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Process Fundamentals

Imagine that, upon graduation, you take a job managing a business whose operating processes need improvement. Perhaps you need to help management understand how to increase the value that operations provides to customers and to improve the profitability of an operation. Or imagine that upon graduation, you take a job in marketing and you need to understand how the decisions made to improve operations will affect your new marketing programs, or how your new marketing programs will affect the ability of operations to do what they need to do. Perhaps you are an executive in a start-up and you are concerned with both sets of issues.

Operations management is about designing, managing, and improving the set of activities that create products and services and deliver them to customers. We call the activities, the people, the technology, the knowledge, and the procedures that dictate how work is organized the ***operating system***. (In this context, when we talk about operating systems, we're usually not talking about Windows, MacOS, or Android.)

The basic building block of operating systems is the ***process***. Most operating systems consist of multiple processes. A process takes inputs (e.g., raw materials, energy) and uses resources (e.g., labor, capital equipment, knowledge) to create outputs that are of greater value to customers (and, thereby, of greater value to the organization).

This note is an introduction to ***process analysis***, a set of concepts and tools that will enable you to describe, measure, diagnose, and improve operating processes.

As a simple example, suppose your mission is to improve a large bakery that supplies supermarket chains with products ranging from breads to pies.

How will you start? First, you have to develop a good understanding of the current operation: the activities that transform flour, water, yeast, and other ingredients into baked goods, and the efforts 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, as well as the business's competitive priorities, that is, the reasons that customers buy from you rather than your competitors. Does the bakery offer lower prices, faster delivery, higher quality, or a better product line that allows its customers to buy all their bakery needs from one source? Only after understanding the physical process

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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 note is to introduce you to tools that can help you understand operations, not just for a bakery, of course, but for any type of organization. These tools are important for improving operations, and for the daily management of an operation and the design of a new operation.

This note 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 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, this note describes ways to measure the performance of a process as well as basic process analysis, methods used to determine process performance, such as calculating what and how much a process is capable of producing, and how quickly. 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 can make managing operations particularly difficult.

Elements of a Process

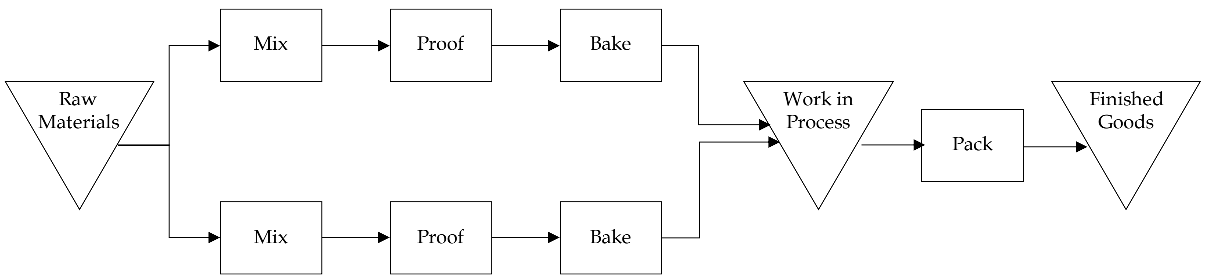
The process is the basic building block of an operating system. Consider some examples of processes. An automobile assembly plant takes raw materials in the form of parts, components, and subassemblies, and transforms them using labor and capital into automobiles. The transformation happens through an assembly process, and the output is an automobile. A restaurant takes inputs in the form of unprocessed or semi-processed agricultural or farmed products, and transforms these inputs into meals using labor (e.g., cooks and servers) and capital equipment (e.g., refrigerators and stoves).

Both of the processes mentioned above have physical products as an output, but some operating systems are services that convert unserved into served customers. Consider an airline: the inputs to the process are fuel, food, and customers who want to travel from an origin to a destination. To transform the customers into served customers who have been transported from their origin to their desired destination, the airline uses resources such as fuel, capital equipment (e.g., airplanes, ground equipment), and labor (e.g., flight crews, ground crews, and maintenance crews). Processes with a service output also include those found in hospitals, insurance companies, and consulting firms. In a hospital, capital, labor, and energy are applied to another input (patients) in order to transform them into healthier or more comfortable people.

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*, such as the one in **Figure 1**, which depicts our bakery example with 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.

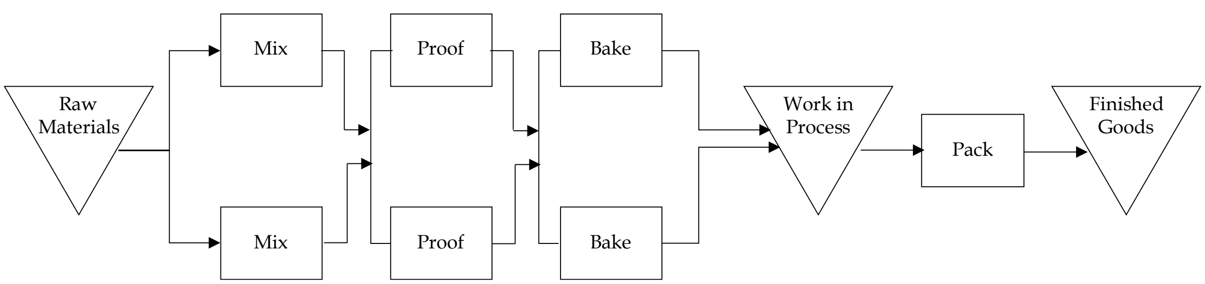
Tasks (activities) are shown as small rectangles, flows as arrows, and the storage of goods as inverted triangles. We see two identical *parallel lines* for mixing, proofing, and baking. Within each line, the tasks of mixing, proofing, and baking are defined as being in a *serial* relationship, because—for a given product or batch, or customer in a service context—one task cannot start until the previous one is complete. The *capacity* (maximum output rate) of the two parallel lines can be determined by adding the capacity of each line. *Work-in-process inventory (WIP)* is shown before packaging (*Pack* in the figure) 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 might 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 (FGI)*, and from there is transported to grocery store customers.

Figure 1 Bakery's Process Flow Diagram 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.

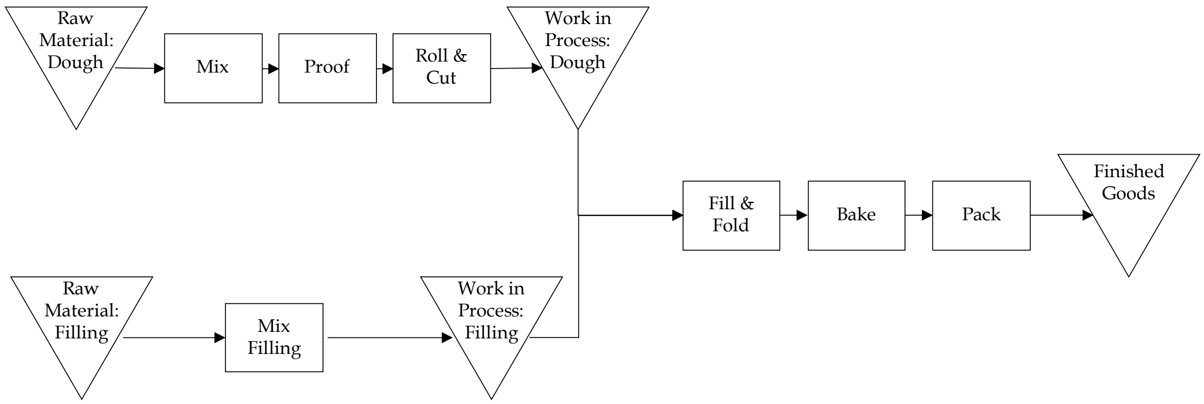
Figure 2 Bakery's Process Flow Diagram with Two Mixers, Proofers, and Ovens



We may also want to show, on a process flow diagram, tasks that are performed in parallel but that 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 tasks. 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 proofing, the longest task, that defines how much bread can be made per hour.

Note that the nature of the parallel processes for making croissants is different from that of the two bread lines working in parallel, as shown in **Figure 1**. To determine the capacity of the bread-making operation up until the the time the dough is baked, we *add* the capacity of each of the parallel bread lines. To determine the capacity of croissant-making, however, we need to consider 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 below, when we do a formal capacity analysis and diagnose where *bottlenecks* will occur.

Figure 3 Process Flow Diagram for Croissant-Making



Some processes require operators to decide whether to route a given unit or a batch to one of several alternative tasks or subprocesses (e.g., a manual drill versus versus an automated drill); such processes are often drawn as what *appears* to be a parallel process akin to the ones shown in **Figures 1** and **2** but it is preceded by a diamond showing that a unit or batch will flow through just one of these subprocesses. Depending on the process, another unit or batch can simultaneously be routed to the other alternative(s).

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

Process Boundaries

Process boundaries determine what is—and thus what is not—included as part of a system. The objective of the analysis drives decisions about what to include within the process boundaries. In the croissant-making example above (**Figure 3**), for instance, if we want to analyze how the preparation of the raw materials affects our production line, we should include the preparation of the dough and fillings within our process boundaries. Alternatively, if the bake and pack tasks are handled by a separate team and are not within our control, we may decide to omit those tasks from the process boundaries.

Managerial judgment is required to consider how our analysis might be affected by what is excluded from the process boundaries. In the examples above, we omitted customer orders from our production system, but it is often important to assess process performance in the context of how well it meets market demand and customer expectations.

In summary, the specifics of the operational problem must be considered in deciding how to draw the process boundaries, but at the same time, one must also account for the potential impacts of what is not included within the process boundaries.

Inputs

A process transforms inputs into outputs. Inputs are items that *flow* into a process from the environment to be transformed into outputs. They include raw materials, components, energy, customers, parts, data, and so on. To analyze a process, we must measure inputs, such as materials and energy, and determine the amount of each needed to make some amount of output. Usually we use physical units to measure the inputs—for example, kilograms of flour and joules for energy. It is sometimes 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 materials and energy. Measuring the cost of inputs becomes more difficult and requires additional care as the time horizon lengthens.

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 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. In others, 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 the output for later distribution.

Although it is a simple matter to count the number of loaves of bread produced daily by the bakery, or to count the number of patients served by a hospital each year, it may not be simple to place a value on a given 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 a pricing mechanism. Thus, 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. "What are the market conditions?" and "What is the competition doing?" are thus important questions to address when analyzing a process.

For a new product, or one that has some improved characteristics, 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. It is often the case that 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, Resources, Flows, and Storage

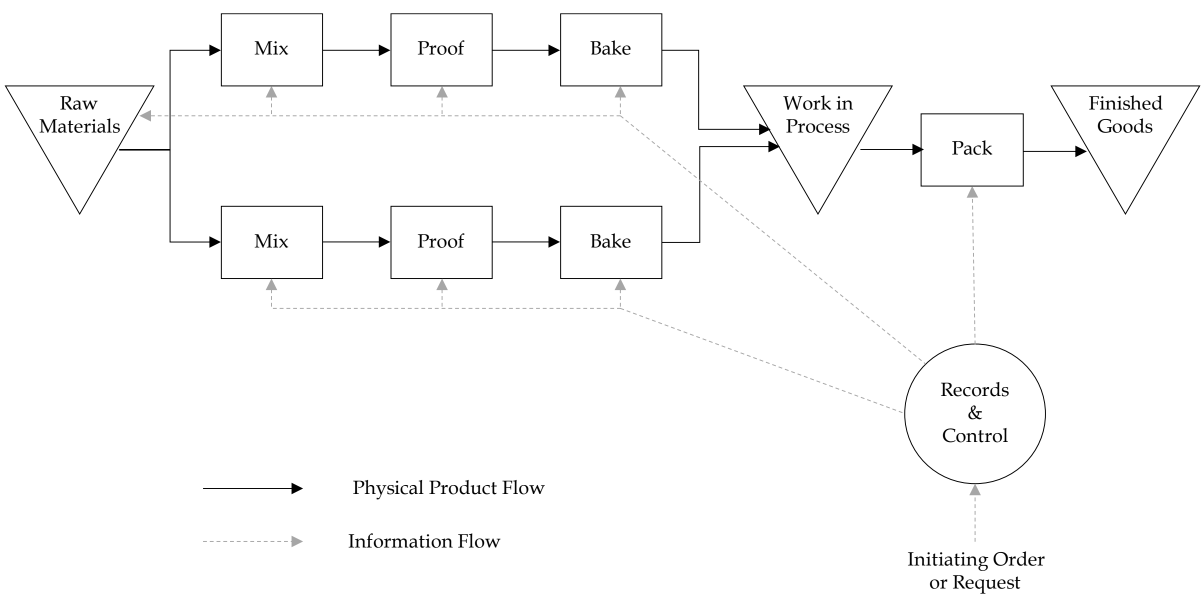
So far, we have discussed what goes into and what comes out of a process. We must also understand what goes on within a process. The specifics of every process are different, but there are four general categories for all activities within a process: tasks, resources, flows, and storage.

Tasks typically are value-adding activities performed by resources like labor and capital to convert the inputs into something more nearly like the desired output. Some examples of tasks are (1) operating a drill press to put holes in 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.

Resources are often categorized into labor (e.g., worker time) and capital (e.g., the cost of fixed assets, machines, buildings). Performing a task may require multiple resources (e.g., a machine and a worker operating the machine), and resources are sometimes shared across different tasks (e.g., one worker operating two machines used in different tasks). The ability of resources to be shared across several tasks depends on their degree of specialization. For example, compared to more flexible workforces, specialized workforces can often perform certain tasks particularly well (e.g., in terms of quality or productivity) but are less able to be allocated across multiple tasks. How many resources we have on hand often determines which process configurations are feasible. In the configuration in **Figure 1**, running the two sets of parallel tasks simultaneously is feasible only if there is a sufficient number of workers. Because each task in the process flow diagram might not have a dedicated resource assigned to it, resource sharing must be taken into account when calculating capacity, as discussed in detail below.

Flows can be categorized into the flow of goods and the flow of information. **Figure 4** depicts a process flow diagram with the flow of physical goods indicated by solid lines and the flow of information by dashed lines.

Figure 4 Information and Physical Process Flow Diagram for the Bakery Process



The bakery's information flows depicted in **Figure 4** are quite simple; they take the form of recipes and production orders. The list of ingredients and quantities for each type of bread that will be made next must go to 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, proofing times must go to the operators responsible for that step, and baking temperatures and times must go to operators of the ovens. We will also have to inform packaging workers of what types and quantities of breads will be arriving at the packaging area so that they can set up their equipment with the correct bags.

In some types of operations, the information flows are combined 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 their 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 fourth activity commonly found within a process. 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 WIP inside the mixers, proofers, and ovens, at the packaging machines, and between each step, as well as 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 area of WIP storage, whereas **Figure 3** shows two. In many processes that are considered continuous, there are at least a few units of WIP on a rack or chute waiting to be fed into a machine. Although these units are technically in storage and could be depicted on the process flow diagram as inverted triangles between processing steps, they are often left off the diagram when they represent a neglible amount of processing time. Similarly, the transport of goods from step to step within the process could be shown as another set of tasks, but unless the necessary times are long, we will generally omit these in process flow diagrams for simplicity.

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 external environment to start the process. In this case, there are two kinds of information: records and controls. The term *records* typically refers to general instructions, such as blueprints and instructions describing how a product should be made (i.e., the "recipe"). These records are product-specific. Records may also be machine-specific, tracking repair and preventive maintenance histories, for example. The term *controls* 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 outlined in the records.

Measuring the Performance of a Process

So far we have defined *process* in general terms and given names to various components of a process, namely, the *inputs*, the *outputs*, and the *tasks*, *resources*, *flows*, and *storage* within the process. We have also noted that a 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 possible *output rate* from a process and is measured in units of output per unit of time, such as tons per day, parts per minute, or customers per hour. A steel mill, for instance, can produce some number of tons of steel per year; an insurance office can process some number of claims per hour. Capacity is easy to define but sometimes difficult 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, which refers to the maximum output rate during a given period of time considering a set of constraints under which the process typically operates (such as raw material delivery schedules, worker breaks, quality yields). Measuring this requires knowing a great deal about the process and carefully analyzing the particular situation at hand.

The *theoretical capacity* of a process provides an upper bound, and might ignore factors such as start-up and shut-down activities (between batches, shifts, and days) to clean or maintain equipment, which requires staff time and temporarily removes equipment from productive use. Whether the theoretical capacity is achievable in practice depends on whether one can design a feasible process that yields that output rate. Factoring in start-up and shut-down issues as well as a host of other issues such as the need for workers to take breaks, which might require making explicit assumptions, is necessary to calculate the *effective capacity* of a process. Moreover, managers might choose to operate a process at an output rate that is less than its theoretical capacity because of lack of demand (a demand constraint) or a slower arrival rate of the supply of inputs (a supply constraint). When referring to capacity subsequently in this document, we mean theoretical capacity.

Managers often believe that the capacity of a process is an absolute fixed quantity. This is rarely the case. 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 theoretical capacity, but its effective capacity might be different due to a variety of internal and external factors, as well as management decisions. The nature and availability of the raw materials being utilized, the mix of products being produced and their order sizes, maintenance time, staffing decisions (e.g., the quantity, nature, and scheduling of labor), and the number of shifts in operation will all impact the effective capacity. The yield of the process is also important. In most instances, the rate of *good* units produced (i.e., those that meet quality specifications) is the relevant capacity measure.

Both effective capacity and capacity utilization (described below) depend on the way the process is managed.

Efficiency

Efficiency is a common metric used to assess the performance of physical processes. Efficiency indicates the amount (or value) of inputs a process requires to generate a particular amount (or value) of output. Efficiency is typically measured as the ratio of output to input, and is often expressed as a dimensionless percentage because both outputs and inputs are usually measured in the same units. For example, the efficiency of an engine is typically expressed as a ratio of output energy to input energy, where an engine with a 75% efficiency can transform 75% of the input energy into usable output energy.

Productivity is a related concept that measures the amount of output produced per unit of input. For productivity measures, the output and input can be measured in different units. For example, a labor productivity metric might measure output in terms of quantity or value produced but measure input in terms of hours of labor.

Profitability is an efficiency metric that measures the amount of economic value generated from a set of resources. Among the many ways to measure profitability, *gross profit margin* is expressed as a percentage and is calculated by subtracting all direct expenses incurred in production (raw materials, labor, etc.) from sales revenues, dividing the result by sales revenues, and then multiplying by 100.

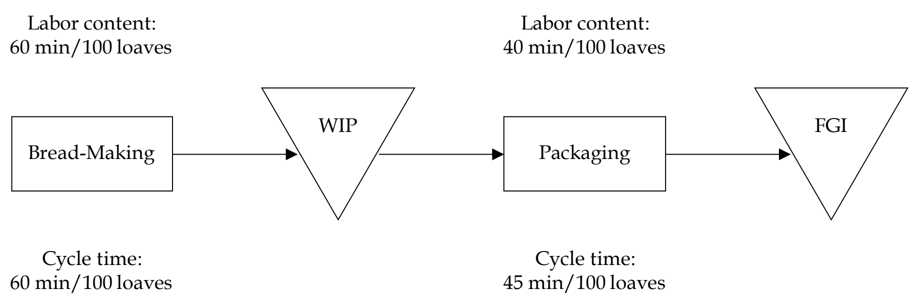
Utilization is another common efficiency measure. Utilization is the ratio of (a) the input or resource the process actually used to create the output to (b) the amount of that input or resource available for use.

Direct labor utilization is often a key efficiency metric in labor-intensive processes, and measures the percentage of time that workers are actually working on a product or performing a service:

$$Direct\ labor\ utilization = \frac{Direct\ labor\ content}{Available\ direct\ labor\ time}$$

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. Consider a simplified bakery process, illustrated in **Figure 5**. Suppose that for a batch of 100 loaves, the packaging equipment has a cycle time of 45 minutes, but the packaging operator spends only 40 minutes to conduct all of their activities such as loading the loaves onto the machines, setting up the right bags on each machine, and making any necessary machine adjustments. As such, the direct labor content in the packaging task would be 40 minutes/100 loaves (or 0.4 minutes/loaf). Suppose the packaging worker is then idle for 20 minutes because the bread-making task (staffed by a different worker) takes 60 minutes, in which case the packaging worker's direct labor utilization is calculated as (40 minutes of direct labor content/60 minutes of available direct labor time) = 67%.

Figure 5 A Simple Bakery Process



To calculate the total direct labor content of a loaf of bread, the direct labor content of bread-making would also need to be included. To calculate this on the basis of producing 100 loaves, you would add the 60 minutes of direct labor content from the Bread-Maker to the 40 minutes of direct labor content from the Packaging worker, for a total of 100 minutes. To calculate the direct labor utilization of both workers, you can divide this by the total available labor time for those workers to produce 100 loaves – that is, the total amount of time you pay them (60 minutes + 60 minutes = 120 minutes), which yields 100 minutes/120 minutes = 83%.

Indirect labor hours (which might include equipment maintenance, management, etc.) are not included in the calculation of direct labor content or direct labor utilization. Firms vary in whether they consider setup time to be direct labor content, but in general setups done by operators on their own machines is classified as direct labor whereas setups performed by dedicated setup workers is classified as indirect labor.[1]

Direct labor content differs from ***direct labor cost***. Direct labor content refers to the work done in actually manufacturing the product or performing the service (and set up work those workers do) and is typically measured in time, and does not refer to the wages paid. Labor cost differs from labor content due to imbalance in the cycle time between different tasks, vacation pay, paid breaks, and so on. Labor *cost* is incurred for both labor *content* and *idle time.*

Machine utilization measures the percentage of time a machine is used and is a measure of capital efficiency. In this context, the time a machine is being used typically includes when a machine is being set up (setup time) and when the machine is actively producing output (run time); it does not include any time when the machine is blocked by being unable to pass its output to the next step, or any time the machine is starved while waiting for input from the previous step. 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 performance. In an automated bakery, machine utilization may be more relevant.

Capacity utilization is a measure of how much output was actually achieved in a given amount of time relative to capacity (how much output could have been achieved during the same amount of time in an ideal situation). If the capacity of a process is 500 units per day and on a given day 480 units are produced, then on that day capacity utilization was 96% (480 units/500 units = 0.96).

Flexibility

Flexibility is another characteristic that should often be considered when analyzing a process. The flexibility of a process refers to its ability to produce a range of product models in quantities desired by customers. Product variety can be produced by processes designed either (a) with flexible resources that can produce a combination of outputs simultaneously or (b) to be changed over to quickly transition from producing one product model to another by using different tasks, resources, and/or inputs. Flexibility is the least precise and hardest to define of the characteristics we have considered thus far, and often must be described in qualitative terms. 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.[2]

Quality

Like flexibility, ***quality*** may be described in different ways. ***Product quality*** can be evaluated using external or internal measures. External quality measures generally assess how well the product design satisfies the wants and needs of customers, especially compared to competing products available in the marketplace. Product performance, features, reliability, durability, serviceability, and design aesthetics

[1] When labor is used to operate machines, direct labor content can be categorized as external time and internal time. *External time* is the time labor is spent to process a unit while the machine is not operating on that unit, such as when labor is used to change the setting on a machine before inserting the unit. *Internal time* refers to the time labor is spent working on a task while the machine is operating, such as to manually guide a unit through the machine.

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

may all be components of product quality. Internal measures of product quality generally compare whether individual units meet product design specifications or performance standards.

In addition to designing, measuring, and controlling product quality, a manufacturer also designs, measures, and controls process quality. *Process quality* refers to the ability of the process to consistently produce products or services within their design specifications. In order to produce them within these specifications, the process must be operating within certain tolerances. Process measures, such as the temperature inside 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 finishing a piece of metal to a certain smoothness, if doing so requires operating outside this range, as 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 the wrong settings or 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.[3]

Process yield is the percentage of total output a process produces over a designated period of time that complies with design specifications. Within a production plant, the impact of poor quality can be increased scrap, rework, yield losses, all of which can result in downtime, additional testing, lost management and worker time, and reduced output rates. If poor quality products leave 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 may want to determine the capacity of your operation. To do this, let's further simplify the bakery example, as illustrated in **Figure 5**. Here, there are two tasks 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 a box representing the entire bread-making line.

The capacity of a process is its maximum output rate, which is determined by the resources available and how they are allocated to the process's various tasks. When calculating capacity, we typically assume we have sufficient inputs so that they are not the bottleneck. In the bakery example, suppose that we have dedicated sets of resources (e.g., workers, oven, packaging equipment) to perform each of the bread-making and packaging tasks, and that we always have sufficient inputs. Based on the size of the mixers in the bakery, suppose that bread is produced in batches of 100 loaves each. The resources assigned to the bread-making task complete a batch of 100 loaves every hour. The *cycle time* is the length of time that passes between successive batches or units produced. Thus, in our example, the cycle time of the bread-making task is 1 hour per batch of 100 loaves, and the cycle time of the packaging task is ¾ of an hour per batch of 100 loaves. Because both tasks need to finish before a batch of output is completed, the entire process of bread-making and packaging can produce output at the rate of only the slowest task, that is, the task with the longest cycle time. (If there were a shared resource like a worker who had to operate both tasks, then we would need to consider the cycle time of that resource

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

too, in order to determine the cycle time of the entire process.) The slowest task or resource in a process (that is, the one with the longest cycle time) is called the *process bottleneck*, or simply the *bottleneck*. The cycle time of an entire process is the cycle time of its bottleneck, which in this example is the bread-making's 1 hour per batch of 100 loaves.

The output rate of a process is simply the inverse of its cycle time. Because this two-step process requires 1 hour to produce a batch of 100 loaves, its output rate is one batch of 100 loaves per hour. To achieve this, each hour, the packaging operation works on the previous batch for ¾ of an hour and sits idle for the remaining ¼ of an hour. Because the cycle times of the two tasks are not balanced, the faster task incurs ¼ of an hour *of idle time* during each hour of operation. To determine the daily output rate, we would need to know the number of hours the bakery operates per day. With any of these metrics, it is important to be explicit about the units (e.g., loaves per hour, minutes per loaf), particularly when performing calculations. Also, we typically ignore start-up and shut-down anomalies and instead focus on stable (or *steady-state*) conditions.

The approach used to calculate output rate in the example above can be generalized as follows: For each task and resource in the process, we determine its cycle time, the amount of time it takes to produce successive units of output, measured in isolation of other tasks. An entire process can be paced only as fast as the slowest task or resource (the one with the longest cycle time), which is the bottleneck. Paced this way, the cycle time of the entire process is determined by the cycle time of the bottleneck task or resource. The output rate of a process (the number of units produced per unit time) is calculated as the inverse of its cycle time.

Care must be exercised when resources are shared across tasks. If a resource is assigned to multiple tasks, then it can complete a cycle only after completing all of its assigned tasks. Suppose in the example above, there is only a single worker available to operate both the bread-making and packaging equipment, and that these tasks requires labor throughout their operation (that is, the machines cannot work without labor). Suppose also that the worker operates the bread-making task for 1 hour to complete a batch, and then operates the packaging task for ¾ of an hour to complete a batch. The cycle time of this worker is then equal to 1¾ hours per batch. The worker then becomes the bottleneck resource, and the output of the bakery is one batch of 100 loaves of bread per 1¾ hours.

To perform our analysis of the capacity of the bakery, 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, we will to try to adhere to a common vocabulary:

Cycle time (CT): The cycle time is the average time between completion of successive units, and can be defined for an individual task or resource, or for portions of a larger process. In other words, cycle time answers the question "How often does a unit complete a task or the process?" or "How often does a resource complete a unit?" When applied to a resource, cycle time refers to the amount of time the resource must spend processing each unit.

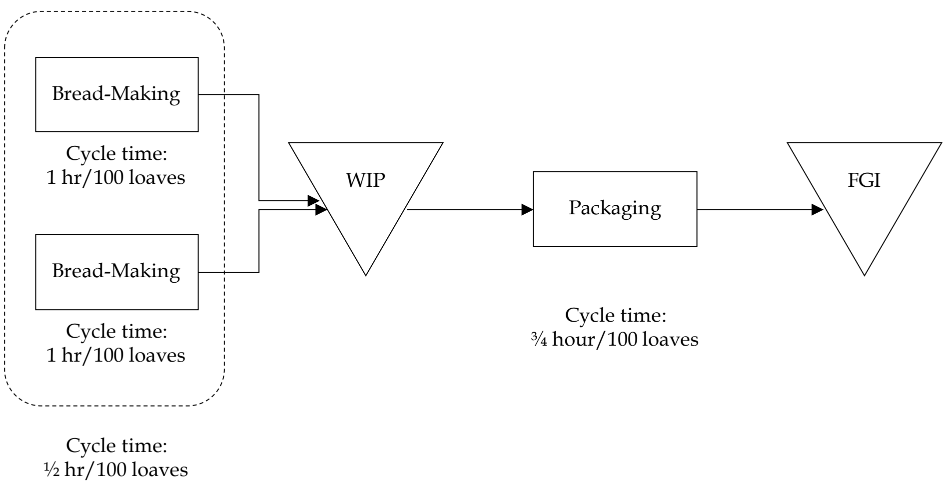
Often a process or portion of a process is not operated at its theoretical capacity. In those instances, you may need to distinguish between the minimum amount of time that *could* elapse between the completion of successive units (the minimum cycle time of the process) and the amount of time required for the process to *actually* complete successive units (the actual cycle time). In the process depicted in **Figure 5**, because bread-making requires 1 hour to finish a batch, the packaging task will receive batches of bread only once per hour. Thus, while packaging requires ¾ of an hour, the task could be operated more slowly. As long as it is operated so that it can package a batch of bread in no more than an hour, there will be no loss of the bakery's capacity.

Bottleneck: The bottleneck of a process is the task or resource that limits production, which is the one with the longest cycle time, such as the bread-making task in **Figure 5**. In some settings, labor, equipment, information, raw materials flow, lack of demand, 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's bottleneck limits how quickly products can move through the process, and thus determines the process *cycle time*. We typically assume that sufficient inputs are available and there is sufficient demand for output, so that we can focus our exploration for bottlenecks to just an operation's tasks and resources. The bottleneck may shift depending on what products are being produced or what labor or equipment is available at any point in time. Because the bottleneck paces a process and limits its capacity, it is an important focal point for management attention.

Idle time: Idle time refers to the time when useful work is not being performed. Both workers and machines can have idle time. 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 20 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 they are *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 ¼ of the time.

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

Figure 6 Cycle Time with Parallel Bread-Making Lines and a Single Packaging Line



Although the cycle time for each bread-making line is 1 hour/100 loaves, the cycle time of the two lines together is ½ hour/100 loaves. One way to see this is as follows: Each bread-making resource must spend 1 hour to produce 100 loaves of bread. Because there are two resources (organized as two parallel lines) "sharing" the task, each resource spends only ½ hour / 100 loaves of bread. Equivalently, bread is produced in batches of 200 loaves every 1 hour, so the average time between successive outputs is ½ hour / 100 loaves. Because the packaging line takes ¾ hour to bag 100 loaves, packaging is the bottleneck of the entire process. If both bread-making and packaging were operated for the same number of hours each day, we would not make bread at the bakery's maximum cycle time rate throughout the day 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 output rate 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.

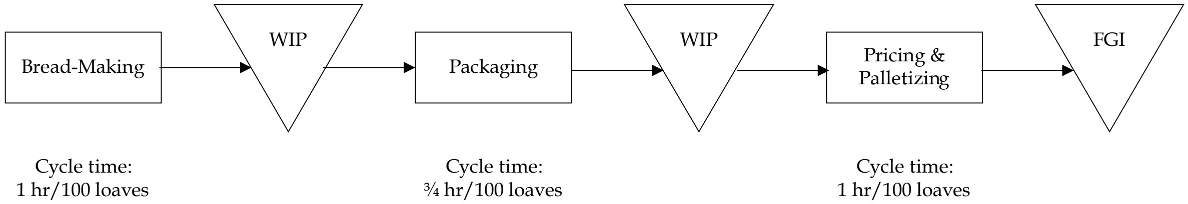
Balance/imbalance: If every step in a process had the same cycle time (and performed consistently at that precise cycle time, with no variability), then the process would be in perfect balance. This is rarely achieved in practice. The processes shown in **Figures 5** and **6** are both imbalanced. If 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.

Takt time: Takt time is the cycle time at which a process would need to be paced in order to meet customer demand. Takt time can be calculated by taking the time available to produce a certain product and dividing by customer demand for that product. For example, if an automobile 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. Thus for the process to fully meet demand, it must be designed so that the process cycle time is no more than 0.96 minutes.

Throughput time (TPT): Throughput time, another common metric used in process analysis, measures how long it takes a unit to be produced (or, in a service operation, how long it takes a customer to be served) from the time the process begins processing the unit (or customer) until the time it is finished. In the bakery example above, you might want to calculate throughput time to make and pack a batch of 100 loaves. To calculate throughput time for the process in **Figure 5**, we can simply add up the task times (1 hour + ¾ hour = 1¾ hours) if we assume: (1) that packaging begins immediately once the 100 loaves are made, and thus the batch spends no time waiting in WIP storage, and (2) that the product is considered finished as soon as it enters the finished goods inventory storage area. The throughput time for the process in **Figure 6**, however, depends on 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 of 100 loaves every ¾ hour, alternating between the two bread-making lines, each of these batches will be able to proceed directly to packaging, resulting in a throughput time of 1¾ hours. Alternatively, we could start a new batch on both bread-making lines at the same moment, every 1½ 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 throughput time of 1¾ hours, the other would have to wait the ¾ hour while the first batch is packaged, and would then take ¾ hour to be packaged, for a total throughput time of 2½ hours. In this arrangement, the average throughput time would be 2.125 hours. **As shown by this example, throughput time can depend on how a process is managed.**

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

Figure 7 Throughput Time Calculation



The throughput time for this process would be 2¾ hours per batch, assuming that batches 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 ¼ hour before pricing and palletizing, and the throughput time would be 3 hours. There would probably be no reason to follow this policy in this situation, but for many assembly lines the units are transferred by conveyor from one step to the next, and the movement of the conveyor must be paced by the slowest step in the process.

So far, we have not considered the direct impact of WIP on throughput time. In the bakery described by **Figure 7**, bread might not flow immediately from one step to the next. If, occasionally, a batch of bread does not bake properly, management might 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 be restarted an hour later. 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. A policy of keeping one batch of WIP as a buffer between steps would add 2 hours to the usual throughput 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 WIP between steps is that it may take some time to move the bread between steps, either manually or on a conveyor. This time would also add to the throughput time.

Cycle time versus throughput time: If only one station is performing a single task, the task's cycle time and throughput time may be equal. When a process involves multiple tasks or steps, the concepts of cycle time and throughput time are quite different. Cycle time refers to how often a unit exits the process, whereas throughput time refers to how long that unit takes between entering and leaving a process including any in-process storage or transport time. The cycle time of the overall process determines the capacity of the process, which limits the volume of product that the process is able to produce, and which in turn, given the product's price, determines the maximum revenue that a process can generate. In contrast, throughput time is an important determinant of the *speed* of a process. For a process that produces customized product to order and carries little finished-goods inventory, throughput time may be an important competitive performance measure because it may be the major determinant of how long a customer will have to wait after placing an order. Similarly, for many services, throughput time determines how long it takes for a customer to be served.

If units must wait between steps, the throughput time for a process may be far greater than the sum of the processing times of its individual tasks. Units may wait in WIP storage 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 throughput 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.

Batch size* (or *lot size): Most processes produce more than one product type. Suppose a process produced three products: P1, P2, and P3. The process could produce 1 unit of P1, then 1 unit of P2, then 1 unit of P3, then 1 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 batch size is equal to 1 unit; in the second case, the batch 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 batch sizes will result in quite different throughput and cycle times. The batch 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 batch sizes.

The size of a 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 batch size may be strictly a management decision. A company making three colors of plastic bowls, for instance, may choose to mold 1,000 of each color before changing over to another color.

Setup time and run time: Setup time refers to the time spent arranging tools, changing colors, setting machine speeds, cleaning equipment, and so on 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 many hours setting up to make the process ready for the transition from producing one product type to producing another. 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*. For the production of a given batch, the setup time is fixed and the run time is proportional to the batch size. This is a useful distinction. Long setup times may make it attractive to produce in large batch sizes because the fixed cost of the setup can be spread over a larger production volume.

Run time per unit is the amount of time actually spent processing the item (or performing the service) independent of the time required to set up the equipment. If units in a batch are processed sequentially, the run time per batch is the run time per unit multiplied by the number of units in a batch (i.e., the time the units in the particular batch are actually being processed on the equipment).

Returning to the concept of throughput time, if we were to follow a unit from when it first enters a process until it leaves, we would see that during 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 waiting due to imbalance in the processing steps, machine downtime, or time spent as WIP inventory waiting for other products to be completed.

All of this discussion assumes that yields are 100%, that is, 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 would complicate the analysis.

When calculating process performance measures, carefully consider the details of the process and the managerial questions 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, by whom, using what resources at any point of 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 assembly 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 that makes 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 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 and resources needed to provide the process outputs. Those choices also determine 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 photocopier. 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 copy is very inexpensive to produce. 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 mix selection, scheduling, setting batch sizes, 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 may seem relatively straightforward for a bakery, the complexity increases with the number of different products, the amount of excess capacity available, the number of different customers and their individual 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, 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 and resources, 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 put in place to make the necessary adjustments in the quantities used, the mixing and proofing times, or the baking times. This may require more sophisticated control of equipment and additional quality control activities. It also requires an information system to inform operators (and the machines, directly, if the system is automated) of the composition of the flour being used and how to compensate for changes in 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 differences in customer satisfaction. This would place an additional burden on the information system.

Product variety is another source of operational complexity. A bakery making 16 different types of bread has to schedule the process to produce the right quantity of each type to meet demand. In addition, setup times may be required to switch the machines from making one type of bread to another. The mixers might have to be cleaned, and the oven temperature might need to be changed.

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 and machines for that period and/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, circumstances such as incomplete mixing or fluctuations in the temperature in different parts of the oven may lead to a lower yield of bread that meets the quality specification. Uncertainty in the subsequent yield of the process—not knowing exactly how many good loaves you will produce 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 fulfill demand when uncertainty exists in yield and/or demand, but inventory may be costly to hold and can 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. 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 can be summarized as:

- Define the process by identifying the tasks and the flows of information and goods, and setting process boundaries. Also, determine where inventory is kept in the process. This effort can be recorded in a process flow diagram.

- 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 Process Analysis Terms

Note: In all of these definitions, the word *process* may refer to the complete process, such as the making of bread from start to finish, or to a task (a segment of the process), such as packaging.

Batch size (or lot size). The number of units of a particular product type that are produced before beginning production of another product type.

Bottleneck. The task or resource that limits the capacity of the overall process, assuming inputs are unconstrained. A bottleneck task or resource has the longest cycle time, and could, for example, be due to the pace at which production equipment can operate, or to the amount of labor available to work on a particular task.

Buffer. Space between process steps to decouple successive tasks, where work-in-progress inventory can accumulate. Buffer space can take the form of physical space (e.g., bins, tables) or time periods (e.g., slack in schedules).

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 an hour.

Cycle time. The average time between successive units being completed by a task or resource. The reciprocal of cycle time is output rate.

Direct labor content. The amount of labor time contained in the production of a given amount of output (e.g., unit or batch).

External time. On a task requiring a machine and labor, the subset of labor time spent working on a unit while the machine is not operating on that unit.

Finished goods inventory (FGI). The number of completed units (or their monetary value) held in storage within a process at a particular moment in time.

Internal time. On a task requiring a machine and labor, the subset of labor time spent working on a unit while the machine is operating on that unit.

Lead time. The amount of time it takes from when buyers place an order, to when they receive the order.

Little's law. An equation that describes the relationship between the averages of three operating metrics in a stable (steady state) process that can be expressed in several ways, including:

- Average work-in-progress = Average output rate × Average throughput time
- Average throughput time = Average work-in-progress ÷ Average output rate
- Average work-in-progress = Average throughput time ÷ Average cycle time
- Average number of customers in a queue = Average arrival rate × Average time a customer spends in the queue

Machine interference. A situation where machine operators need to wait to use a machine because it is occupied completing an operation for a different unit.

Machine time. The amount of time a machine is used on each unit of a product.

Output rate. The rate at which the process is delivering output, usually expressed in units per time. The reciprocal of output rate is cycle time. A process' maximum output rate is its capacity.

Process flow diagram. A diagram depicting the tasks in a process and the flows connecting them. Such diagrams tend to focus on tasks and the flows of inputs and work-in-progress, but information flows may also be depicted.

Raw material inventory. The amount of raw material held (units or their monetary value) in storage within a process at a particular moment in time.

Run time. The amount of time spent processing each unit (or performing a service) independent of the time required to set up the equipment. If units in a batch are processed sequentially, the run time per batch is the run time per unit multiplied by the number of units in a batch.

Setup time. The time spent arranging tools, changing dyes, setting machine speeds, cleaning equipment, and so on in preparation for the beginning of work on a batch or a specific product type.

Steady state. A process is in steady state when it is stable, which corresponds to its average input rate equaling its average output rate. In a service context, this occurs when the average customer arrival rate equals the average customer exit rate. In a manufacturing process, this occurs when work enters and exits the system at the same average rate. Little's Law applies to systems in steady state. Steady state differs from transient states like start up and shut down periods.

Takt time. The cycle time necessary to meet customer demand.

Throughput time (TPT). The amount of time each unit (or customer, in a service) spends in a process, from start to finish. This includes time during which the unit is actively being worked upon at each step of the process, as well as any time spent waiting between steps.

Work-in-process inventory (WIP). The number of partially completed units (or their monetary value) within a process at a particular moment in time. If the process includes buffers to store inventory between tasks, then WIP is the total number of units being worked on as well as those waiting in these buffers.

Utilization. The ratio of a resource used to the amount of the resource that was available to be used. *Labor utilization* is the ratio of labor time spent processing a unit or order to the total amount of labor time available. Differences between labor time used and labor time available can be due to inefficiencies in the process that led to lost working time, as well as to imbalances in the cycle times at each step of the process that led to idle time of workers at some tasks while those at others were working. *Machine utilization* is the ratio of (a) machine time spent actively processing a unit or order (not including any time when the machine is *blocked* by being unable to pass its unit to the next step or *starved* while waiting for a unit from the prior step) to (b) the total amount of machine time available. *Capacity utilization* is the proportion of capacity actually used, or the ratio of the output rate of the process to the process's capacity.

Yield. The percentage of total output a process produces during a designated period of time that complies with design specifications. Calculated over a specified period of time by dividing *output that meets specifications* by *total output*.

Source: Some of these definitions were adapted from Professor W. Bruce Chew, "A Glossary of TOM Terms," HBS No. 687-019.