Process Fundamentals

Imagine that upon graduation you take a job managing a large bakery supplying supermarket chains with products ranging from breads to pies. Your mission is to improve the profitability of the operation. How will you start? Well, first, you will have to develop a good understanding of the current operation, the activities that take place to transform flour, water, yeast, and other ingredients into baked goods, and the effort involved in each activity—such as the labor, materials, and equipment required at each step. You will also need to understand the different products the bakery offers, and the reason that customers buy them from you and not your competitors. Do you have lower prices, faster delivery, higher quality, or a better product line that allows your customers to buy all their bakery needs from one source? Only after understanding the physical process itself, how it links to the performance of the bakery, and the level of performance required by customers, can you begin to look for opportunities to improve the bakery's profitability.

The goal of this overview is to provide tools that can help you understand operations, not just for a bakery, of course, but any type of operation. These tools are important not only for improving operations, but also for the daily management of an operation, or for the design of a new operation.

This overview begins by discussing the activities that take place in a "process". Analytical tools such as the process flow diagram are provided to help you walk into a new operation, such as your bakery, and understand how each of the process steps fits together. You'll be introduced to the types of management choices for designing, operating, and improving processes. Next, measures of the performance of a process and basic process analysis, the method used to determine what and how much a process is capable of producing, are introduced. You'll see how different types of processes can be used to make the same product, and how managers choose which process to use. Finally, the note focuses briefly on the complexity stemming from uncertainty and variability in the process, factors that make managing operations particularly difficult.

Elements of a Process

Throughout this course you will hear the terms "process," "operation," and "operating system." These will be used to mean any part of an organization that takes inputs and transforms them into outputs of greater value to the organization than the original inputs. In most situations we will focus on a subset of the entire organization—a single process that transforms a set of inputs into useful outputs. When talking about a set of processes, and in some cases the entire organization involved in transforming inputs into outputs, we will use the somewhat broader terms "operation" or "operating system."

Research Associate James Leonard and Professor Ann E. Gray prepared this note as the basis for class discussion. It is a rewritten version of an earlier note by Professor Paul W. Marshall, "A Note on Process Analysis," HBS No. 675-038.

Consider some examples of processes. An automobile assembly plant takes raw materials in the form of parts, components, and subassemblies. These materials, along with labor, capital, and energy, are transformed into automobiles. The transformation process is an assembly process and the output is an automobile. A restaurant takes inputs in the form of unprocessed or semiprocessed agricultural products. To these, labor (a cook and a server, for example), capital equipment (such as refrigerators and stoves), and energy (usually gas and / or electricity) are added, and the output is a meal.

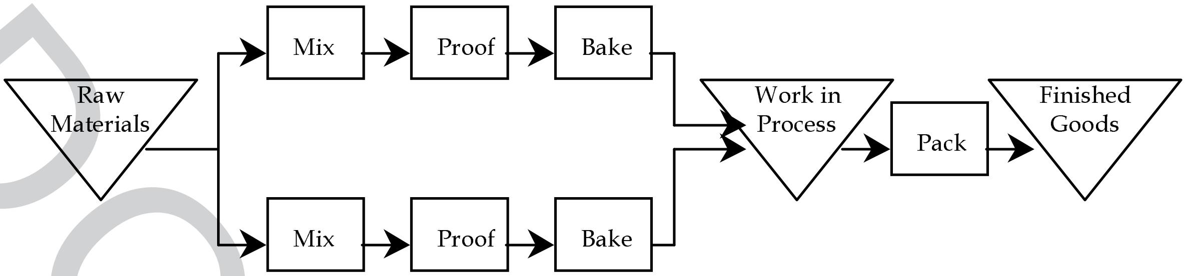
Both of the processes mentioned above have physical products as an output. However, the output of some operating systems is a service. Consider an airline. The inputs are capital equipment in the form of airplanes and ground equipment; labor in the form of flight crews, ground crews, and maintenance crews; and energy in the form of fuel and electricity. These are transformed into a service, namely, a means of transportation between widely separated points. Processes with a service output also include those found in a hospital, or in an insurance company. In a hospital, capital, labor, and energy are applied to another input, patients, in order to transform them into healthier or more comfortable people.

More formally, *a process is a collection of tasks, connected by flows of goods and information, that transforms various inputs into more valuable outputs*. People, machines, and procedures are generally involved in the transformation. In order to understand a process it is useful to have a simple method of describing the process and some standard definitions for its components. A convenient way to describe an operating system is a *process flow diagram*.

Returning to our bakery example, let's assume there are two distinct production lines in the bakery for making bread. Flour, yeast, and water enter at the left and are converted into loaves of bread through mixing, proofing (letting the dough rise), baking, and packaging. This is a bit of a simplification, but we'll use it for illustration. There are two mixers, two proofers, and two ovens organized so that the ingredients mixed on the first mixer are automatically fed into the first proofer, and then sent to the first oven. All of the baked loaves of bread are packaged on the same packaging line. **Figure 1** shows the process flow diagram for the bakery.

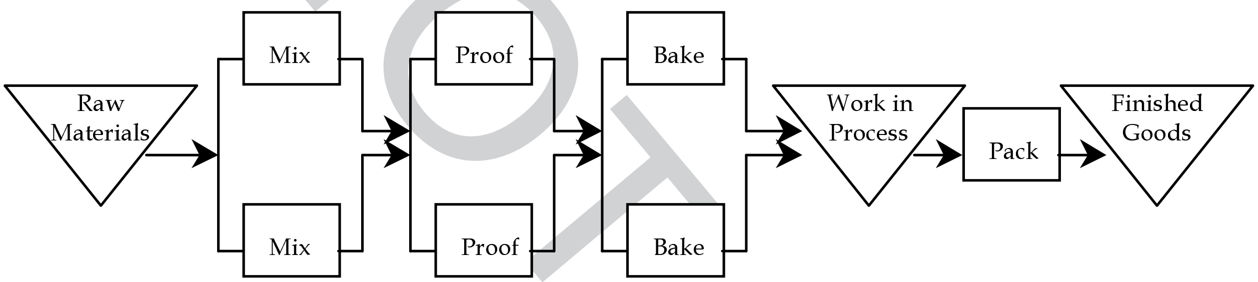
Tasks in this process are shown as small rectangles, flows as arrows, and the storage of goods as inverted triangles. We see two identical *parallel lines* for mixing, proofing, and baking. Within each line, the tasks of mixing, proofing, and baking are defined as being in a *series* relationship, because one step cannot start until the previous one is complete. The maximum capacity of the two parallel lines would be found by adding the capacity of each line. Work-in-Process Inventory (WIP) is shown before packaging because, at times, the bakery may produce different types of bread at the same time, one on each line, yet only one type can be packaged at a time. If there were parallel packaging lines, there may not be the need for holding WIP between baking and packaging except, perhaps, to allow the bread time to cool. Once packaged, the bread moves into Finished Goods Inventory, and from there is transported to grocery store customers.

Figure 1 Process Flow Diagram for Bread-Making with Two Parallel Baking Lines



If the mixers, proofers, and ovens were not set up as two distinct lines, and the product could flow from *each* mixer to *either* proofer, and then to *either* oven, we would draw the process as in **Figure 2**. In this case, it is the individual *tasks* that operate in parallel, instead of two distinct parallel lines. (The distinction between these configurations will become important when performing a more detailed process analysis to determine the *capacity* of the system.)

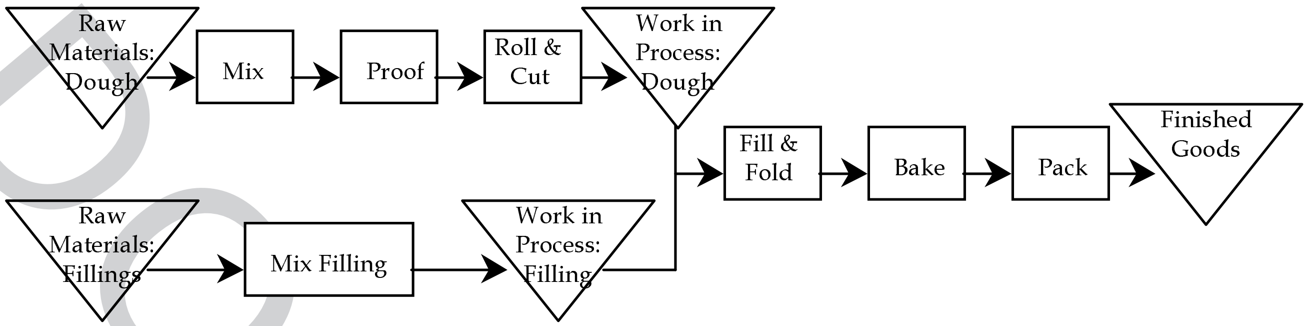
Figure 2 Process Flow Diagram for Bread-Making with Two Mixers, Proofers, and Ovens



We may also want to show on a process flow diagram tasks that are performed in parallel but which must *both* be completed before the process can continue. For example, our bakery makes filled croissants in addition to breads. For these, the mixing, proofing, rolling, and cutting of the pastry take place in parallel with the mixing of the filling as shown in **Figure 3**. All these tasks must be completed before the croissants can be filled and baked. Proofing the dough takes longer than any of the other pastry-making steps. Proofing also takes longer than mixing the filling. This means that the rate at which filling and folding takes place is limited by the rate at which the *dough*, not the filling, is ready. And the rate at which the dough is ready is limited by the rate at which proofing takes place. It is the rate of the proofing step, the longest task, that defines how much bread can be made per hour.

Note that the nature of the parallel activities for making croissants is different from that of the two bread lines working in parallel as in **Figure 1**. To determine the capacity of the bread-making operation up until the dough is baked, we *add* the capacity of each of the parallel bread lines. To determine the capacity of croissant-making, however, we would take the *minimum* of the capacity of the two different parallel processes, in this case, the capacity of pastry making. This is because the output of the two lines must be *combined* to make the final product. We will revisit this issue in Section 1.2, when we do a formal capacity analysis.

Figure 3 Process Flow Diagram for Croissant-Making



Once a process has been described using a process flow diagram, its components must be analyzed in order to draw some conclusions about its *performance* as a whole. In the following sections we will discuss each component of the process—the inputs, outputs, tasks, flows, and storage of goods—and begin to develop measurement and analysis methods along the way.

Inputs

The inputs to a process can be divided into at least four categories: labor, materials, energy, and capital. To analyze an operating system we must measure these inputs and determine the amount of each needed to make some amount of output. Usually we use physical units to measure the inputs—hours for labor and joules for energy, for example. Sometimes it is more useful to measure the input in dollars by determining how much it would cost to purchase these units. Thus, in many analyses it will be necessary to consider the economic conditions influencing the cost of labor, materials, energy, and capital. Measuring the cost of inputs thus becomes more difficult and requires additional care as the time horizon lengthens.

Determining how much of any input is needed to make a given output entails varying degrees of difficulty. Some inputs (e.g., labor and materials) are fully consumed to produce an output and thus are easy to assign to that unit of output. For example, it is easy to measure how much energy the oven uses to bake a batch of bread. Other inputs, however, are utilized in the production of an output, but are not fully consumed—the oven itself, for instance. The capital input is often the most difficult of the four categories to assign to a specific output because it is almost impossible to measure how much capital is consumed at any point in time. Generally accepted accounting rules are often used to allocate fixed costs, such as capital, to each unit of output.

Outputs

The output of a process is either a good or a service. The process flow diagram in **Figure 1** shows that the product is stored in Finished Goods Inventory (FGI) before leaving the system. In some organizations the finished goods inventory is kept apart from the operating system producing the good and is managed separately. Sometimes, the finished goods inventory does not exist at all: the process produces the output directly for distribution. In fact, this is an important characteristic of most processes providing services. It is often not easy (or possible) to store it for later distribution.

Although it is a simple matter to count the number of loaves of bread produced by the bakery, or to count the number of patients served by a hospital, it may not be simple to place a value on this output. The question of valuing the outputs can be approached from an economic point of view if a market will place a value on the output through the pricing mechanism. So, if we know the revenue that can be obtained from selling the good or service, that should serve as a measure of its value. For this reason, we must have a good understanding of the economic environment within which the process exists. Thus, "What are the market conditions?" and "What is the competition doing?" are important questions to address when analyzing a process.

For a new product, or one that has some improved characteristics, however, the question of what price *will be* paid for the output is difficult to answer unless some other information is known about the output. Here, we will consider three output characteristics: the *cost* of providing the output, the *quality* of the output, and the *timeliness* of the output. Often none of these measures is easily obtained, but they can serve as a checklist in our analysis of operating systems. If we are going to consider making a new type of bread, or increasing the quality of the bread, we may not know the price we can get for it. However, we do know that to value the new product, it is important to take into account the new product's characteristics, market conditions (is there an oversupply of specialty or high-end breads?), and the competitive situation (should we match the price of a competitor's similar product?).

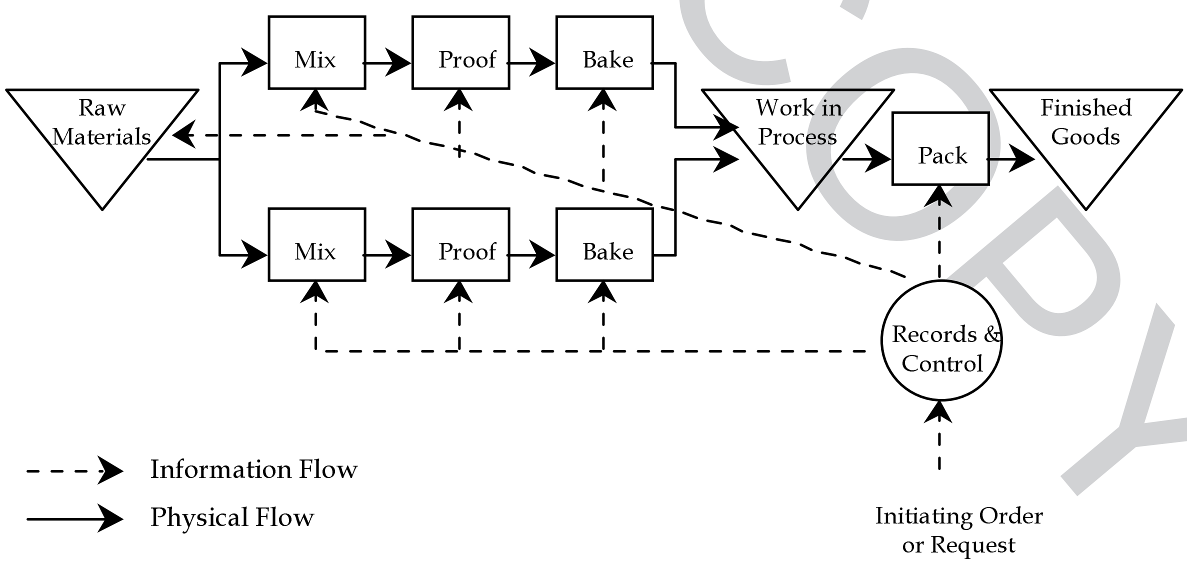
Tasks, Flows, and Storage

So far we have discussed what goes into and what comes out of a process. We must also understand what goes on inside a process. The specifics of every process are different, but there are three general categories for all activities within the process: tasks, flows, and storage.

A task typically involves the addition of some input that makes the product or service more nearly like the desired output. Some examples of tasks are (1) operating a drill press to change a piece of metal; (2) inspecting a part to make sure it meets some standard; (3) flying an airplane; and (4) anesthetizing a patient before an operation. A task quite often takes the form of added labor and capital; in processes with some form of automation, capital and/or material may be substituted for labor in a task.

There are two types of flows to be considered in each process: the flow of goods and the flow of information. **Figure 4** depicts a process flow diagram with the flow of information shown explicitly—the flow of physical goods is indicated by solid lines and the information flow by broken lines.

Figure 4 Information and Physical Process Flow Diagram for the Bread-Making Process



Information flows in the bread-making process depicted in **Figure 4** are quite simple; they take the form of recipes and production orders. The list of ingredients and quantities for the type of bread that will be made next must go the operators or material handlers in charge of getting the raw material ingredients to each mixer. Information on mixing times and methods must go to the operators of the mixers, and baking temperatures and times must go to operators of the ovens. We will also have to inform packaging of what types and quantities of breads will be arriving to the packaging area so that they can set up their equipment with the correct bags.

In some types of operations, the information flows take place with the physical flows, often in the form of a routing slip attached to a single product or a batch of products. The analogy here would be the entire recipe and the production order moving with the bread. The oven operator, for instance, would receive baking instructions with the proofed dough as it arrives at the oven. If the operator could not or would not need to adjust the oven in advance, not providing this information in advance would not cause any production delay and would simplify the information flows. Other information that might be included on the routing slip includes the packaging lines that the loaves should be sent to (if there are multiple packaging lines), the appropriate bags to use for packaging, the supermarket name and location, the delivery date and time, and possibly even the truck into which the finished product should be loaded.

When the information does not physically move through the process with the goods, the worker may need to go to a central location to obtain the information before performing the task, or the worker may have the necessary information at the workstation or in his or her head. In analyzing a process it is often important to consider the information flows in addition to the physical flow of goods or services.

Storage (the holding of inventory) is the last of the three activities within a process we will define. Storage occurs when no task is being performed and the good or service is not being transported. In **Figures 1 - 4** we have shown the storage of goods as inverted triangles. While the bakery is operating, there will usually be work-in-process inside the mixers, proofers, and ovens, at the packaging machines, as well as some work-in-process inventory between each step, and raw materials and finished goods inventory in the warehouse. If there is no storage between two connected tasks there must be a planned continuous flow between these tasks to allow the receiving task to operate continuously. **Figures 1** and **2** show only one work-in-process storage, whereas **Figure 3** shows two. In many processes that are considered continuous, there are at least a few units of work-in-process inventory on a rack or chute waiting to be fed into a machine. Although technically these units are in storage and could be depicted on the process flow diagram as inverted triangles between processing steps, when these units represent just a few minutes of processing time they are often left off of the diagram.

It is also possible, and in fact necessary, to store information. This storage is shown as a circle in **Figure 4**, with an arrow coming in from the environment to start the process. In this case, there are two kinds of information: records and control. The term *records* typically refers to general instructions, such as blueprints and instructions of how a product should be made (i.e., the "recipe"). These records are product-specific. Records may also be machine-specific, tracking repair and preventative maintenance histories, for example. The term *control* usually refers to information specific to a given order, such as the order quantity, customer name or number, due date and routing procedure for the order, or special instructions that make the order different from the generally accepted procedures explained in the records.

Measuring the Performance of a Process

So far we have defined the process in general terms and given names to various components of the process, namely the *inputs*, the *outputs*, and the *tasks*, *flows*, and *storage* within the process. We have also noted that the process does not exist in isolation. Economic conditions influence the values of inputs and outputs, and the state of technology influences the nature of the tasks and flows. Using these concepts as a base, we can now explore some process characteristics, concentrating on four: *capacity*, *efficiency*, *flexibility*, and *quality*.

Capacity

Capacity is the maximum rate of output from the process and is measured in units of output per unit of time: a steel mill, for instance, can produce some number of tons of steel per year, or an insurance office can process some number of claims per hour. *Capacity is easy to define and hard to measure.* It is often possible to determine the *theoretical capacity* of a process—the most output it could generate under ideal conditions over some period of time. For planning purposes and management decisions, however, it is more useful to know the *effective capacity* of a process. And to measure effective capacity, we must know a great deal about the process, carefully analyzing the particular situation at hand.

Managers often believe that the capacity of a process is an absolute fixed quantity. This is rarely true. The capacity of a process can change for many reasons, and we will encounter several cases where this is a key factor. The steel mill, for instance, may be designed for some ideal capacity, but its effective capacity may be different due to a variety of internal and external factors, and management decisions. The nature and availability of the raw materials being utilized, the mix of products being produced, the quantity and nature of the labor input, and the number of shifts of operation will all impact the effective capacity. The yield of the process is also important. In most instances, the rate of *good* units produced is the relevant capacity measure.

Efficiency

Efficiency is a measure that relates the amount or value of the output of the process to the amount or value of the input. "Efficiency" is widely used to measure physical processes. Every engine has an efficiency, expressed as a ratio of output energy to input energy. So, an engine with 75% efficiency can deliver 75% of the input energy as useful output energy. The energy efficiency of physical systems cannot exceed 100%; the useful output energy is always less than the energy input. This is not generally true of economic processes, however. For example, if the process is going to generate sufficient resources to support its own continued operation, the *value* of the output should exceed the value of the input. If we measure the value of output by the revenues it will bring in the market, and if we measure the value of inputs by their costs, the measure of efficiency is profit, i.e., revenue minus cost. Thus, the profit is the value of output minus the value of input. Profit, however, is a very simplistic definition of efficiency; measuring efficiency is generally much more complex.

In some cases, the price received for the product is not a good representation of the economic value of the output. In certain markets, for example, it may be possible initially for a company to sell a product of low quality at a standard price. Over time, however, the company's reputation may be hurt by doing this, and *all* of the company's products, not just the low quality product, might become less desired by the market. The long-term loss in revenue should have been considered when establishing the cost and quality level of the original product. When determining the efficiency of a process as measured by profitability, it is important to look at long-run profits, not just the profit generated from any short-run action.

Utilization is another common measure. Utilization is the ratio of the input the process actually used in creating the output to the amount of that input available for use. In a labor-intensive process, for instance, direct labor utilization is often an efficiency measure. If, say, 100 workers are employed in a given process, and during an eight-hour shift 700 hours of labor were consumed in the actual manufacture of product, then the direct labor utilization during that shift was 87.5% ([700 hours / (100 X 8 hours)] = 0.875). In a similar way, to measure capital efficiency, companies often pay a great deal of attention to machine utilization, which measures the percentage of time machinery is actively producing output.

In a small bakery where workers mix the dough, form loaves, and move the product from one step to another by hand, labor utilization is a critical measure of bakery performance. In an automated bakery, machine utilization may be more relevant.

Flexibility

A third characteristic we want to consider in analyzing a process is its *flexibility*. This is a measure of how long it would take to change the process so that it could produce a different output, or could use a different set of inputs. Flexibility, which allows a process to respond to changes in its environment, is also the least precise and hardest to define of the characteristics we have considered thus far. Flexibility must often be described in qualitative terms; doing so, however, does not make it any less important to managers.

Returning to our bakery, its flexibility may be described by the different types of bread that can be produced on a given line, or whether pastry products can also be made on the same line as bread products. Another type of flexibility may further be measured by the time required to switch the line from producing one type of product to another.[1]

Quality

Like flexibility, *quality* may be described in different ways. Product quality can be evaluated using external measures—comparing the product with others available in the marketplace—or using internal measures—comparing individual units with one another or with the product design specification. External quality measures generally assess how well the product design satisfies the wants and needs of customers. Product performance, features, reliability, durability, serviceability, and design aesthetics may all be components of product quality. Internal measures of product quality generally assess whether individual units meet design specifications.

In addition to designing, measuring and controlling *product* quality, a manufacturer also designs, measures and controls *process* quality. In order to produce a product with certain specifications, the process must be operating within certain tolerances. Process measures, such as the temperature in a kiln or the amount of force applied by a punch press, are generally used in assessing process quality. Any piece of processing equipment has specific capabilities defined by the range of process specifications it is able to achieve. A piece of equipment may not be able to perform a certain type of operation, such as grinding a piece of metal to a certain smoothness, if doing so requires operating outside this range or it may not be able to *consistently* perform the operation properly. In other circumstances, the equipment is capable of consistently operating within certain specifications, but is not operating consistently within these specifications because of poor equipment control. Both the design of the process and the way in which the process is operated are important determinants of process, and thus, product quality[2].

---

[1] A more detailed description of different types of process flexibility and how they can be managed can be found in: Upton, David, "The Management of Manufacturing Flexibility," *California Management Review*, Winter, 1994, or Upton, David, "What really makes factories flexible?," *Harvard Business Review*, July-August, 1995.

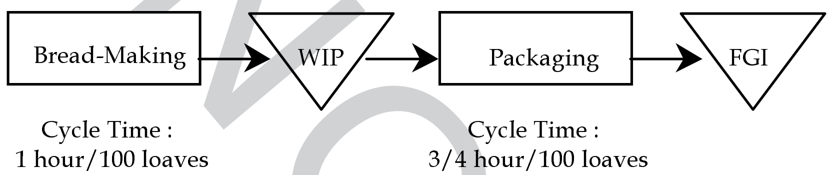
[2] A more detailed description of different measures of quality can be found in: Garvin, David A., "Competing on the eight dimensions of quality," *Harvard Business Review*, November-December, 1987, or Garvin, David A., and Artemis March, "A Note on Quality: The Views of Deming, Juran, and Crosby," Harvard Business School Note 9-687-001, 1987.

Within the plant, the impact of poor quality can be increased scrap, rework, yield losses resulting in lost capacity, downtime, additional testing, and lost management and worker time. If poor quality product leaves the factory, the impact can include a loss of goodwill toward the company and its brands, time and cost responding to customer complaints, and repair costs.

Process Terminology and Process Analysis

As the new manager of the bakery, once you understand its products and the process steps, and you have created a process flow diagram, you will want to determine the capacity of your operation. To do this, let's further simplify the bread-making example, as illustrated in **Figure 5**. Here, there are two steps required to prepare bread. The first is bread-making, which includes preparing the dough and baking the loaves, and the second is packaging the loaves. There is only a single line for mixing, proofing, and baking, and it is illustrated by one box representing the entire bread-making line.

Figure 5



Based on the size of the mixers in the bakery, bread is made in batches of 100 loaves each. Bread-making completes a batch of 100 loaves every hour; thus, one hour is the bread-making *cycle time* for a batch of 100 loaves. Although packaging needs only 3/4 of an hour to place the 100 loaves in bags (its cycle time), the rate at which the entire process can operate is paced by bread-making. Thus, over the course of a day, packaging will incur *idle time* during the 1/4 hour periods in which the next batch of bread is still being made but packaging has already completed bagging the previous batch. Bread-making is the *bottleneck* of the operation. The cycle time for the entire process is 1 hour, the maximum of the cycle times of the two operations in series. Given the cycle time for the entire process, we can determine its *capacity*. Simply put, if the cycle time is 1 hour per 100 loaves, the line has a capacity of 100 loaves per hour, the inverse of the cycle time. To determine the daily capacity, we would need to know the number of hours the bakery is in operation per day. With any of these terms of measurement, it is important to be very explicit about the units (i.e., loaves per hour, minutes per loaf), particularly when performing calculations.

To perform our analysis of the capacity of the bread-making line above, we introduced some new terms and concepts. While we have provided formal definitions below, we must also stress that **calculating these measures requires close attention to the specifics of a particular process.** In addition, **different firms sometimes define these terms in different ways** for their own internal use. This variation is reflected in some of our case materials. However, for the purposes of class discussion, it makes sense to try to adhere to a common vocabulary.

Cycle Time (CT): The cycle time of a process is the average time between completion of successive units. In other words, cycle time answers the question, "How often does a unit complete the process?" Cycle time can be similarly defined for portions of a process. The cycle time of a particular task in a process reflects the average time between finishing the task for one unit and finishing the task for the next unit.

Sometimes a process is not operated at its maximum production rate. In those instances, you may need to distinguish between the rate at which units *can* complete the process (the minimum cycle time of the process) and the rate at which they actually *do* complete the process (the actual cycle time).

Bottleneck: The bottleneck of a process is the factor which limits production. Usually, we will speak of the task with the longest cycle time as a bottleneck, such as bread-making in **Figure 5**. In other situations, the available labor may be the bottleneck. In some settings, information, raw materials flow, or even a specific order may be a bottleneck. Just as the neck of a bottle limits the rate at which the liquid inside can be poured, a process bottleneck limits how quickly products can move through the process, and thus determines the process *cycle time*. The bottleneck may shift depending on what products are being produced or what labor or equipment is available at any point in time. Because bottlenecks pace a process and limit its *capacity*, they are important focal points for management attention.

Idle Time: Idle time refers to the time when useful work is not being performed; the term can be applied to a worker or to a machine. Time spent waiting to receive or deliver a unit is idle time unless there is some other useful task to be performed in the interim. Idle time can be present even in a perfectly balanced process. A worker in the packaging department, for example, may merely load twenty loaves of bread on a machine and then stand by while it bags the bread. This time might be idle time for the worker (unless he or she is *needed* to monitor the equipment's performance), while it is not idle time for the packaging machine. In **Figure 5**, the packaging machine will be idle 1/4 of the time.

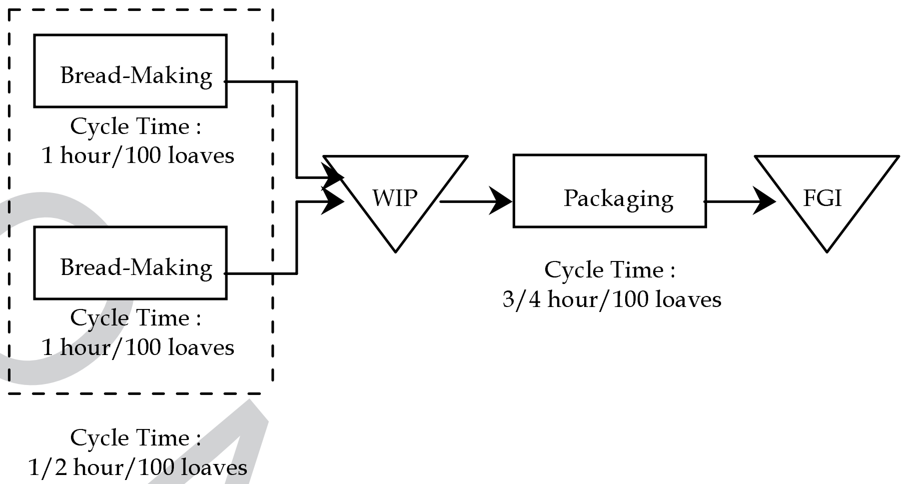
Capacity: Capacity is a measure of how much can be produced or serviced in a specified period of time, e.g., tons per day, parts per minute, customers per hour. The capacity of a process is determined by the process bottleneck. Capacity utilization is a measure of how much output was actually achieved relative to capacity (how much output could have been achieved in an ideal situation). If the capacity of a process is 500 units per day and on a given day 480 are produced, then on that day capacity utilization was 96% (480 units/500 units = 0.96). We may speak of the capacity of a task, a machine, a worker, a work area, or of an entire process.[3] Cycle time and capacity are closely related. If the cycle time of a task is 30 minutes per unit, then the capacity of that task is 2 units per hour.

Capacity seems a straightforward measure, and for a specific task producing a specific product it often will be. But finding relevant capacity measures for an entire process can be complicated. In many cases, the system capacity will depend on the size and mix of products and order sizes. And because the capacity of an entire process is affected by product mix, staffing, labor contract issues, maintenance time, etc., the effective capacity and capacity utilization will depend upon the way the process is managed.

Suppose we have two lines for bread-making, as shown in **Figure 6.**

[3] Companies such as Toyota Motor Manufacturing ensure that capacity exceeds customer requirements by calculating the *takt time*. This is determined by taking the time available to produce a certain product and dividing by customer demand for that product. The result, the takt time, is the production rate necessary to meet demand, and, if possible, a process should be designed with this takt time in mind. (For example, if an assembly line is available for 16 hours (960 minutes) per day and customer demand is 1,000 cars per day, the takt time is 0.96 minutes per car.)

Figure 6



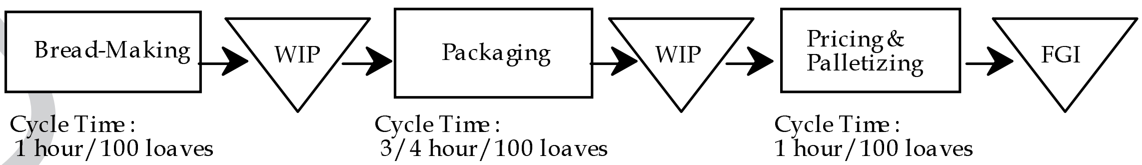
Although the cycle time for each bread-making line is 1 hour/100 loaves, the cycle time of the two lines together is 1/2 hour/100 loaves or, equivalently, 0.005 hour/loaf. Because the packaging line takes 3/4 hour to bag 100 loaves (or 0.0075 hour/loaf), *it* becomes the bottleneck of the process. If both bread-making and packaging were operated for the same number of hours each day, we would not make bread at its maximum cycle time rate because we would not have the capacity to package it. There is, therefore, an *imbalance* in the cycle times of the two parts of the process. If, however, we could operate packaging for three shifts and bread-making for two shifts each day, then the daily capacity of each would be identical. To do this requires building up a shift's-worth of inventory each day as work-in-process that packaging would then bag during the third shift.

Balance/Imbalance: If every step in a process had the same cycle time (and performed consistently at that precise cycle time, with no variability), then the process would be in perfect balance. This is virtually never achieved in practice, however. The processes shown in **Figures 5 and 6** are both imbalanced. If a system is not perfectly balanced there will be potential *idle time* at the non-bottleneck parts of the process. Although the cycle times are imbalanced in **Figure 6**, we can balance the daily capacity at each of the two steps by adjusting the hours worked per day in each step.

For the processes above, we might want to know the *manufacturing lead time*-—how long it takes to actually make and pack a batch of 100 loaves. For the process in **Figure 5**, the manufacturing lead time is 1 and 3/4 hours, as long as packaging begins immediately once the 100 loaves are made. The manufacturing lead time for the process in **Figure 6**, however, depends upon how the process is managed. Let's assume that we operate both steps in the process (bread-making and packaging) for the same number of hours per day. If we start a new batch every 3/4 hour, alternating between bread-making lines, each of these batches will be able to proceed directly to packaging, resulting in a manufacturing lead time of 1 and 3/4 hours. We could start a new batch on both bread-making lines at the same time, every 1 and 1/2 hours (any more rapidly would mean that we would be producing more bread than we could package). While one batch would move immediately to packaging, for a manufacturing lead time of 1 and 3/4 hours, the other would have to wait the 3/4 hour for the first batch and would then take 3/4 hour to be packaged, for a total manufacturing lead time of 2 and 1/2 hours. Thus, the average manufacturing lead time would be 2 and 1/8 hours. **As seen by this example, manufacturing lead time is a function of the way in which a process is managed.**

Now, let's assume that our bakery operation consists of three steps, as in **Figure 7.**

Figure 7



The manufacturing lead time for this process would be 2 and 3/4 hours, assuming that the batches of bread do not wait at all between steps. As in the last example, management decisions regarding scheduling could affect the lead time. If, for example, each step began operation at the same time, every hour on the hour, then packaged bread would wait for 1/4 hour before pricing and palletizing and the manufacturing lead time would be 3 hours. In this situation there would probably be no reason to follow this policy, but for many assembly lines the units are transferred by conveyor from one step to the next, and movement of the conveyor is paced by the slowest step in the process.

So far, we have not considered the direct impact of work-in-process on manufacturing lead time. In the bakery described by **Figure 7**, bread may not flow immediately from one step to the next. If, occasionally, a batch of bread does not bake properly, management may choose to keep an inventory buffer of one batch between steps to minimize disruptions. If there is a bad batch of bread, then, the packaging line would *not* have to shut down and, an hour later, be restarted. It would simply use up the batch in the buffer. Suppose we manage the process so that every step begins operation every hour on the hour. Then, a policy of keeping one batch of work-in-process as a buffer between steps would add 2 hours to the usual manufacturing lead time. To see this, imagine following a small amount of flour through the entire process. After being made into bread, it now waits 1 hour for the batch ahead of it before moving into packaging. After packaging, it then waits 1 hour until the batch ahead of it is completely priced and palletized.

Another reason why there may be work-in-process between steps is because it may take some time to move the bread between steps, either manually or on a conveyor. This time would also add to the manufacturing lead time.

Manufacturing lead time (MLT) (also called *throughput time (TPT))*: Manufacturing lead time refers to the length of time spent in the process. For a single task the cycle time and manufacturing lead time may be equal if only one station is performing the task. When a process involves multiple tasks or steps, the concepts of cycle and manufacturing lead time are quite different. Cycle time refers to how often a unit "drops off" the end of the process whereas manufacturing lead time refers to how long that unit takes between entering and leaving the process, including any in-process storage or transport time.

If units must wait between steps, the manufacturing lead time for a process may be far greater than the sum of the processing times of its individual tasks. Units may wait as work-in-process inventory between tasks, either while other batches are being processed, or while other units in their own batch are processed. Idle time may also add to the manufacturing lead time. This often occurs when a line is imbalanced but is paced by a conveyor at the speed of the slowest task, resulting in idle time between most steps of the process.

Lot Size (also called Batch Size): Most processes produce more than one product type. Suppose a process produced three products: P1, P2, and P3. The process could produce one unit of P1, then one unit of P2, then one unit of P3, then one unit of P1 and so on until we had 100 units each of P1, P2, and P3. Alternatively the process could produce 100 units of P1 before beginning production on 100 units of P2. In the first case, the lot size is equal to one unit; in the second case, the lot size is 100 units. If time must be expended setting up the equipment to make the transition from producing P1 to producing P2, then these two different lot sizes will result in quite different throughput and cycle times. The lot size, then, is number of units of a particular product type that will be produced before beginning production of another product type. Different product types in the same plant may have different lot sizes.

The size of a lot, or batch, may be constrained by physical limitations such as, in our bakery example, the size of the mixers or ovens. It may be determined by the size of an order (e.g., a customer orders 300 units of a special part). Or, the lot size may be strictly a management decision. A company making three colors of telephones, for instance, may choose to mold 1,000 plastic casings of each color before changing over to another color.

Setup Time/Run Time: Setup time refers to the time spent arranging tools, changing dies, setting machine speeds, cleaning equipment, etc., in preparation for the beginning of work on a specific type of product. Depending on the type of process, it might be necessary to spend from a few minutes to a few hours setting up to make the process ready for the transition from producing one product type to producing another product type. Setup time does not necessarily mean idle time for the task or process, however. It may be possible for a worker to do much of the setup for the production of a second product type "off-line" during the production of the first product type. This minimizes the amount of machine capacity lost due to setups. For our purposes, *setup time* refers to any time that is necessary for production but *is independent of the number of units to be produced*. In this respect, for production of a given lot, the setup time is fixed and the run time is proportional to the lot size. This is a useful distinction. Long setup times, for example, may make it attractive to produce in large lot sizes because the fixed cost of the set up can be spread over a larger production volume.

Run time per unit is the amount of time actually spent manufacturing the item (or performing the service) independent of the time required to set up the equipment. If units in a lot are processed sequentially, the run time per lot is the run time per unit multiplied by the number of units in a lot (i.e., the time the units in the particular lot are actually "running" on the equipment). This simple calculation is more complicated, however, if the equipment produces in batches, like an oven or kiln, or if there are multiple equipment stations involved.

Returning to the concept of manufacturing lead time (throughput time), if we were to follow a unit from when it first enters a process until it leaves, some of this time it would be worked on (run time), it may spend some of the time waiting for a machine to be set-up (setup time), and some of the time the unit would be waiting due to imbalance in the processing steps, due to machine downtime, or due to time spent as WIP inventory waiting for other products to be completed.

In addition to measures of cycle time, capacity, and manufacturing lead time, to evaluate a process you may also want to know the direct labor content and the direct labor utilization.

Direct Labor Content: Different organizations and disciplines use the term "direct labor content" in different ways. For our purposes, "direct labor content" refers to the actual amount of work "contained" in the product. Returning to the process in **Figure 5**, let's say that for a batch of 100 loaves, while the packaging equipment has a cycle time of 3/4 hour, the packaging operator spends only 40 minutes in activities such as loading the loaves onto the machines, setting up the right bags on each machine, and making any necessary machine adjustments. The direct labor content in packaging would be 40 minutes/100 loaves or 0.4 minutes/loaf. For the total direct labor content of the bread, the direct labor content of bread-making would need to be included. Indirect labor hours (maintenance, materials handling, management, etc.) are not included in the calculation of direct labor content. Setup time may or may not be included in direct labor content. Exactly what goes into direct labor content varies by firm, but, generally, setups performed by dedicated setup workers are not included because those workers are usually classified as indirect labor, and setups done by operators on their own machines are included, because these workers are classified as direct labor.

Note that direct labor content is not the same as direct labor cost. "Content" refers to the work done in actually manufacturing the product or performing the service (or setting up to do so), not to the wages paid. Labor cost differs from labor content due to imbalance, vacation pay, paid breaks, etc. Recall that the process cycle time in **Figure 5** is 1 hour/100 loaves. Even if the packaging operator is busy for only 40 minutes of every hour, the operator is paid for an entire hour. Thus, *idle time* adds to labor cost but does not affect labor content.

Direct Labor Utilization: Rather than measure idle time or direct labor content in minutes, it is often more useful to talk in percentage terms. Direct labor utilization is a measure of the percentage of time that workers are actually working on a product or performing a service, i.e.,:

$$\text{Direct Labor Utilization} = \frac{\text{Direct labor content}}{\text{Total available labor time}}$$

Total available labor time consists of both direct labor content and any idle time. In the example above, direct labor utilization in packaging is 67% ([40 minutes/60 minutes] X 100). Part of the reason that the utilization is not 100% is due to the imbalance between packaging and bread-making (this accounts for 15 minutes of idle time per hour), while part (5 minutes of idle time per hour) is due to the work design (driven by the level of mechanization) in the packaging operation. If there are as many packaging operators as bread-making operators, and if the bread-making operators are 100% utilized, the overall direct labor utilization would be the average of the two numbers, or 83%.

All of this discussion has assumed that yields are 100%, i.e., that every unit that starts through the process goes all the way through every step of the process without mishap. The presence of rejects and/or rework complicates the analysis, of course. The impact of defects resulting in yields of less than 100% will be explored in subsequent modules.

When calculating process performance measures, carefully consider the details of the process and the managerial question you are seeking to answer. A good conceptual understanding of the terms in this overview will guide you in applying them to new environments and new types of decisions.

So far we have described some of the physical attributes of operating systems and how to measure their performance. We now turn to the decisions made in the management of operating systems.

Management Decisions

There are three general categories of decisions that must be made to manage an operation. First, is the *design* of the operation, and of the distinct processes that constitute the operation. Second, is the ongoing set of decisions—the *operating decisions*—that determine what is made at any point in time. Finally, there are *process improvement* decisions, which may be made, for example, to increase the output, lower cost, or improve the range of products that can be produced. You will be exposed to an extensive range of management decisions through the cases in this course, going far beyond the list below.

Design Choices. To start a new operation, the type of process must be selected. Although a high-volume continuous line might be chosen for a large bakery that makes only breads, a smaller, more flexible set of mixers and ovens might be chosen for a bakery making a wide variety of small batches of specialty breads, pies, cookies, cakes, rolls, and croissants. After selecting a general process type, the actual technology must also be chosen. The choice of process is likely to limit somewhat the choice of technology. When purchasing a high-volume continuous line, a firm is likely to have the option of selecting a much higher degree of automation than if purchasing individual machines designed for lower volumes and a wider variety of products. Other design choices include specifying the capacity of the operation, with an eye to future sales forecasts and the cost of adding capacity later to meet those forecasts. The way that the equipment is situated in the space available—the process layout—must also be determined, in conjunction with the pattern of material and information flows.

The choices made in designing a particular process determine in large part the inputs needed to provide the process outputs. It also determines in large part the range of outputs possible. As a simple example, consider two alternatives for providing copies of some information, one using a printing press and the other using a copier. The press involves several tasks to produce the information such as typesetting, proofreading, and press operation. The copier, on the other hand, requires only an operator and an original document containing the information and requires no setup activity. The cost of providing copies is different for each type of process. The printing press has a much higher setup cost but each additional copy is very cheap. Thus, for large numbers of copies the press has an economic advantage.

Ongoing Operating Decisions. Once an operation is up and running, the main management tasks are often order selection, scheduling, setting batch size, and inventory management. The bakery's manager(s) would need to determine, for example, when to make whole-wheat bread and when to make raisin bread over the coming week, how much of each to make, whether to take an order from a new grocery store, and how much inventory to hold as raw materials, work-in-process, and finished goods. Although these decisions for a bakery may seem relatively straightforward, the complexity increases with the number of different products, the lack of excess capacity available, the number of different customers and their requirements, and the cost of holding inventory.

Process Improvement Decisions. Managers can decide to physically alter the process by changing technology or adding machines or workers. They can redesign the physical or information flows, or change the design of individual tasks, or improve the methods by which the process is managed. These decisions are much like design decisions, but the existing system puts additional costs and constraints on the changes that can be made. The objective of process improvements may be to improve the cost, quality, or timeliness of the output. It may also be to make the process more flexible, allowing entirely new outputs to be made.

Management Complexity

Variability and uncertainty in the inputs, in the transformation process itself, in the outputs, or in demand increase the complexity of managing an operation. This can be illustrated using our bakery example. The simplest bakery produces one type of bread on a single line. No routing or product mix decisions need to be made, and very little information needs to be managed. The primary management tasks involve fixing any problems that arise, scheduling overtime if necessary, and looking for ways to improve the efficiency of the process or the quality of the bread.

Once there is variability in the process, it becomes more difficult to manage. One source of variability may be the inputs. If the flour purchased from different vendors is slightly different, methods must be in place to make the necessary adjustments in the quantities used, the mixing and proofing times, or the baking time. This may require more sophisticated control of equipment and additional quality control activities. It also requires an information system in place to inform operators (and the machines, directly, if the system is automated) of the composition of the flour being used and how to adjust for it. The bakery may also want to track the use of the different flour in such a way that they could determine if the differences in the flours lead to any additional customer complaints. This would place an additional burden on the information system.

Also, the more types of bread that the bakery makes, i.e., the higher the variability in outputs, the more difficult it is to manage. A bakery making 16 different types of bread has to schedule the process so that each type is made in the right amount, and demand is met. In addition, a set-up is involved in switching the machines from making one type of bread to another. The mixers will have to be cleaned and the oven temperature may need to be reset. Moreover, variability in demand also adds to the complexity of managing the bakery. If bread demand is seasonal, even if that demand is perfectly predictable, many more loaves will have to be produced during certain months of the year—and that may entail increasing the number of workers for that period or scheduling overtime.

In our discussion so far, the factors adding to management complexity have all been sources of *variability*, that is, changes that are known and anticipated. But *uncertainty* in inputs, in the process itself, in outputs or in demand also leads to management complexity. Thus, in the bakery, it may happen that, owing to incomplete mixing or to fluctuations in the temperature in different parts of the oven, for example, not all the bread that comes out of the oven is good. Uncertainty in the subsequent yield of the process—not knowing exactly how many good loaves you will get from a given amount of dough—makes the scheduling task much more difficult. It also will probably require additional labor to sort out the bad bread, and may require that yield information be kept so that scheduling can be adjusted as necessary to ensure that demand is met. Uncertainty in demand also adds to management complexity. Inventory is often used to make it easier to fill demand when uncertainty exists in yield and/or demand. But inventory may be costly to hold, and can also increase management complexity because it, too, must be managed.

As you analyze new case situations, consider what it is that makes the management task complex in the different environments presented. Look for ways to eliminate the sources of complexity or to simplify the task of managing it.

Summary

In the bakery example presented here, we have not tried to address a management problem. In any real case it is clear that the nature of the problem should guide your analysis. Instead, we have tried to show the first two of several steps that might be useful in an analysis designed to address a management issue. These steps are summarized below.

1. Define the process—determine the tasks and the flows of information and goods. Also, determine where inventory is kept in the process. This effort can be recorded in a process flow diagram.

2. Determine the capacity or range of capacities for the process. This will require an analysis of each task and a comparison of how these tasks are balanced. In addition, determine the effect of inventory in the system on the capacity of tasks and flows. Inventories may allow the process to operate out of balance for some time, but in the long run the capacity of the process is limited by the capacity of its slowest task.

In many instances you will also need to determine the cost of inputs and relate these costs to the value of the output in some market by comparing the cost, quality, and timeliness of this output to the needs of the market.

We've seen that we cannot fully describe a process simply by the physical tasks, but that we need to consider management decisions ranging from how information is used to how work is scheduled in the process.

Glossary of TOM Terms

Manufacturing Lead Time (MLT): The amount of time each unit spends in the manufacturing process (sometimes called **Throughput Time**). This includes time spent actively being worked upon at each step of the process as well as any time spent waiting between steps. The concept of a lead time applies to the total time spent in any process in which the start and finish are well-defined events. We can talk about lead times, for example, in service operations, or in the entire order-to-delivery process.

Cycle Time (CT): Average time between completion of successive units. It is directly related to the output rate. A process with an output rate of 4 units per hour has a cycle time of 15 minutes.

Work-in-Process (WIP): Number of units in the process at any point in time. If the process includes buffer inventories between steps, then the work-in-process is the total number of units being worked upon as well as waiting in inventory between steps. The units in inventory are usually referred to as Work-in-process *inventory*, to distinguish them from raw materials inventory or finished goods inventory.

Bottleneck: The production resource that limits the capacity of the overall process. This is usually the production equipment at the step with the lowest overall capacity, i.e., the longest cycle time. In some situations, the bottleneck resource may be labor available at a particular step or steps.

Capacity: The maximum rate of output of a process, measured in units of output per unit of time. The unit of time may be of any length: a year, a day, a shift, or a minute.

Utilization: Ratio of the input actually used over the amount of the input available. Labor utilization is the ratio of the actual labor time spent processing to the total amount of labor time available. Differences between the two can be due to inefficiencies in the process that lead to lost working time, as well as to imbalances in the cycle times at each step of the process that lead to idle time of workers at some steps while those at others are working. Capacity utilization is the ratio of the capacity actually used (i.e., the **output** of the process) to the total capacity available.

Process Flow Diagram: Diagram depicting the activities in a process and the flows between them. While most process flow diagrams focus on the physical processing of goods, information processing may also be depicted.

Lot Size (also called **Batch Size**)**:** Number of units of a particular product type that is produced before beginning production of another product type.

Note: In all of the above definitions, a "process" may refer to the complete production process, such as the making of bread from start to finish, or to a segment of the complete process, such as the packaging process.

Source: Adapted from Professor W. Bruce Chew, "A Glossary of TOM Terms," HBS No. 687-019.