Calculating the Capacity of Chemical Plants

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Production capacity is a vital statistic for describing the performance of a chemical plant, but there is no universally accepted definition or means to evaluate it. This article provides a comprehensive definition of capacity and details the options for deriving it.

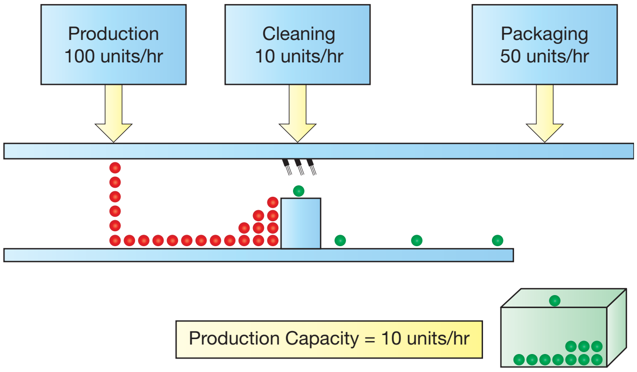
The production capacity of a chemical plant is a fundamental measure of its economic potential, and an integral factor in the assessment of a chemical plant's value. Although capacity is a central concept in production planning and scheduling, operations management and chemical engineering literature do not offer a cohesive explanation or means for determining it. This article provides this missing insight with a definition and description of capacity that encompasses the various disparate descriptions offered, as well as a means to calculate and evaluate it.

Production system performance

A production system transforms inputs of raw materials, energy, and labor into product outputs. This system can be decomposed into processing steps that occur in process equipment and inventory buffers such as storage tanks, hoppers, and silos.

The performance of a single processing step can be evaluated in terms of the material throughput, equivalent to the mass flowrate; the work-in-process (WIP), described as the mass of material within the processing equipment; and the flowtime, calculated by dividing the WIP by the throughput. For the production of continuous entities such as solids, liquids, and gases, the link between the throughput, WIP, and flowtime is the mass balance. For discrete entities such as manufactured goods, this relationship is described by queueing theory (sometimes considered to be a branch of operations research), and more specifically by Little's Law, which states that the WIP is equal to the maximum throughput multiplied by the flowtime *(1)*.

A simple definition of capacity is the maximum throughput for a single processing step. (Subsequent sections discuss the important subtleties that this definition ignores, but for the moment, this will suffice.) For chemical manufacturing operations, the production system usually takes the form of a series of processing steps; this is referred to as a serial production system. The capacity of a serial production system is governed by the slowest processing step in the sequence, called the bottleneck (Figure 1). Because of the limitations placed on the process by the bottleneck, the



▲ **Figure 1.** The production capacity of this three-step process is governed by the cleaning step, because it operates at the slowest rate. This step is considered to be the bottleneck of the process. Although the system is producing and packaging units at rates 5 to 10 times faster than the cleaning step, the production capacity is limited by, and is equivalent to, the capacity of the bottleneck — 10 units per hour.

The maximum sustainable average throughput should not threaten the integrity of the equipment, result in a hazardous release of material or energy, or violate an environmental permit.

capacity of the production system depends on the capacity of the bottleneck.

Continuous and batch chemical processing plants can be modeled as a serial production system. The primary difference between the capacity analysis of a continuous operation and that of a batch operation is the form of the mass balance. This article only considers continuous production systems. (References 2–4 discuss production capacity for batch processes.)

Defining production capacity

Capacity is often expressed in vague, imprecise, and inconsistent terms, but fragments of the descriptions provided by the production and operations management literature can be combined to create a comprehensive definition of capacity.

Production throughput is a dynamic quantity that fluctuates often. An accurate and meaningful measurement of throughput depends on the sensitivity of the mass flow measurement and the period of observation. Therefore, to obtain a capacity that accurately describes the production system, the calculation should be based on an average value of throughput.

Reference 5 defines capacity as "the maximum average rate at which entities can flow through the system" and explicitly acknowledges the need for an average value. However, this definition does not specify an appropriate period of observation over which the maximum average rate of throughput should be maintained.

Reference 6 introduces the term "sustainable" to the definition of capacity: "[the] maximum sustainable flowrate if it were fully utilized (without interruptions, downtime, time wasted to setups, idle periods, and so on)." This, too, implies that capacity should be based on a time-averaged interval, and the word "sustainable" suggests that capacity is a throughput that can be maintained for an extended period of time.

Reference 7 states that "production capacity is the highest sustainable output rate which can be achieved with the current product specifications, product mix, worker effort, plant, and equipment." By introducing the influence of constraints (*i.e.,* product specifications, product mix, etc.), this definition suggests that the capacity of a production system is not the instantaneous maximum value of throughput for a single piece of equipment, but rather the maximum throughput of the system, sustained for an extended period of time subject to production constraints.

One factor that sets chemical manufacturing apart from many other manufacturing sectors is the large quantities of hazardous materials and energy it uses and produces. All of the previous definitions of capacity overlook this important inherent aspect of chemical production. Furthermore, a design requirement for every chemical plant is that it must operate in a manner that ensures the health and safety of the environment and personnel. As a result, a useful definition of capacity must include a clause that dictates that the maximum sustainable average throughput should not threaten the integrity of the equipment, result in a hazardous release of material or energy, or violate an environmental permit. These requirements are typically documented as safe operating limits for the facility.

When we combine the relevant components from each of these descriptions, we get a clear, useful, and accurate picture of capacity. This working definition can be stated as the maximum average throughput that simultaneously satisfies the following four constraints:

- it takes into account the production restrictions imposed by the existing equipment, materials, and labor
- it is sustainable for an extended and specified period of time
- it assures product quality requirements
- it does not exceed the safe operating limits of the facility.

Deriving production capacity

Three fundamentally different types of production capacity include design capacity, demonstrated capacity, and effective capacity. The design capacity is a theoretical value based on first principles that usually serves as the design basis for a process plant. In contrast, the demonstrated capacity is an empirically derived value that is determined from measurements of the plant's operating performance. The effective capacity takes into account plant availability.

Capacity:

The maximum average throughput that satisfies four constraints:

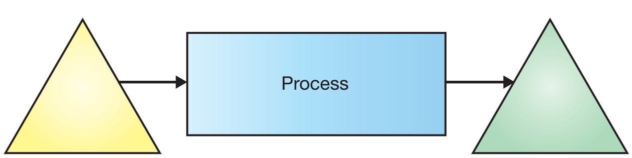
- it takes into account the production restrictions imposed by the existing equipment, materials, and labor
- it is sustainable for an extended and specified period of time
- it assures product quality requirements are met
- it does not exceed the safe operating limits of the facility.

Determine the bottleneck. As discussed previously, to correctly determine the capacity, the bottleneck of the process must be identified and characterized. The bottleneck can be quantified theoretically, as the design capacity, or empirically, as the demonstrated capacity. The implementation of either method depends on the structure and function of the flowsheet.

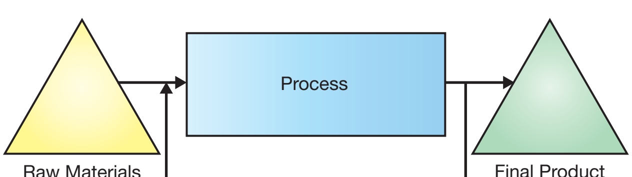
The process flowsheet (Figure 2) represents the sequence of storage and transformation operations that comprise the process. Storage operations include raw material storage, intermediate tanks, and product storage. Transformation operations include material handling, separations, chemical reactors, and heat exchangers.

The flowsheet organizes the storage and transformation operations into a desired process, composed of three basic flow paths — serial, parallel, and/or recycle. In a serial flow path, material flows directly from one operation to the next. A parallel path consists of two or more serial paths into which the incoming flow is split; typically, parallel paths are utilized for multiple-train processes. In a recycle path, one stream is split into two streams, one of which continues down the serial path while the other stream is reintroduced at some upstream point (Figure 3).

When each operation in the flowsheet is designed, it is sized according to the design basis. This suggests that the capacity of a chemical process is simply its design basis, and that capacity is therefore determined before operation begins. However, the actual throughput depends on physical limitations of the equipment and the commercial availability of resources from vendors. As material flows through the processing operations, the actual throughput, at steady state, is limited by the operation with the lowest throughput (*i.e.,* the bottleneck). In addition to processing operations, other potential sources of bottlenecks include logistical constraints, utility limitations, safe operating limits, and environmental restrictions.



▲ **Figure 2.** This type of process flow diagram is typically used in operations management literature to depict a production system.



▲ **Figure 3.** This process flow diagram includes a recycle stream that recirculates some of the product stream back through the system for further processing.

Determine the design capacity from process calculations. The design capacity is usually dictated by the design basis for the process flowsheet. The process design document (*e.g.,* the basis of design) specifies the product throughput. To verify the stated design capacity, it is necessary to establish the throughput of the bottleneck, which may be explicitly identified in the design documents. If the bottleneck is not identified, it can be determined by inspection of equipment ratings and analysis of the process mass balances.

For simple processes, the bottleneck can be determined by the rated throughput, the operating limit of a specific piece of equipment, or a limit in an environmental permit. In these instances, the bottleneck can be established by inspection.

For more complex processes, the mass balances for each process unit must be checked. If reactor yields and separation splits are known, this can be reasonably straightforward; if these values are not available, then more sophisticated process simulation may be needed.

It is important to document the evaluation process to communicate to other parties the methodology behind the design capacity calculation.

Determine the demonstrated capacity by empirical testing. The motive for determining the demonstrated capacity is to improve on the design (*i.e.,* theoretical) capacity calculation by incorporating empirical data. Usually, a plant's performance must be measured as a contractual requirement during plant commissioning to demonstrate the achievement of a performance guarantee. This assessment is governed by a structured test plan that prescribes how to operate the plant at steady state, at specific conditions, for a discrete period of time. The test is meant to demonstrate the maximum-throughput operation of the plant while satisfying the four capacity constraints. In addition to the usual production monitoring process measurements, supplementary measurements and sampling may be necessary to validate estimated values of reactor yields and separation splits. The test plan also includes data quality objectives (*e.g.,* sensitivity, accuracy, precision) for each process measurement. Depending on the complexity of the operation, the test plan may also need to address other operating issues, such as those in Table 1. It is essential that the appropriate facility managers review and approve the test plan.

When a formal test plan is not required, demonstrated capacity may be measured using plant performance data obtained in the normal course of operation. During this time, the analyst reviews the historical process data and identifies data sets that may represent the maximum average throughput from the plant. These instantaneous process measurements are unlikely to satisfy the governing mass balances due to confounding effects such as sampling error, measurement uncertainty, calibration error, signal noise, and, most significantly, the cumulative residence time of the material in the process. To mask the effects of the confounding variables, the analyst must choose a reasonable time-averaging interval that will generate averaged data suitable for mass balance analysis. A first approximation for this time-averaging interval is several times the cumulative residence time for the process. If an estimate of the cumulative residence time is not available, the analyst may have to select a time interval, select the relevant process data for the interval, and test it for mass balance closure.

A simple test for mass balance closure compares the averaged process data with accounting data *(8)*. The relevant accounting data, which are typically compiled monthly, consist of inventory measurements of raw materials, work in process, and finished goods. The advantage of this approach is that it is a comparison of data derived from a set of diverse measurements. A more sophisticated approach is to use formal process data reconciliation methods *(9)*, which employ a least-squares estimation algorithm to adjust the process data to obtain the best conformance with the mass balances.

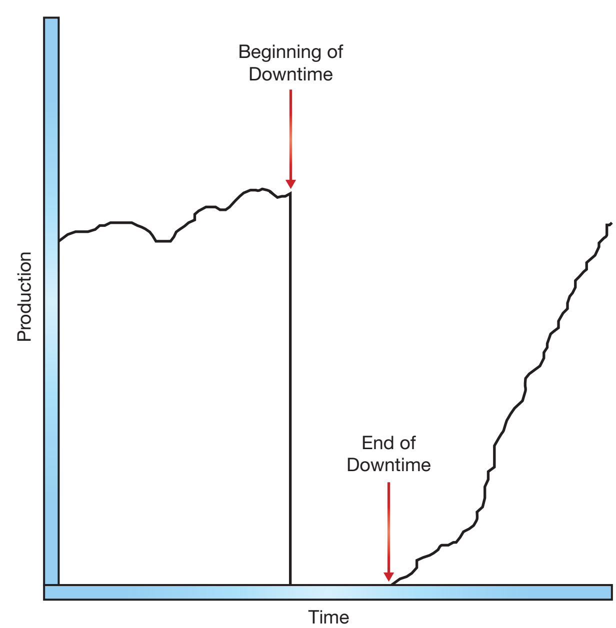
Determine the effective capacity from plant availability. To calculate effective capacity, the availability of the plant, which is defined as the fraction of time that the plant is up and running, must first be determined. Availability is calculated as the ratio of uptime to the mission time. The mission time is the sum of the uptime and downtime (*i.e.,* zero production); to determine the effective capacity annually, the mission time is set at one year.

The monthly operating data displayed in Table 2 can be used to calculate availability and effective capacity. The availability of the plant is the ratio of the uptime, 342 days, to the total time of observation, 365 days, so the calculated availability is 93.7%. The effective capacity is the product of the availability and the design capacity, so if the design capacity is 200,000 m.t./yr, the effective capacity is 187,400 m.t./yr.

Downtime is the time interval when the plant is not running, and can be planned or unplanned. Examples of planned downtime include turnarounds, vessel cleaning, and preventative maintenance activities, while unplanned downtime is caused by equipment failures, utility failures, or power outages.

Table 1. Consider these points when developing a capacity assessment test plan.

Operator Assignments
Will there be operator shift changes during the test?
How will shift changeover be handled?
Will staffing for the test require additional personnel?
Will there be dedicated test program operators or will they have other duties?
Operating Procedures
Will the test program use standard operating procedures (SOPs) or will the SOPs require modification?
If the SOPs will be modified, have the appropriate management of change (MOC) procedures been implemented and approved?
Has a pre-startup safety review (PSSR) been performed for the test program?
Process Measurements
Are the routine process measurements satisfactory for the test program?
Will any additional or nonroutine process measurements be taken?
How will process measurements be recorded and archived?
Will normal measurement sampling intervals provide the desired resolution for the test?



▲ **Figure 4.** To calculate effective capacity, downtime is modeled as a step function, with an abrupt drop in production to zero output. Any production rate above zero, even if it is significantly lower than normal operation, is considered facility uptime.

Table 2. Example plant operating data.													
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
Mission Time, days	31	28	31	30	31	30	31	31	30	31	30	31	365
Uptime, days	31	26	30	30	31	29	15	31	29	31	30	29	342

Table 3. Example monthly catalytic activity data.												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Catalyst Activity, %	100	98	96	94	92	90	88	86	84	82	80	78

For the purpose of calculating effective capacity, downtime is modeled as a step function (Figure 4). This is because downtime does not include reduced or degraded performance due to factors such as pipe scaling, heat exchanger fouling, accumulation of trace contaminants, or catalyst deactivation. Unless these factors force production to zero, the reduced production is still considered uptime.

The effective capacity can account for declining production rates in the uptime calculation with a time-averaging algorithm. Consider a fixed-bed catalytic reactor that experiences linearly declining catalyst activity. Fresh catalyst was loaded and the reactor was started in January. Table 3 shows the monthly catalytic activity data for the observational period (one year). The average catalytic activity over the 12-mo period is 89%. If the catalytic reactor is the bottleneck for this process unit, then the annualized production capacity must be based on the average catalytic activity of 89%. If the design capacity is 200,000 m.t./yr, the effective capacity is 178,000 m.t./yr.

Closing thoughts

Production capacity is an important factor that needs to be calculated to determine equipment size, satisfy contractual requirements, aid supply chain management, benchmark against competitors, and obtain operating permits from regulators. There is no single way to measure capacity, and there are numerous factors to consider, many of which are unique to a specific process or facility. With these guidelines, a well-documented methodology, and the involvement of the appropriate stakeholders, a clear and unambiguous determination of a chemical plant's capacity can be realized. CEP

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