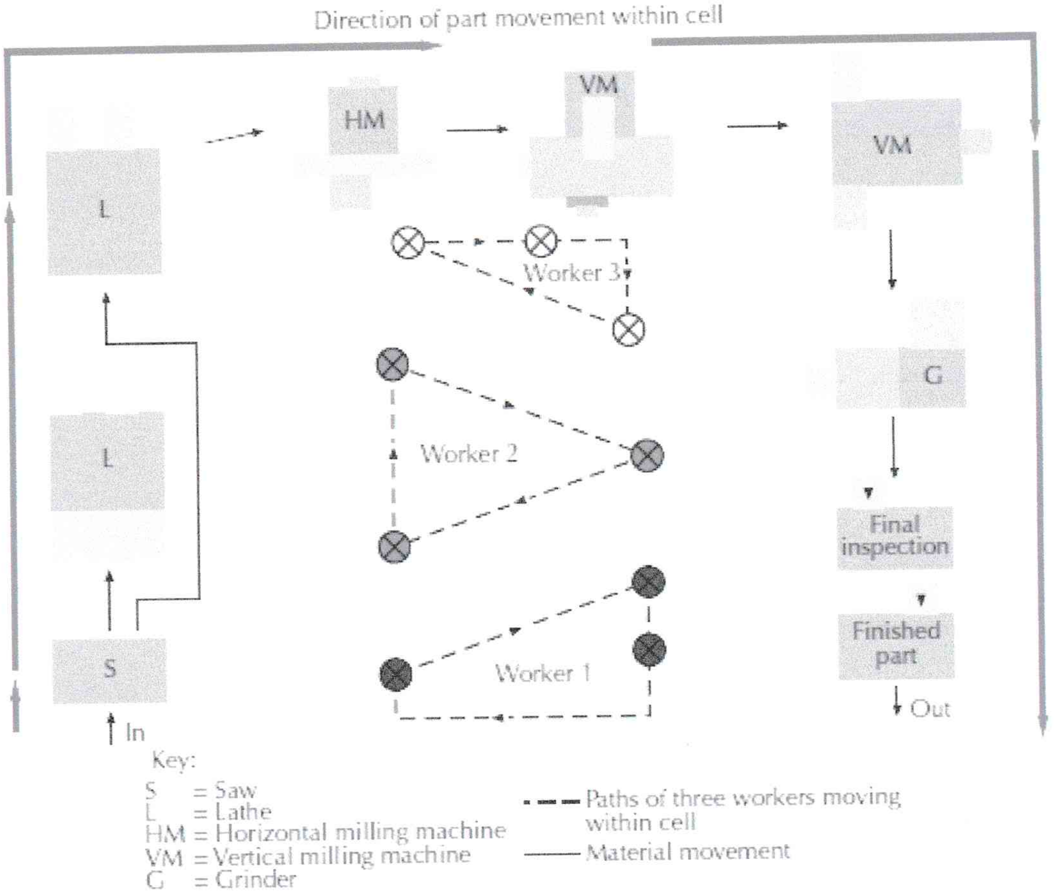


FIGURE 7.13 **A Manufacturing Cell with Worker Paths**

Source: J.T. Black, "Cellular Manufacturing Systems Reduce Setup Time, Make Small Lot Production Economical." *Industrial Engineering* (November 1983). Reprinted with the permission of the Institute of Industrial Engineers, 3577 Parkway Lane, Suite 200, Norcross, GA 30092, 770-449-0461. © 1983.

Advantages of Cellular Layouts Cellular layouts have become popular in the past decade as the backbone of modern factories. Cells can differ considerably in size, in automation, and in the variety of parts processed. As small interconnected layout units, cells are common in services, as well as manufacturing.

The advantages of cellular layouts are as follows:

- ***Reduced material handling and transit time.*** Material movement is more direct. Less distance is traveled between operations. Material does not accumulate or wait long periods of time to be moved. Within a cell, the worker is more likely to carry a partially finished item from machine to machine than wait for material-handling equipment, as is characteristic of process layouts where larger loads must be moved farther distances.

- ***Reduced setup time.*** Since similar parts are processed together, the adjustments required to set up a machine should not be that different from item to item. If it does not take that long to change over from one item to another, then the changeover can occur more frequently, and items can be produced and transferred in very small batches or lot sizes.
- ***Reduced work-in-process inventory.*** In a work cell, as with assembly lines, the flow of work is balanced so that no bottleneck or significant buildup of material occurs between stations or machines. Less space is required for storage of in-process inventory between machines, and machines can be moved closer together, thereby saving transit time and increasing communication.
- ***Better use of human resources.*** Typically, a cell contains a small number of workers responsible for producing a completed part or product. The workers act as a self-managed team, in most cases more satisfied with the work that they do and more particular about the quality of their work. Labor in cellular manufacturing is a flexible resource. Workers in each cell are multifunctional and can be assigned to different routes within a cell or between cells as demand volume changes.
- ***Easier to control.*** Items in the same part family are processed in a similar manner through the work cell. There is a significant reduction in the paperwork necessary to document material travel, such as where an item should be routed next, if the right operation has been performed, and the current status of a job. With fewer jobs processed through a cell, smaller batch sizes, and less distance to travel between operations, the progress of a job can be verified visually.
- ***Easier to automate.*** Automation is expensive. Rarely can a company afford to automate an entire factory all at once. Cellular layouts can be automated one cell at a time. **Figure 7.14** shows an automated cell with one robot in the center to load and unload material from several

CNC machines and an incoming and outgoing conveyor. Automating a few workstations on an assembly line will make it difficult to balance the line and achieve the increases in productivity expected. Introducing automated equipment in a job shop has similar results, because the "islands of automation" speed up only certain processes and are not integrated into the complete processing of a part or product.

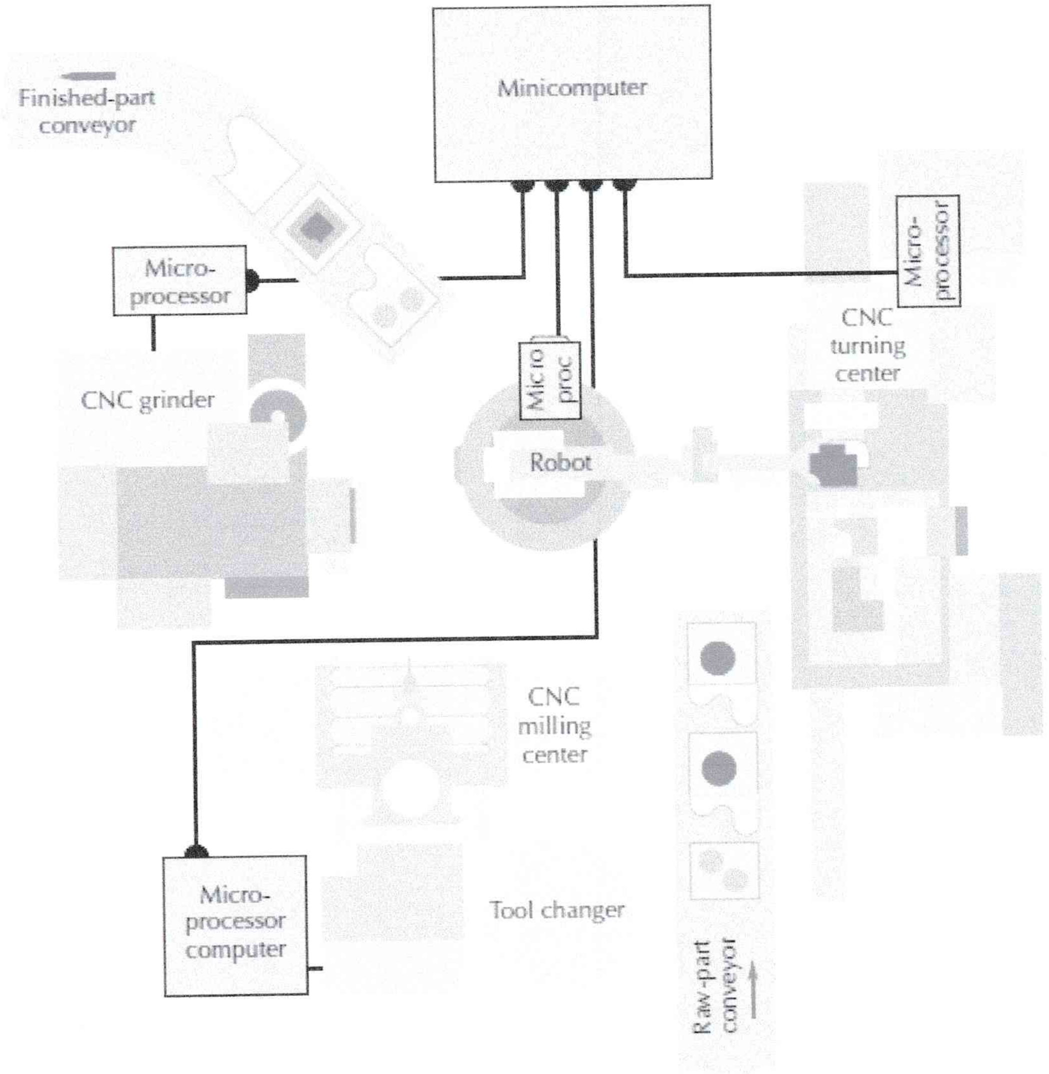


FIGURE 7.14 **An Automated Manufacturing Cell**

Source: J. T. Black, "Cellular Manufacturing Systems Reduce Setup Time, Make Small Lot Production Economical." Industrial Engineering (November 1983). Reprinted with the permission of the Institute of Industrial Engineers, 3577 Parkway Lane, Suite 200, Norcross, GA 30092, 770-449-0461, © 1983.

Disadvantages of Cellular Layouts In spite of their many advantages, cellular layouts are not appropriate for all types of businesses. The following disadvantages of cellular layouts must be considered:

- ***Inadequate part families.*** There must be enough similarity in the types of items processed to form distinct part families. Cellular manufacturing is appropriate for medium levels of product variety and volume. The formation of part families and the allocation of machines to cells is not always an easy task. Part families identified for design purposes may not be appropriate for manufacturing purposes.
- ***Poorly balanced cells.*** Balancing the flow of work through a cell is more difficult than assembly-line balancing because items may follow different sequences through the cell that require different machines or processing times. The sequence in which parts are processed can thus affect the length of time a worker spends at a certain stage of processing and thus delay his arrival to a subsequent stage in his worker path. Poorly balanced cells can be very inefficient. It is also important to balance the workload among cells in the system, so that one cell is not overloaded while others are idle. This may be taken care of in the initial cellular layout, only to become a problem as changes occur in product designs or product mix. Severe imbalances may require the reformation of cells around different part families, and the cost and disruption that implies.
- ***Expanded training and scheduling of workers.*** Training workers to do different tasks is expensive and time-consuming and requires worker cooperation. Some tasks are too different for certain workers to master. Although flexibility in worker assignment is one of the advantages of cellular layouts, the task of determining and adjusting worker paths within or between cells can be quite complex.
- ***Increased capital investment.*** In cellular manufacturing, multiple smaller machines are preferable to single large machines. Implementing a cellular layout can be economical if new machines are being purchased for a new facility, but it can be quite expensive and disruptive in existing production facilities where new layouts are required. Existing equipment may be too large to fit into cells or may be underutilized when placed in a single cell. Additional machines of the same type may have to be purchased for different cells. The cost and downtime required to move machines can also be high.

Flexible Manufacturing Systems

A **flexible manufacturing system (FMS)** consists of numerous programmable machine tools connected by an automated material handling system and controlled by a common computer network. It is different from traditional automation, which is fixed or "hard wired" for a specific task. *Fixed automation* is very efficient and can produce in very high volumes, but is not flexible. Only one type or model of product can be produced on most automated production lines, and a change in product design would require extensive changes in the line and its equipment.

Flexible manufacturing system Can produce an enormous variety of items.

An FMS combines flexibility with efficiency. Tools change automatically from large storage carousels at each machine, which hold hundreds of tools. The material-handling system (usually conveyors or automated guided vehicles) carries workpieces on pallets, which can be locked into a machine for processing. Pallets are transferred between the conveyor and machine automatically. Computer software keeps track of the routing and processing requirements for each pallet. Pallets communicate with the computer controller by way of bar codes or radio signals. Parts can be transferred between any two machines in any routing sequence. With a variety of programmable machine tools and large tool banks, an FMS can theoretically produce thousands of different items as efficiently as a thousand of the same item.

The efficiency of an FMS is derived from reductions in setup and queue times. Setup activities take place *before* the part reaches the machine. A machine is presented only with parts and tools ready for immediate processing. Queuing areas at each machine hold pallets ready to move in the moment the machine finishes with the previous piece. The pallet also serves as a work platform, so no time is lost transferring the workpiece from pallet to machine or positioning and fixturing the part. The machines in an advanced FMS, such as five-axis CNC *machining centers*, simultaneously perform up to five operations on a workpiece that would normally require a series of operations on individual machines.

FMS layouts differ based on the variety of parts that the system can process, the size of the parts processed, and the average processing time required for part completion. **Figure 7.15** shows a simple FMS where parts rotate on a conveyor until a machine is available for processing.

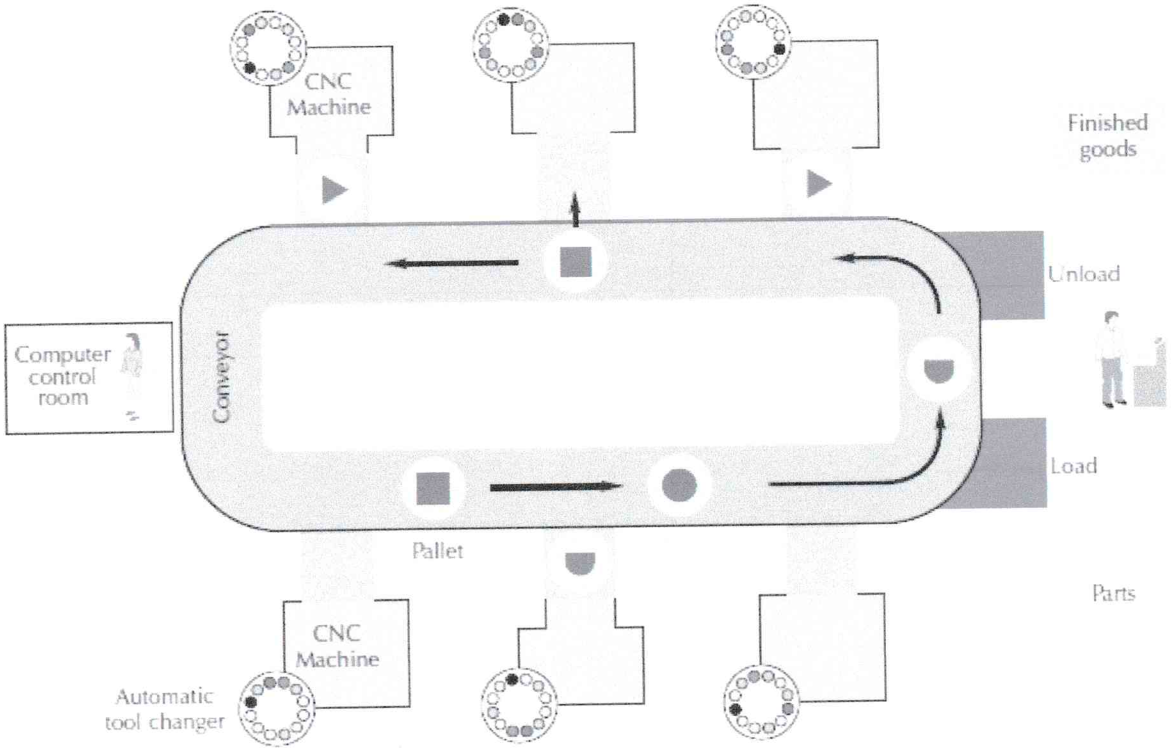


FIGURE 7.15 **A Flexible Manufacturing System**

Mixed-Model Assembly Lines

Traditional assembly lines, designed to process a single model or type of product, can be used to process more than one type of product but not efficiently. Models of the same type are produced in long production runs, sometimes lasting for months, and then the line is shut down and changed over for the next model. The next model is also run for an extended time, producing perhaps half a year to a year's supply; then the line is shut down again and changed over for yet another model; and so on. The problem with this arrangement is the difficulty in responding to changes in customer demand. If a certain model is selling well and customers want more of it, they have to wait until the next batch of that model is scheduled to be produced. On the other hand, if demand is disappointing for models that have already been produced, the manufacturer is stuck with unwanted inventory.

Recognizing that this mismatch of production and demand is a problem, some manufacturers concentrated on devising more sophisticated forecasting techniques. Others changed the manner in which the assembly line was laid out and operated so that it really became a **mixed-model assembly line**. First, they reduced the time needed to change over the line to produce different models. Then they trained their workers to perform a variety of tasks and allowed them to work at more than one workstation on the line, as needed. Finally, they changed the way in which the line was arranged and scheduled. The following factors are important in the design and operation of mixed-model assembly lines.

Mixed-model assembly line Processes more than one product model.

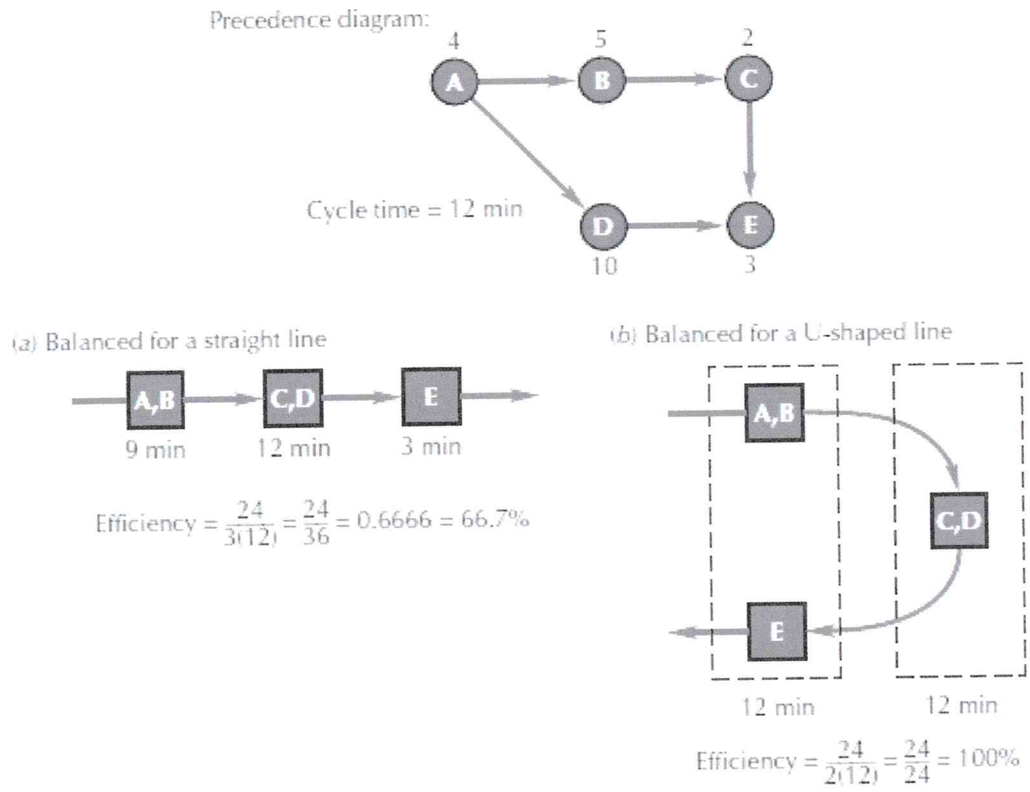


FIGURE 7.16 **Balancing U-Shaped Lines**

- ***Line balancing.*** In a mixed-model line, the time to complete a task can vary from model to model. Instead of using the completion times from one model to balance the line, a distribution of possible completion times from the array of models must be considered. In most cases, the expected value, or average, times are used in the balancing procedure. Otherwise, mixed-model lines are balanced in much the same way as single-model lines.

- ***U-shaped lines.*** To compensate for the different work requirements of assembling different models, it is necessary to have a flexible workforce and to arrange the line so that workers can assist one another as needed. Figure 7.16 shows how the efficiency of an assembly line can be improved when a U-shaped line is used.
- ***Flexible workforce.*** Although worker paths are predetermined to fit within a set cycle time, the use of average time values in mixed-model lines will produce variations in worker performance. Hence, the flexibility of workers helping other workers makes a tremendous difference in the ability of the line to adapt to the varied length of tasks inherent in a mixed-model line.
- ***Model sequencing.*** Since different models are produced on the same line, mixed-model scheduling involves an additional decision—the order, or sequence, of models to be run through the line. From a logical standpoint, it would be unwise to sequence two models back to back that require extra long processing times. It would make more sense to mix the assembling of models so that a short model (requiring less than the average time) followed a long one (requiring more than the average time). With this pattern, workers could "catch up" from one model to the next.

Another objective in model sequencing is to spread out the production of different models as evenly as possible throughout the time period scheduled. This concept of *uniform production* will be discussed in Chapter 16, "Lean Production."

Summary

Capacity planning is the process of establishing the overall level of productive resources for a firm. It involves long-term strategic activities, such as the acquisition of new facilities, technologies, or businesses, that take a year or more to complete.

Capacity expansion can *lead* demand, *lag* behind demand, or meet *average* demand. The *best operating level* for a facility often includes a *capacity cushion* for unexpected occurrences. The tendency of high levels of output to cost less per unit is known as *economies of scale*. This normally holds true up to a certain level of output, at which point *diseconomies of scale* can take over.

Facility decisions are an important part of operations strategy. An effective layout reflects a firm's competitive priorities and enables the firm to reach its strategic objectives. Batch production, which emphasizes flexibility, is most often organized into a *process layout*, whereas mass production uses a *product layout* for maximum efficiency. Because of their size and scope, projects tend to use *fixed-position layouts*. *Service layouts* may try to process customers through the system as quickly as possible or maximize customer exposure to products and services.

In the current manufacturing environment of new product introductions, rapidly changing technologies, and intense competition, the ability of a manufacturing system to adapt is essential. Thus, several hybrid layouts have emerged that combine flexibility and efficiency. Reductions in setup times have made *mixed-model assembly lines* feasible. The newest *flexible manufacturing systems (FMSs)* can process any item that fits the dimensions of the pallet on which it is transported. *Manufacturing cells* that resemble small assembly lines are designed to process families of items. Some companies are placing wheels and casters on their machines so that the cells can be adjusted as needed. Others are experimenting with modular conveyor systems that allow assembly lines to be rearranged while workers are on their lunch break.

As important as flexibility is, the cost of moving material is still a primary consideration in layout design. Today, as in the past, layout decisions are concerned with minimizing material flow. However, with reduced inventory levels, the emphasis has shifted from minimizing the *number* of loads moved to minimizing the *distance* they are moved. Instead of accumulating larger loads of material and moving them less often, machines are located closer together to allow the frequent movement of smaller loads. Planners, who used to devote a considerable amount of time to designing the location of storage areas and the movement of material into and out of storage areas, are now concerned with the rapid movement of material to and from the facility itself. The logistics of material transportation is discussed in Chapter 11, "Global Supply Chain Procurement and Distribution."

Key Terms

balance delay The total idle time of an assembly line.

best operating level The percent of capacity utilization at which unit costs are lowest.

block diagram A schematic layout diagram that includes the size of each work area.

capacity The maximum capability to produce.

capacity cushion A percent of capacity held in reserve for unexpected occurrences.

capacity planning A long-term strategic decision that establishes the overall level of productive resources for a firm.

cellular layout A layout that creates individual cells to process parts or customers with similar requirements.

cycle time The maximum amount of time an item is allowed to spend at each work-station if the targeted production rate is to be achieved; also, the time between successive product completions.

diseconomies of scale When higher levels of output cost more per unit to produce.

economies of scale When it costs less per unit to produce higher levels of output.

facility layout The arrangement of machines, departments, workstations, and other areas within a facility.

fixed-position layout A layout in which the product remains at a stationary site for the entire manufacturing cycle.

flexible manufacturing system (FMS) Programmable equipment connected by an automated material-handling system and controlled by a central computer.

line balancing A layout technique that attempts to equalize the amount of work assigned to each workstation on an assembly line.

mixed-model assembly line An assembly line that processes more than one product model.

Muther's grid A format for displaying manager preferences for department locations.

precedence requirements Physical restrictions on the order in which operations are performed.

process layout A layout that groups similar activities together into work centers according to the process or function they perform.

product layout A layout that arranges activities in a line according to the sequence of operations that are needed to assemble a particular product.

production flow analysis (PFA) A group technology technique that reorders part routing matrices to identify families of parts with similar processing requirements.

relationship diagram A schematic diagram that denotes location preference with different line thicknesses.

unit load The quantity in which material is normally moved, such as a unit at a time, a pallet, or a bin of material.

Key Formulas

Desired Cycle Time

$$C_d = \frac{\text{production time available}}{\text{desired units of output}}$$

Actual Cycle Time

$$C_a = \text{maximum workstation time}$$

Theoretical Minimum Number of Workstations

$$N = \frac{\sum_{i=1}^{j} t_i}{C_d}$$

Efficiency

$$E = \frac{\overset{j}{\underset{i=1}{\Sigma}} t_i}{nC_a}$$

Balance Delay

$$1 - \text{efficiency}$$