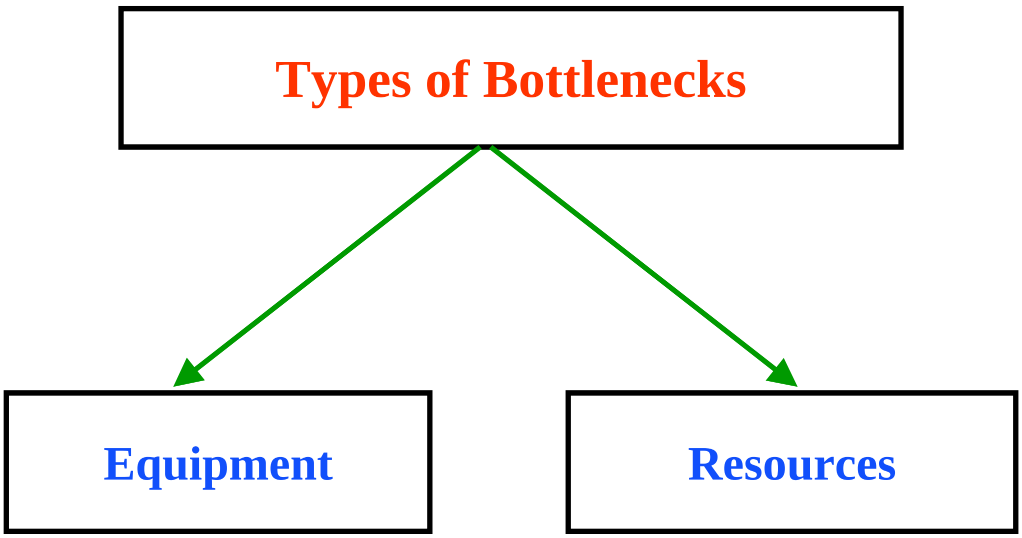
9.0 Throughput Analysis and Debottlenecking

The annual (or campaign) throughput of a batch manufacturing facility is equal to batch throughput (size) times the number of batches that can be processed per year. Therefore, we can increase annual throughput by increasing the batch throughput (size) or the number of batches per year or both at the same time.

Annual Throughput = **Batch Throughput** x **Number of Batches per Year**

In our effort to increase annual throughput we run into bottlenecks that are either equipment or resource (e.g., utilities, labor, demand for raw materials) related.



The equipment or resource that limits the number of batches per year is the **Scheduling or Time Bottleneck**. The equipment or resource that limits the batch throughput (amount of material processed per batch) is the **Batch Size bottleneck**. The equipment or resource that limits that annual (or campaign) throughput is the **Throughput bottleneck**. Either the Time or the Batch Size bottleneck is also the Throughput bottleneck.

Please note that for a batch process the “Batch Size” and the “Number of Batches per Year” are interdependent. More specifically, as the batch throughput is increased (operating closer to the maximum), the cycle time of most procedures will increase resulting in longer recipe cycle times and fewer batches per year. Consequently, the maximum annual plant throughput cannot be simply set equal to the maximum batch size times the maximum number of batches per year. Instead, it can be calculated in an iterative way by gradually increasing the batch size and letting SuperPro calculate the corresponding maximum number of batches.

➔ Identifying Equipment Time (Scheduling) Bottlenecks

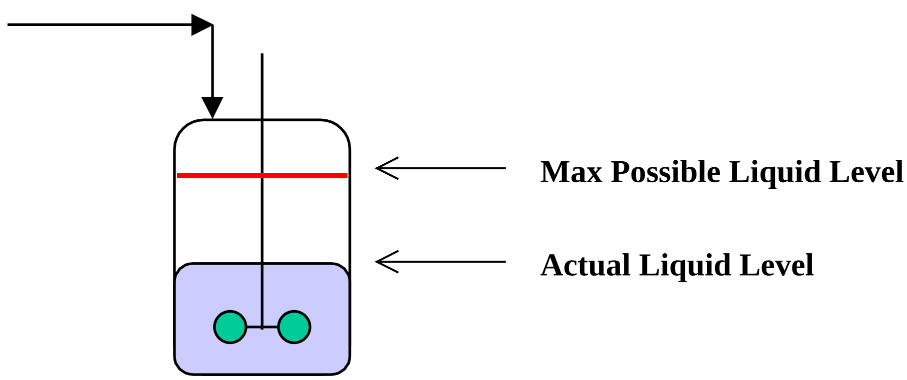
Information on the equipment scheduling bottleneck is provided on the Recipe Scheduling Information dialog (see Chapters 2 and 6). The same information can be visualized graphically on the Equipment Occupancy chart. The scheduling (or time) equipment bottleneck is the piece of equipment that has the longest cycle time. This piece of equipment determines the minimum time between consecutive batches (also known as minimum recipe cycle time) and consequently the maximum number of batches per year. For main equipment items that are shared by multiple procedures, their cycle time is set equal to the time interval between the start of the first procedure that is hosted by the equipment to the end of the last procedure that is hosted by the same equipment. Please note that resources also can become time bottlenecks (see section on resource bottlenecks below).

➔ Identifying Equipment Size and Throughput Bottlenecks

The Batch Size bottleneck can be identified by considering the Capacity and Time utilization of each equipment item.

Equipment Capacity Utilization

This variable represents the equipment capacity utilized during a certain procedure. For instance, if a piece of equipment that can process up to 100 kg/h of a certain material it is operated at a rate of 80 kg/h, its equipment capacity utilization will be 80%. If a piece of equipment is of vessel type, its capacity utilization can be defined based on the ratio of actual and maximum liquid levels for a certain operation. The figure below illustrates this in detail. The Capacity Utilization for a unit procedure is calculated by selecting the maximum capacity utilization among all operations of that procedure. The cyclical equipment with storage capacity that has the highest capacity utilization determines the maximum batch size and therefore is the batch size bottleneck.



$$\text{Equipment Capacity Utilization} = \frac{\text{(Actual Liquid Level)}}{\text{(Max Liquid Level)}} \times 100$$

Equipment Uptime

This variable represents the percent of overall operating time that a certain piece of equipment is occupied. For batch processes, the equipment uptime can be defined as follows:

$$\textbf{Equipment Uptime} = \frac{\textbf{(Total Time Equipment is Utilized per Batch)}}{\textbf{(Recipe Cycle Time)}} \times 100$$

Recipe Cycle Time is the time interval between consecutive batches. If a piece of equipment is used by multiple procedures (in a batch plant), the equipment uptime accounts for the overall (of all procedures) utilization in time.

Many procedures have uptimes (as well as cycle times) that are proportional to the amount of material processed per cycle. For example, if you have a disk-stack centrifuge that processes material in a continuous fashion without accumulating anything and double the batch volume, the uptime of the centrifuge will also double. Equipment items of this type usually operate at 100% capacity utilization and changes in batch size only affects their uptime. This is an important point to understand; just because a piece of equipment is listed as having 100% Capacity Utilization, it not necessarily the throughput bottleneck.

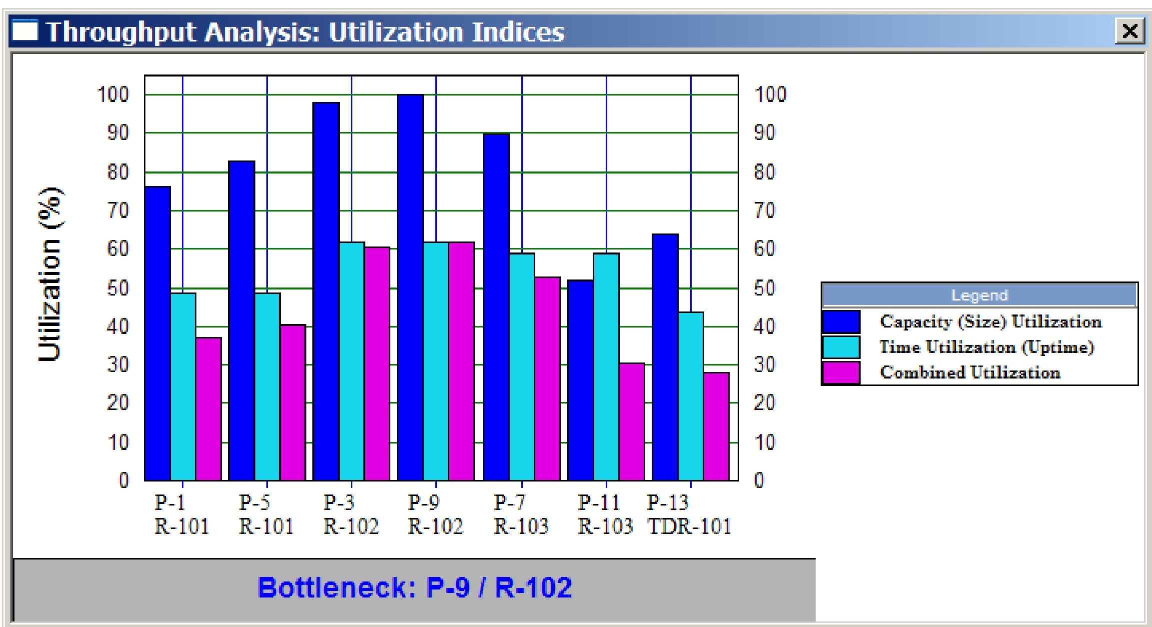


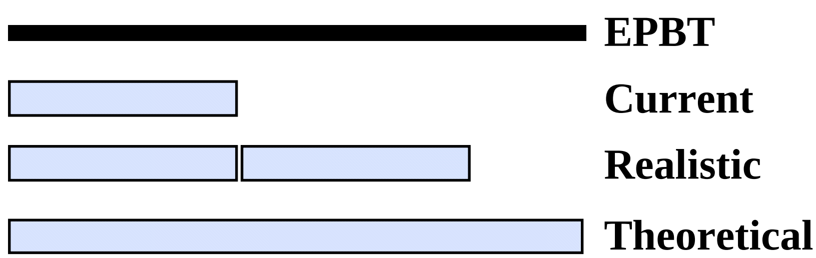
Figure 9.1: Throughput Analysis Utilization Chart.

Combined Utilization

Combined Utilization of a procedure is its Equipment Capacity Utilization times its Equipment Uptime. To have a Combined Utilization of 100%, the procedure's equipment would have to be run at full capacity and its cycle time would have to be the same as the recipe cycle time. The procedure with the highest Combined Utilization is identified as the throughput bottleneck for the process. Figure 9.1 shows a sample of a utilization chart that displays the Capacity, Time, and Combined utilization of each procedure of a process. This chart is generated by selecting “**View \ Throughput Analysis Charts \ Utilization**” from the main menu of the application. Please note that only procedures whose equipment is in Rating mode (size was specified by the user) are included in this analysis. According to this methodology, procedure P-9 that utilizes vessel R-102 is identified as the throughput bottleneck. This methodology points in the right direction regarding bottleneck identification, but it cannot guarantee identification of the right bottleneck when cyclical procedures are included in the process. Cyclical procedures (i.e., procedures that go through cycles of activities, such as batch chromatography steps) impose constraints on time utilization and may lead to situations where the true throughput is a procedure that does not have the highest combined utilization. . For instance, if the recipe cycle time of a batch process is 100 h, and a reaction step in a vessel takes 60 h, in a regulated environment where batch integrity is maintained (that’s the case with the pharmaceutical industry), the reaction vessel can have a practical maximum uptime of 60%. If the specific vessel operates at full size utilization, it will be the throughput bottleneck even if some other equipment has a higher combined utilization.

Potential Batch Size

A better way of identifying throughput bottlenecks is by calculating the Potential Batch Size (PBS) of each procedure. For procedures that have cycle times proportional to batch size (e.g., disk-stack centrifugation, pumping, etc.), the PBS is calculated by assuming 100% equipment capacity utilization and 100% uptime. For procedures whose cycle times are not proportional to their throughputs (e.g., vessel procedures, chromatography, etc.), their PBS is calculated under Conservative, Realistic, and Theoretical assumptions for their uptime (see figure below). The Equipment Capacity utilization is assumed 100% in all the cases.



1) In the **Conservative** case, the Equipment Uptime is kept the same as its current uptime.
2) In the **Realistic** case, the Equipment Uptime is set to correspond to the highest number of complete cycles that can be performed in that piece of equipment within the time window of the current recipe cycle time.
3) In the **Theoretical** case, the Equipment Uptime is assumed to be at 100%. This would require mixing of partial lots of product, which typically is not be an option in the regulated industries (e.g., pharmaceutical industry).

The objective is to identify the TRUE throughput bottleneck based on the realistic scenario. The conservative scenario corresponds to the case where we operate all the equipment items at 100% capacity utilization but without making any changes in the number of cycles per batch. Figure 9.2 shows a sample of the PBS chart for the same process whose utilization chart is shown in Figure 9.1. All three indicators of this approach identify P-9 (in R-102) as the bottleneck as well. That's a good sign that indeed P-9 (in R-102) is the true bottleneck of this process. This chart of Figure 9.2 is generated by selecting "**View \ Throughput Analysis Charts \ Potential**"

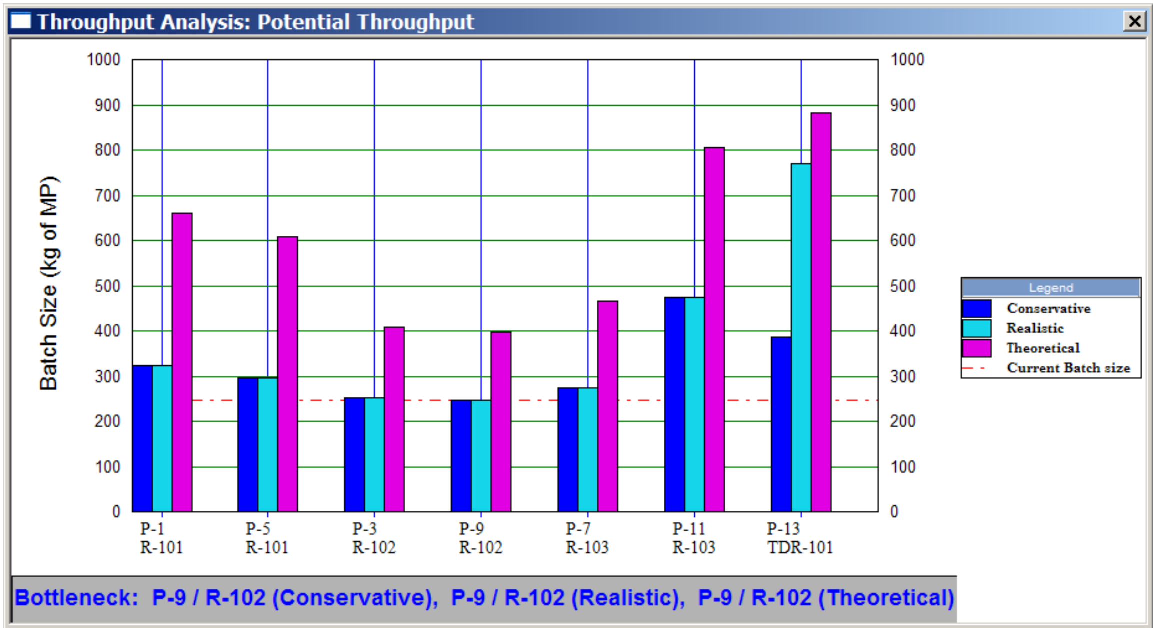
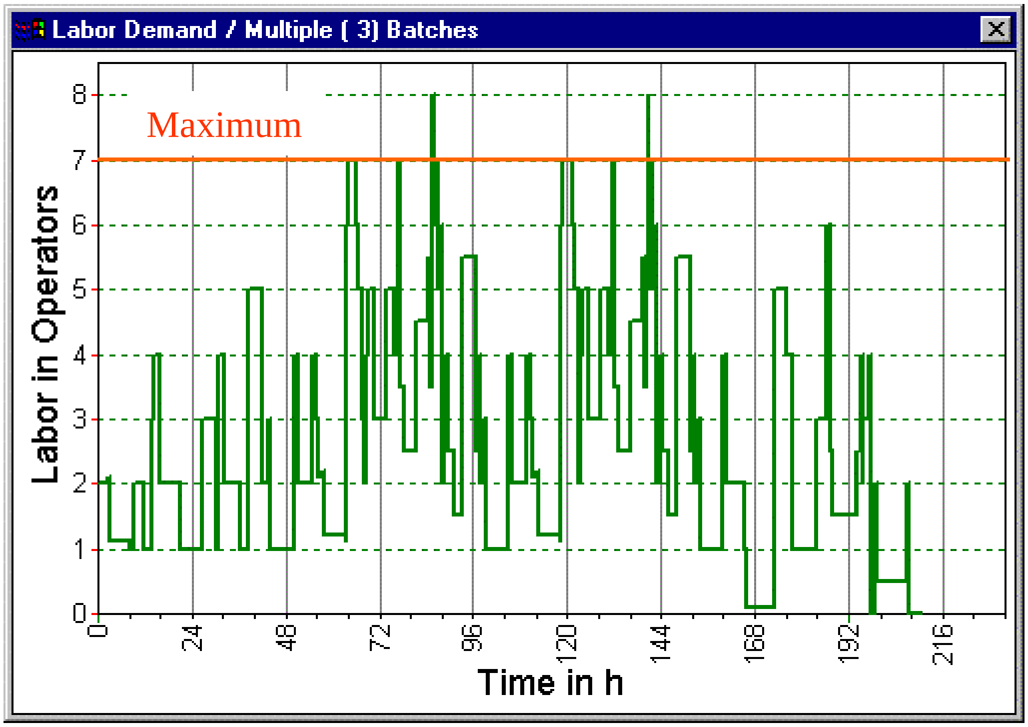


Figure 9.2: Throughput Analysis Utilization Chart.

➔ Resource Bottlenecks

Resources can become size and time bottlenecks when their average or instantaneous demand exceeds their average or instantaneous capacity, respectively. For instance, the figure below shows the demand for labor as a function of time for three consecutive batches of a process. For short periods of time, there is a need for up to eight operators. If seven (red line) is the maximum number of operators that can be available at any time, then, certain operations will have to be delayed to accommodate that constraint. That delay of operations may increase the recipe cycle time and reduce the maximum number of batches per year and therefore become the new time bottleneck. The current version of Pro-Designer does not identify resource time bottlenecks. However, it calculates and displays the demand for any resource (e.g., raw materials, heating/cooling utilities, power, and labor) and enables the user to visualize and interactively eliminate potential resource bottlenecks. In SchedulePro, however, the user may specify a maximum and the scheduling algorithm automatically delay the execution of certain operations in order to meet those constraints.



9.1 Throughput Analysis Report

The Throughput Analysis Report includes the info of Figures 9.1 and 9.2 in tabular format along with additional more detailed info on procedure/equipment utilizations and potential batch sizes. The report can be generated by selecting "**Reports \ Throughput Analysis**" from the main menu of the application. A thorough debottlenecking exercise is described in the "**Examples \ SynPharm**" directory.

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