Process Analytics Using *ProModel Workstation Simulator™*

Introduction

One of the most challenging aspects of designing production and service systems, as well as any supply chain system, is predicting system performance. Suppose, for example, you are designing an assembly line or work cell having six stations with variable operation times, random equipment failures, limited buffer capacity and shared operators. How would you estimate the output capacity of such a system? More importantly, how would you know what changes, if any, should be made to best meet performance objectives?

Obviously, the greater the system complexity, the more difficult it is to predict how it will perform and what impact design changes will have. The one thing most systems experts agree on, however, is that increasing complexity tends to have an adverse effect on all aspects of system performance including throughput, resource utilization, work-in-process, cycle time and quality.

System complexity is primarily a function of the **interdependencies** and **variability** in the system. Interdependencies occur when operations are linked together in series or when they must compete for the same resources. Variability occurs when there is variation in operation times, yields, downtimes, etc. The performance and predictability of a system is inversely proportional to the degree of interdependency and variability in the system (see Figure 1).
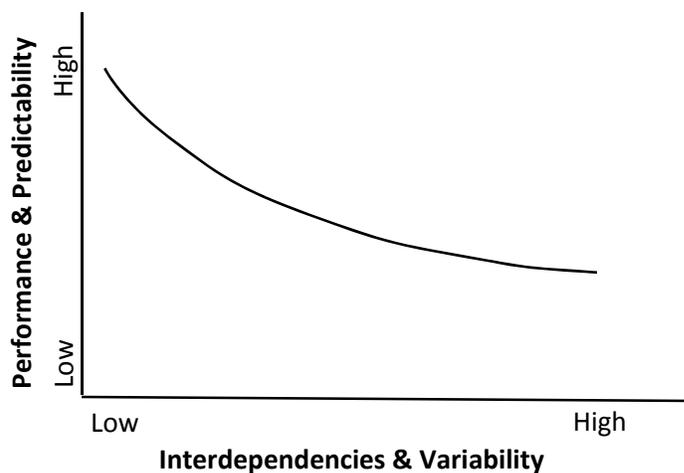

Figure 1. System Performance and Predictability is Inversely Proportional to System Interdependency and Variability

Computer simulation is a powerful analytic tool that is capable of capturing the complex relationships in a system and eliminating the guesswork in systems planning. Because it imitates the actual operation of a system, simulation provides invaluable insight into system behavior and gives quantitative measures of system performance. Process improvements can be made by simulating alternative designs or operating strategies and comparing their results to see which solution is the most cost effective.

The exercises below are designed to help you (1) improve your intuition about the way interdependencies and variability impact system performance, (2) analyze alternative ways to mitigate this impact, and (3) gain a better understanding of the predictive capability of simulation.

ProModel Workstation Simulator

***ProModel Workstation Simulator*™** is an Excel interface to ProModel[1] that simplifies the modeling and simulation of basic serial processes. A serial process is a sequence of workstations (in this case up to six) through which work items (e.g., parts, orders, documents, etc.) are individually processed. Work items advance to the next workstation only when it is available (i.e., it is not occupied by another work item) or has an input buffer with available capacity. Move times are considered to be negligible and are therefore ignored in the simulation.
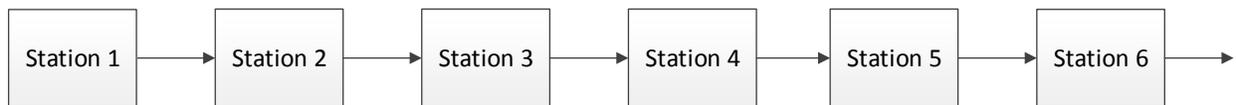
For each exercise below you will simulate and evaluate alternative process configurations to see how their performance compares. You will also get a chance to test how reliable your intuition is and learn how to make informed process decisions. The three principal decision variables you will be experimenting with for a given process are (1) the operation time for each workstation, (2) the degree of variation in operation time, and (3) the buffer or storage capacity between workstations.

Defining a Process Model

To define and simulate a process model, open the Excel file called ***ProModel Workstation Simulator***. (Be sure to click on Enable Content if a security warning appears when you open the file.) The worksheet that appears has fields for entering values for each decision variable. Alternatively, you can just select the appropriate Exercise number at the top of the worksheet and the values are automatically provided.

You are free to change any cell value that has blue text. If you wish to copy and paste values, be sure to select "Paste Values" from the Paste options menu so that the formatting of the cell is preserved.

Running the Simulation

After defining the process, click on the **Simulate** button to simulate the process. As you watch the animation you will see the work items moving from station to station. If a work item turns dark blue it is because it is **blocked**, which happens when the next station is either occupied or has a full input buffer.

---

[1] **ProModel** is a software product created by ProModel Corporation. For more information on this and other ProModel products and services, go to http://promodel.com.

When a workstation is empty it is because it is **starved.** This happens when upstream operations are unable to keep it fed.

Performance statistics are also displayed in the animation window while the simulation is running. These same statistics are summarized in the simulation results that are fed back to the Excel worksheet after the simulation finishes.

The simulation clock is displayed in the upper right-hand corner of the animation window. To adjust the speed of the animation, drag the speed bar at the top of the animation window. You can also disable the animation by clicking on the animate button (▦) on the tool bar.

Viewing Results

When a simulation finishes the results of the simulation appear in the Simulation Results table in the Excel worksheet. It is recommended that you copy and paste this table to the end of each exercise you perform so you can refer to it when answering the exercise questions. For example, if you were to complete an exercise involving the simulation of four processes with increasingly greater operation times, the Results table that you would copy and paste below might look something like this:

Operation Time	1 minute	2 minutes	3 minutes	4 minutes
Total Output	508.7	283.7	190.87	143.8
Avg. CT (minutes)	59.19	32.7	35.29	38.03
Avg. WIP	58.39	16.26	11.75	9.48
Avg. Station Utilization	96.56	96.92	97.47	97.64

Processes having operation times that are variable produce simulation results that are also variable and therefore fluctuate from run to run—similar to the random outcome when you roll dice. To determine what the *expected* outcome is of a random process it is necessary to run multiple **replications**—like multiple rolls of the dice. As a general rule, the greater the process variability, the more replications that are needed to get a good estimate of the expected or mean process performance. ***ProModel Workstation Simulator*** allows up to 100 replications, which is ample for providing reasonably accurate estimates of performance. The mean, minimum, maximum, standard deviation and 95% confidence interval are reported together with the results of each replication. In order to speed up the simulation when running multiple replications, animation is automatically disabled after the first replication.

Definition of Metrics

Below is an explanation of each output metric reported in the Results table:

Total Output – The total number of work items completed during the 10-hour simulation run. Since Station 1 is never starved (i.e., the line is fed as much as it can handle), the output of the system is also the same as the *capacity* of the system.

Average Work-in-Process (WIP) – The average number of work items in the system during the simulation.

Average Cycle Time (CT) – The average time work items spend in the system (a.k.a. average flow time).

Average Workstation Utilization – The average percentage of time that workstations are busy doing work. It is the sum of all workstation utilizations divided by the number of workstations.

It is also helpful to know **Little's Law** which expresses the relationship between output, WIP and CT as

Output rate = WIP/CT

Exercise 1 – Predicting the Performance of Non-complex Systems

Imagine a process consisting of a single workstation with a constant operation time of 1 minute. Naturally, one would expect the output capacity of such a process to be exactly 60 items per hour. This is an example of a process having neither interdependencies nor variability. In this first exercise we will explore how easy it is to predict the performance of a process that has either independencies or variability, BUT NOT BOTH. Two scenarios are presented.

1A – Predicting the Performance of a System with Variability, but No Interdependencies

The first scenario has only 1 workstation with an operation time of 1±1 minute (i.e., operation times vary uniformly between 0 and 2 minutes). With only one station there are no interdependencies, but with the variation in operation time, the process does have variability. Though this variability may seem high, it isn't nearly as high as the variability that would be characteristic of a process with downtimes or operator interruptions.

Before simulating the process, record below your own estimate of what the Output, WIP, CT and Utilization would be for a 10-hour production run.

	Your Estimate
Total Output	
Avg. WIP	
Avg. CT (min.)	
Avg. Utilization (%)	

Now simulate 30 replications of exercise 1A and paste the results below.

Questions

1.1 How would you explain the difference between your estimate and the simulation results?

1.2 What are the minimum and maximum output values obtained from the 30 replications?

1.3 What is the 95% confidence interval and what does it mean?

1B – Predicting the Performance of a System with Interdependencies, but No Variability

The second scenario is a process with six workstations having exactly 1-minute operation times (i.e., there is no variability). There are also no input buffers, which makes the system highly interdependent.

| Station 1 | → | Station 2 | → | Station 3 | → | Station 4 | → | Station 5 | → | Station 6 | → |
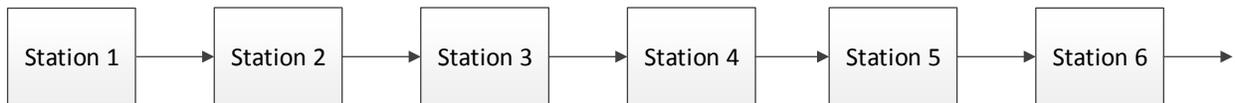
Record below what you would expect the performance to be for a 10-hour production run assuming the simulation starts with a work item already at each station (i.e. the system starts out full).

	Your Estimate
Total Output	
Avg. WIP	
Avg. CT (min.)	
Avg. Utilization (%)	

Now simulate just 1 replication of this process (exercise 1B) and past the results below.

Questions

1.3 Even though this process has interdependencies, why is it relatively easy to predict its performance?

1.4 Why was only 1 replication needed to determine the exact performance of this process?

Exercise 2 – Predicting the Performance of Complex Systems

This exercise examines the impact on system performance when interdependencies and variability occur together in a system. It essentially tests whether the general shape of the plot in Figure 1 is accurate.

2A – Predicting the Performance of a System with Interdependencies AND Variability

Continuing with the six-station line in the previous exercise, record below how you think the same process would perform if there is a ±1 minute variation in the operation time of each station.

	Your Estimate
Total Output	
Avg. WIP	
Avg. CT (min.)	
Avg. Utilization (%)	

Simulate 30 replications of this process (exercise 2A) and paste the results below.

Questions

2.1 What was the percentage drop in output and average workstation utilization compared to exercise 1B and what made the performance of this process more difficult to predict?

2.2 Verify that the average WIP and average CT conform reasonably close to Little's law.

Before continuing on, change the number of replications to 1 and simulate the process slowing down the animation so you can observe what is happening at each workstation. Note that workstations are sometimes starved (i.e., they are empty because of the lack of work) and sometimes blocked (i.e., the work item turns dark blue because it can't advance). Whenever a workstation is either starved or blocked, it is not being utilized and therefore not producing output.

2B – Comparative Analysis of Increasingly Complex Systems

Now run six different simulations (30 replications each) of a process with operation times for each station of 1±1 minute, and all input buffers set to 0. Start with 1 station and increment the number of stations after each run. Once you have made all six runs for exercise 2B, paste the results below.

Questions

2.3 Plot the total output for all six runs. How nearly does the plot match Figure 1?

2.4 Plot the average station utilization for all six runs. How nearly does the plot match Figure 1?

Exercise 3 – Utilizing Buffers to Compensate for Complexity

As illustrated in the previous exercise, as the degree of interdependency and variability increases in a process, output and utilization decrease. The traditional, non-Lean way of mitigating the effect of complexity on system performance is to insert buffers between workstations. Buffers change a process

from a "pull" system, where items are produced or conveyed to the next workstation only on demand, to a "push" system, where items are produced and conveyed to the next workstation regardless of whether it is ready for them. While buffers reduce the interdependency between workstations, they create WIP, which drives up inventory carrying costs.

In this exercise you will evaluate the impact that different buffer sizes have on a process consisting of six workstations with the same mean and variation in operation times. By comparing the process performance of each, the optimal buffer size can be determined.
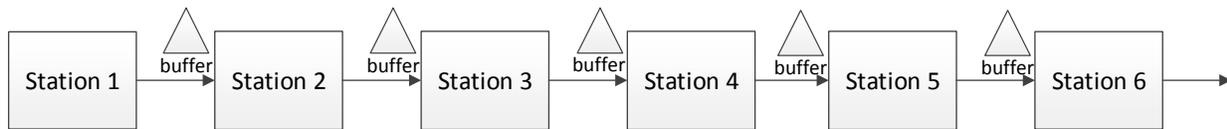
3A – Impact of Unlimited Buffer Capacity

For this first process we will set the input buffer capacity for each workstation to 999. The operation time for each station is 1±1 minute. Just for fun, enter your best guess for performance below.

	Your Estimate
Total Output	
Avg. WIP	
Avg. CT (min.)	
Avg. Utilization (%)	

Now simulate 30 replications of the process (exercise 3A) and paste the results below.

Questions

3.1 Based on the mean operation time of each station, if the buffers completely decoupled the stations from each other, one would expect an output of roughly 600 units as in exercise 1A. Why is the output of the simulation about 6 units less than that?

3.2 Run two or three **single**-replication simulations of the process and watch how buffer levels fluctuate during the simulation. Note the buffer levels and workstation utilizations at the end of each simulation. Do these values tend to get greater, smaller or stay about the same from station to station? (Be sure to click OK when you see the message – "Simulation is Finished.")

3B – Assessing the Impact of Different Buffer Capacities

Building off the same process as 3A, run six experiments (30 replications each) with progressively increasing buffer capacities (0, 1, 2, 3, 4, & 5). Simulate all six options and paste the results below.

Questions

3.3 How would you characterize the increase in output and utilization as buffer capacity increases?

3.4 How much buffer capacity is needed to achieve a production level of 100,000 units a year if there are 2,000 production hours in a year?

Exercise 4 – Impact of Reduced Variability in Complex Systems

Though buffers can help reduce the degree of interdependency in a system and thereby improve output and machine utilization, they unfortunately also increase WIP levels and cycle times (notice the high WIP and cycle times of exercise 3A), which increases inventory carrying costs and customer lead times. A more cost-effective, Lean approach is to focus on reducing variability in the system. Lean advocates favor this approach because it reduces WIP and cycle time while still maximizing output.

Reductions in operation time variability can be achieved through better training and work practices, having a good process control system in place, and utilizing the right equipment and tools for the job.

4A – Comparative Analysis of Decreasing Variability on System Performance

Process performance can be improved in all areas if the variation in operation times can be reduced, even though the mean operation time stays the same. Simulate six production lines, each having 6 workstations, 1-minute operation times and 0 buffer capacity. Start with a variation in operation time of ± 1 min. and reduce it by .2 minutes for each successive simulation and paste your results below.

Questions

4.1 How would you characterize the increase in output and utilization as the variation in operation time decreases?

4.2 Assuming a company having this process currently experiences an operation time variation of ±1 minute, what would the payback period be for a $100,000 investment in training and process improvement to reduce variation by 40% if the added profit per unit is $10.00 and there are 2,000 production hours in a year?

Exercise 5 – Bottleneck Analysis and Management

So far we have been dealing with balanced lines in which each workstation has the same mean operation time and variation. But what if the process has a bottleneck workstation (i.e., one workstation is slower than the others)? How does that change the process dynamics? How can a bottleneck be effectively managed so that it doesn't overly limit the output capacity of the system?

5A – Identifying the Bottleneck in a "Pull" System

Simulate for 10 hours a 6-station production line with zero buffer capacity. Set all operation times to 1±1 minute except station 4 (the bottleneck) which takes 1.2 ±1 minutes. Run 30 replications and paste the results below.

Questions

5.1 An axiom of systems theory states that a system can produce no more than its weakest link and often much less. In this exercise, how does the system output compare to the bottleneck capacity? How do you explain the disparity between the two?

5.2 Run a single replication of the same process and speed up (but don't disable) the animation. Note the utilization statistics displayed on the process layout at the end of the simulation. How do they help indicate which station is the bottleneck?

5B – Identifying the Bottleneck in a "Push" System

Simulate the same production line as in Part A, only change the input buffer capacity for each station to 999. Run 30 replications and paste the results below.

Questions

5.3 What percentage of the bottleneck capacity is the process achieving now and how does that compare with the percentage achieved exercise 5A? How do you explain the increase in output?

5.4 Run a single replication of the same process and note the utilizations and buffer levels at the end of the simulation. How do they help indicate which station is the bottleneck?

5.5 Reset the number of replications to 30 and determine, through trial and error, what the minimum capacity should be for the input buffers of all workstations **upstream** of the bottleneck (including the bottleneck) in order to obtain a system output that is at least 95% of the bottleneck capacity.

(In Theory of Constraints this method of "pulling from the bottleneck" is called drum-buffer-rope (DBR) production. The drum is the pace of the bottleneck which is the limiting factor of what can be produced. The buffer is the WIP upstream of the bottleneck which protects the bottleneck from being starved. The rope ties station 1 to the bottleneck so that once the buffers upstream of the bottleneck become full, station 1 only starts another part when the bottleneck station completes a part. Be sure to leave the input buffer capacities **after** the bottleneck at 999. This is just for protection against ever *blocking* the bottleneck.)

5C – Does the Position of the Bottleneck Matter?

If given the choice, it is often best to have the bottleneck at the beginning of a process. That way WIP is kept to a minimum while still maximizing output, and no DBR system needs to be put in place to control the introduction of parts into the system.

For this exercise run a 6-station simulation with the operation time of station 1 set to 1.2 minutes and all others set to 1 minute. Set the variation for all stations to ±1 minute and all input buffers to 999. Then simulate the process for 30 replications and paste the results below.

Questions

5.6   How are these results any better or worse than 5B where the bottleneck was at station 4 instead of station 1?

5.7   Where in the production sequence would you place the bottleneck station if one of the other stations in the process had a 10% reject rate? (Assume you want to maintain an output that is at least 95% of the bottleneck capacity?)

Congratulations! You have successfully completed this set of exercises in process analytics using ***ProModel Workstation Simulator***.