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Process Analytics Simulation: Solutions

The purpose of the set of simulation experiments that you have just conducted is to examine the effects of variability on production processes. You are presented with two challenges, each of which has four stages (Prepare and Process 1-3) that require you to analyze a specific production process.

We often conduct analyses as if the processing times are fixed and certain. In reality, of course, this is rarely the case. These exercises are meant to provide insight into how uncertainty might change some of the conclusions we might be tempted to draw based on fixed processing times. Despite the numerous simplifications embodied in the schematic models with which you are working, most of the conclusions that you draw can be generalized to complex, real-world processes.

When you analyze the production process, assume it is steady state and that as you begin working at the beginning of your shift, you will be inheriting the process just as it was left by the prior shift. Thus, the production line will likely include work in progress from the prior shift.

Discussion of Challenge 1

Challenge 1, Prepare tab: Questions 1, 2, and 3

Consider a simple, 2-workstation process in which each workstation has a processing time of 1 minute. Assuming there is no uncertainty in the processing times of the 2 workstations (i.e., each workstation always takes exactly 1 minute to perform its tasks before sending the unit on), then:

Question 1: What is the cycle time (in minutes) for this process? Round your answer to the nearest integer.
Question 2: What is the hourly output rate (in units per hour) of this process? Round your answer to the nearest integer.

Professor Robert S. Huckman; Aizan Radzi ((Product Manager - Technology Products–Simulations); and Professors Willy Shih, Roy D. Shapiro, and Michael W. Toffel prepared this exercise with the assistance of Professor Kris J. Ferreira as the basis for class discussion rather than to illustrate either effective or ineffective handling of an administrative situation. The Process Analytics Simulation was created by the Technology Products-Simulations team consisting of Andrew Dugan, Leo Haskin, Daniel Letona, Peggy Nelson, Aizan Radzi, and Craig Tateronis.

Question 3: What is the percent utilization for the two workstations? Round your answer to the nearest integer and enter a number between 0-100.

Solutions to Challenge 1 Questions 1, 2, and 3

In the deterministic case (i.e., without uncertainty) in which all processing times are exactly 1 minute,[1] the line is completely synchronized, meaning that units move into and out of each of the workstations at the same instant. In the steady state, a finished unit leaves the system every minute; the system cycle time is thus 1 minute. Accordingly, the output rate in the steady state is 60 units per hour and workstation utilization is 100%.

Answers	
Question 1:	1 minute
Question 2:	60 units per hour
Question 3:	100%

Challenge 1 Questions 4, 5, and 6

Question 4: The effects of processing time variability

Now consider the process flow diagram shown in Process 1. This is a 2-workstation line with variability in the processing time of each step. Each workstation has an average processing time of 1 minute, but that time can vary by ±0.5 minutes. Processing an individual unit on a given workstation will take between 0.5 minutes and 1.5 minutes. Because this simulation's variability is based on a uniform distribution, this means that the amount of time it takes to accomplish the task at the workstation will vary uniformly around the average of 1 minute (i.e., any processing time between 0.5 minutes and 1.5 minutes is equally likely).

Before running Process 1, how (directionally) would you expect your answers to Questions 1-3 in the Challenge 1, Prepare tab to change?

Question 4 Answer Choices:

A. All three (cycle time, output rate, and workstation utilization) will remain unchanged. Over the long run, any variability in the line will level out

B. All three (cycle time, output rate, and workstation utilization) will increase

C. Cycle time will decrease. Output rate and workstation utilization will increase

[1] To simulate this, you can change the task time for each workstation in Process 1 to 1±0 minutes.

✓D. Cycle time will increase. Output rate and workstation utilization will decrease

Note: Because this question asks students to make an educated guess about what will happen when variability is introduced (prior to having run the simulation itself), students will receive credit for ANY answer choice submitted.

Question 5: The effects of processing time variability (continued)

Now run Process 1 to consider how that compares to your expectations. The simulation will run for the length of an 8-hour work shift. For this first run of the simulation, you might want to set the speed to "Fast."

When the simulation is over, look at the summary statistics in the Line Metrics panel. How do the line metrics (cycle time, output rate, and average utilization) compare to your answers to Questions 1-3 in the Challenge 1, Prepare tab?

Question 5 Answer Choices:

A. All metrics improved: cycle time decreased; output rate and average utilization increased

✓B. All metrics worsened: cycle time increased; output rate and average utilization decreased

Question 6: The effects of processing time variability (continued)

Now run Process 1 again, and this time, don't speed up the animation. What do you observe happening throughout the simulated work shift?

Question 6 Answer Choices:

I. Workstations A and B are sometimes working on their tasks at the same time

II. Workstation A is sometimes blocked. It has completed its task but is waiting on B

III. Workstation B is sometimes starved. It has completed its task but is waiting on A

A. I only

B. II and III

✓C. I, II, and III

D. None of the above

Solutions to Challenge 1 Questions 4, 5, and 6

It is tempting to think that over a long enough period, even in the presence of uncertainty in processing times, "things will average out." As the analysis in Question 5 shows, this is not the case—slow processing hurts us; fast processing only helps in the relatively rare case in which both workstations are simultaneously fast.

As the simulated run for Question 5 shows, both output rate and workstation utilizations are significantly less than in the deterministic case. Running the animated simulation slowly shows visually why this is true—typical scenes are depicted in **Figures A** and **B**. In **Figure A**, Workstation A is *blocked*; it has finished its tasks yet has nowhere to send the unit it has just finished. Workstation B has not yet finished working on its unit and thus cannot accept another. This *material movement discipline*—that one workstation cannot send on a unit that it has completed until the next workstation is empty, and that the first workstation thus cannot begin work on a new unit—is fundamental to an *in-line* process with no work-in-process buffers. Whenever Workstation A is blocked, it must remain idle until Workstation B is finished. Then, and only then, can Workstation A send on its unit and begin work on another. Your simulation shows that this idling consumes more than 14% of its time.[2]

Figure A Workstation A is Blocked by Workstation B

Figure B shows the other side of the coin—the impact of uncertain processing times on Workstation B. Whenever it finishes before Workstation A, it is *starved* and must wait until Workstation A completes its unit. In the interim, it remains idle. For Workstation B, as was true above for Workstation A, this idling consumes more than 14% of the time.

[2] For this very simple process, knowledge of probability theory and some fancy mathematics would allow us to calculate that the utilization is 6/7, or 85.7%, for both workstations and that hourly output rate is 60 x (6/7), or approximately 51 units. Given the statistical variations you would expect in a simulation running for 480 minutes of simulated time, your answers may be a bit higher or lower than these theoretical results.

Figure B Workstation B is Starved

The very nature of uncertain processing times makes it exceedingly rare that the two workstations will finish at *exactly* the same time. In this tightly coupled system, one workstation will nearly always have to wait for the other to finish, and there is no way to "make up" this enforced idleness. That is, things do not average out in the way we might be tempted to expect. The bottom line is that more than 14% of what we might consider *theoretical capacity* (i.e., available capacity if there were no uncertainty) is lost.

Answers	
Question 4:	Any answer
Question 5:	B. All metrics worsened: cycle time increased; output rate and average utilization decreased
Question 6:	C. I, II, and III

Challenge 1 Question 7

Question 7a: Increasing processing time variability
Now that you have some insight into the impact of processing time variability, try investigating what happens with more or less variability. Observe what happens when you keep the average processing time equal to 1 minute but increase or decrease the variability. For example, in Process 1, first click Reset Shift. Then, edit both workstations to set their Time Variation to ±1.0 minute (note: workstation settings cannot be changed while the simulation is running). Once you have increased the variability values for each workstation, from ±0.5 minute to ±1.0 minute, run Process 1. How do line output rate and workstation utilizations differ from what you observed in Questions 5 and 6?

Question 7a Answer Choices:

A. Workstation A will complete its task more quickly, leading to a lower line output rate

B. Workstation B will complete its task more quickly, leading to a higher line output rate

C. The increased variability will balance out, so the average output rate will not change from the ±0.5 scenario.

✓D. Both Workstation A and B will experience reduced utilization, leading to a lower line output rate

Question 7b: Decreasing processing time variability

Now, decrease the processing time variability. In Process 1, click Reset Shift, then change each workstation's Time Variation, from ±0.5 minute to ±0.2 minute. What do you observe?

Question 7b Answer Choices:

A. With reduced task time variability, Workstation A will be blocked by Workstation B more frequently

✓B. With reduced task time variability, one workstation is still blocked or starved for nearly every unit of work

C. The lower the variability, the longer the workstation that finishes first may have to wait for the other workstation to finish

D. All of the above

Solution for Challenge 1 Questions 7a and 7b

The greater the variability, the longer the workstation that finishes first may have to wait for the other workstation to finish. Thus, the greater the variability, the more idle time. The more idle time, the lower the utilization and the lower the average output rate. For the scenario you ran in Question 7a, utilization drops to 75%, and hourly output rate drops to approximately 45 units.[3]

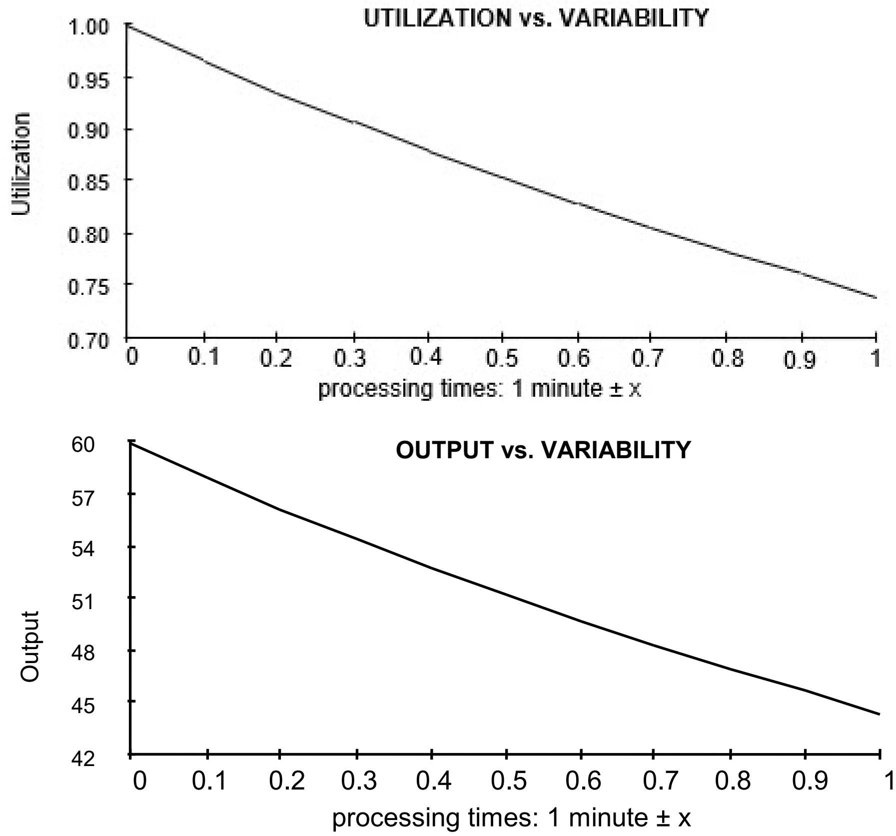
Similarly, as shown by the scenario in Question 7b, *reducing* variability *increases* system performance. Note, however, that even with lower variability, in virtually all instances, one of the two

[3] Again, your results will vary a bit due to the inherent sampling error of the simulation.

workstations is still idle for every unit, but the average length of the idle periods is reduced. With less idle time, the utilization of each workstation rises and the average output rate increases.

Figure C shows plots of the non-linear relationship between the range of processing times (the average remains 1 minute) and both average output rate and utilization.

Figure C Effect of Processing Time Variability on Average Workstation Utilization and Hourly Output Rate for a Two-Workstation Process



Answers	
Question 7a:	D. Both Workstation A and B will experience reduced utilization, leading to lower line output rate
Question 7b:	B. With reduced task time variability, one workstation is still blocked or starved for nearly every unit of work

Challenge 1 Questions 8 and 9

Question 8a: Experimenting with line length

Now that you have experienced how different degrees of variability affect a 2-workstation line, investigate what happens in a longer line. Click on Process 2, which is a 4-workstation line. As you can observe, this is again a balanced line (with respect to average processing times) in which all 4 workstations have processing times ranging from 0.5 minutes to 1.5 minutes.

Before simulating Process 2, what are your expectations (directionally) of the line output rate and average workstation utilization relative to those performance measures observed in Process 1?

Question 8a Answer Choices:

A. Line output rate and average utilization will increase

✓B. Line output rate and average utilization will decrease

C. Line output rate will increase but average utilization will decrease

D. Both will remain unchanged

Question 8b: Experimenting with line length (continued)

Run Process 2 to test your expectations. After first running the process at "Fast" speed, try running it again for a while at a slower speed to observe what is happening. Why does overall performance decline?

Question 8b Answer Choices:

A. A slow Workstation D will block all other workstations

B. A slow Workstation B will starve Workstations C and D

C. A slow Workstation C will block Workstations A and B

✓D. All of the above

Question 9: The effects of variability on long assembly lines

Now look at Process 3, a 6-workstation line, which has the same parameters (i.e., processing times uniformly distributed between 0.5 minutes and 1.5 minutes). Run this process and observe the output rate and workstation utilization.

From your observations of the 2-, 4-, and 6-workstation lines, what generalizations might you draw about the impact of variability on longer assembly lines?

Question 9 Answer Choices:

A. A 6-workstation line's average workstation utilization is higher than that of a 4-workstation line

B. The utilization of the last workstation in a 6-workstation line is the same as the utilization of the last workstation in a 4-workstation line

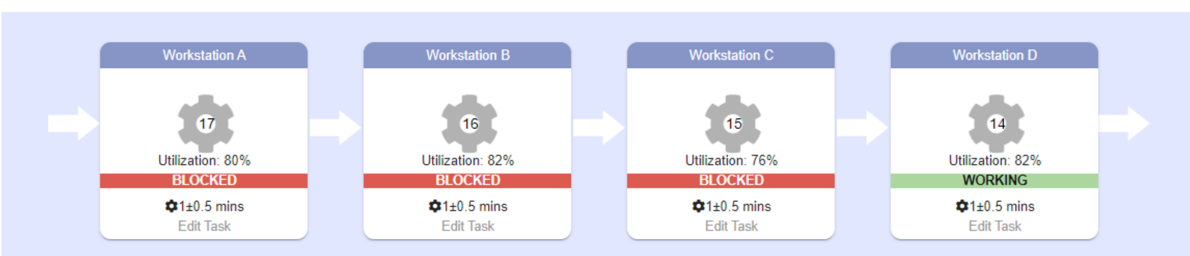
✓C. When multiple workstations are starved, workstations further along the line remain starved for longer

D. All of the above

Solutions for Challenge 1 Questions 8 and 9

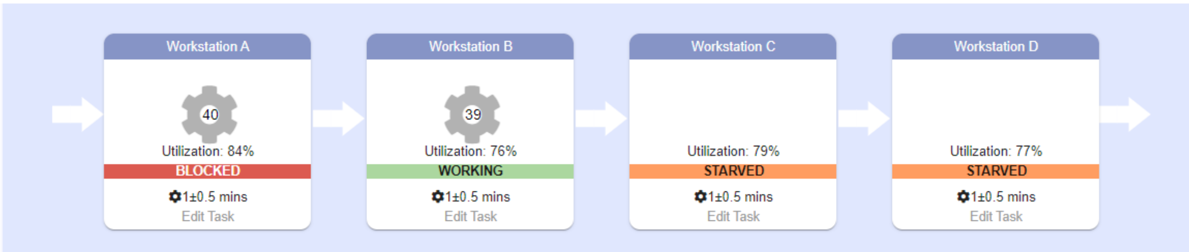
While processing time variability might be considered tolerable for the simple 2-workstation line, it is more of a problem for longer lines. **Figures D–F**, captured while the 4-workstation line was running, illustrate how variable processing times can affect such a line. For example, recall that in Question 5, Workstation A was blocked only when Workstation B ran sufficiently slowly. **Figure D** depicts the kind of extreme situation that can occur when the final workstation in a 4-workstation system runs sufficiently slowly—not only is its immediate predecessor blocked, so are the other two workstations! In particular, Workstation A can be blocked by *any* of the other three workstations. It is no surprise, therefore, that we find it more often blocked than we did in Question 5.

Figure D Workstations A, B, and C are Blocked



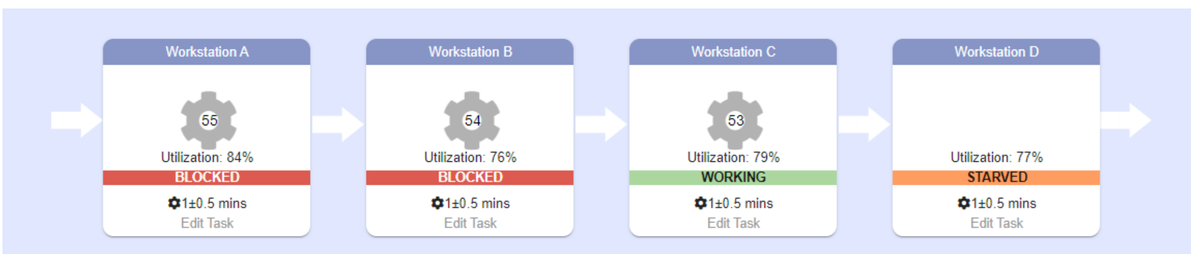
In **Figure E**, we notice the reverse situation. Here, Workstation B is running so slowly that it has starved not only Workstation C, but also Workstation D. Additionally, note that Workstation D will remain idle not only until Workstation B finishes, but also until Workstation C finishes its work on that piece. We can expect Workstation D to have more idle time than the final workstation in Question 5.

Figure E Workstation A is Blocked, and C and D are Starved



Note also from **Figure E**, another complication that can arise here that we never encountered in the 2-workstation model—at the same instant some workstations can be blocked while others are starved. In **Figure E**, Workstation B is apparently running so slowly that it has blocked its predecessor while starving both its successors. **Figure F** shows a similar situation—Workstation C is running so slowly that it has blocked both its predecessors while starving its successor. For a 6-workstation model, the situation is even more troublesome.

Figure F Workstations A and B are Blocked, and D is Starved

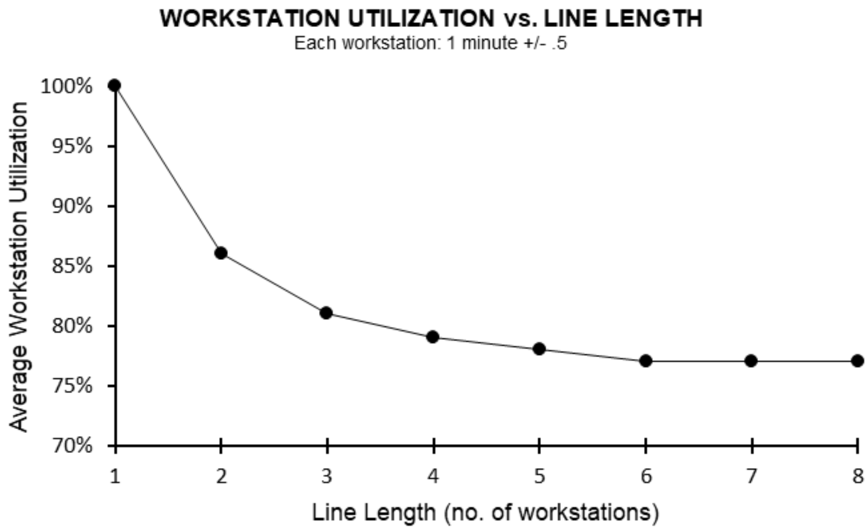


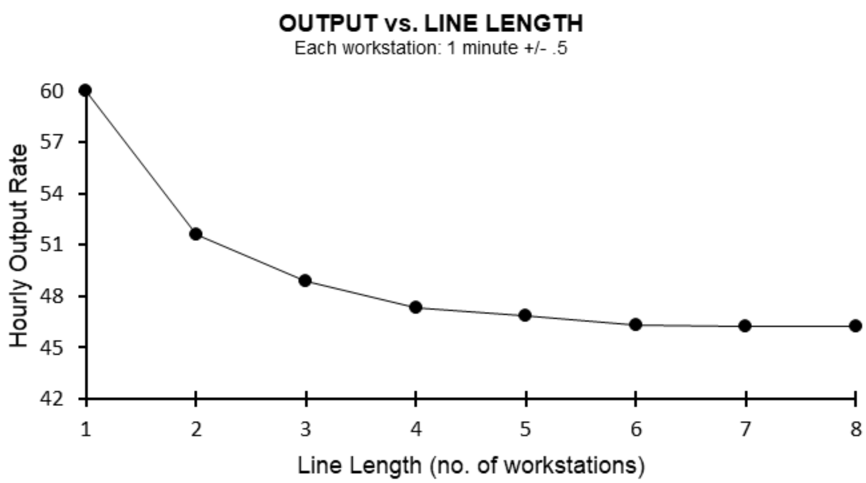
These examples illustrate:

1. the effects of machine interference add up rather than cancel out. There are many more combinations of blocking and starving that occur for longer lines, so more idle time occurs, and
2. for instances in which multiple workstations are starved, workstations that are further along in the process remain starved for longer.

Figure G plots output rate and workstation utilization as a function of the length of the line while all other parameters remain unchanged. The fact that both performance measures drop sharply is now no surprise. What may be surprising is the decrease in performance levels out at 8 to 10 workstations. This is understandable if one were to calculate the likelihood of a situation like that depicted in **Figure D**. In a long line, the probability of one workstation blocking a long string of its predecessors or starving a long string of its successors decreases asymptotically as the length of that string grows.

Figure G Effect of Line Length on Average Workstation Utilization and Hourly Output Rate





Answers	
Question 8a:	B. Line output rate and average utilization will decrease
Question 8b:	D. All of the above
Question 9:	C. When multiple workstations are starved, workstations further along the line remain starved for longer

Challenge 1 Question 10

Question 10a: Experimenting with unbalanced lines

For all processes 1, 2, and 3 above, the lines have on average been balanced (i.e., the mean Task Times have been identical). Let's investigate a simple unbalanced line.

Return to Process 1. How would you expect line output rate and average workstation utilization to change if we could speed up or slow down the Task Time (without changing its Time Variation) of only one workstation?

Start experimenting by clicking Reset Shift. Then, edit Workstation A to make it twice as fast as B, so that the mean processing time (Task Time) is only 0.5 minutes—but maintain ±0.5-minute variability—and run the process (note: it will be useful to run the process for some time at a slower speed). Afterwards, reverse the settings so that Workstation B is twice as fast as A.

Question 10a Answer Choices:

A. Speeding up Workstation A will reduce its utilization rate

B. Speeding up Workstation B will reduce its utilization rate

C. Speeding up either workstation will shift the line's bottleneck

✓D. All of the above

Question 10b: Bottlenecks in operations
Following your findings from Question 10a, which of the following statements is correct?

Question 10b Answer Choices:

A. Speeding up either workstation increases the line output

B. Speeding up either workstation increases the utilization of the other workstation

✓C. Both A and B are correct

D. None of the above

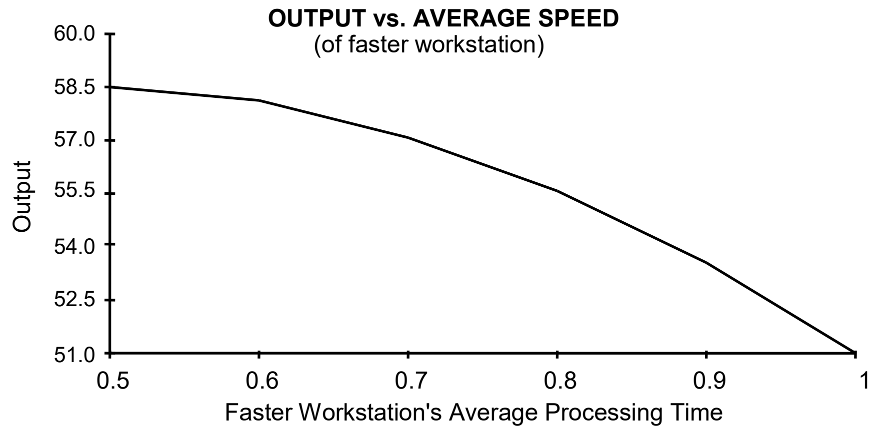
Solution for Challenge 1 Question 10

In our analyses of assumed-to-be-deterministic assembly lines earlier in the course, we noted that speeding up non-bottleneck operations has no effect on cycle time and therefore no effect on output rate. Indeed, speeding up non-bottleneck operations in a deterministic line simply creates more idle time for the operations being sped up. It is not surprising, therefore, that we only focused on improving the performance of the bottleneck operations.

As your analysis of this question shows, it is more complicated in the presence of uncertainty. With uncertain processing times, it is possible that the operation that is faster *on average* could—for any particular unit—be slower and, hence, temporarily be the bottleneck. In other words, in the presence of uncertainty in processing times, the bottleneck can shift from unit to unit. Thus, as we notice in this analysis that there can be benefit to speeding up a workstation that on average is not the bottleneck if, depending on variability, such a workstation may block or starve the workstation that is on average the bottleneck.

In particular, for our 2-workstation model, speeding up one workstation allows the other to run at closer-to-full utilization, as the slower on average workstation is less frequently blocked or starved by its faster on average partner. However, as the bottleneck workstation gets closer and closer to 100% utilization, speeding up the other workstation has diminishing effect, just as we had come to expect in the deterministic case. The non-bottleneck operation just becomes increasingly idle. **Figure H** shows the effect of various amounts of "speed up" on the hourly output rate.

Figure H Effect of Fastest Workstation's Average Processing Time on Hourly Output Rate



Answers	
Question 10a:	D. All of the above
Question 10b:	C. Both A and B are correct

Discussion of Challenge 2

In Challenge 1, you observed the negative impact that variability has on the performance of a tightly coupled line as measured by the decrease in workstation utilization and, consequently, in output rate. In this second set of exercises, you will explore the effects of reducing that negative impact – *decoupling* the line by adding work-in-process inventory buffers between workstations. You will also begin to compare the benefits of decoupling to those of reducing variability directly.

This exercise starts with the simple 2-workstation processes of Challenge 1, Process 1, and asks you to investigate the impact of a work-in-process buffer placed between the two workstations, as well as the impact of buffers of varying sizes. You will also return to longer lines and investigate both buffer location and size.

Challenge 2, Prepare tab: Question 1

Question 1:
Consider the 2-workstation process that you worked with in Challenge 1, in which both workstations had a mean processing time of 1 minute and a uniform distribution of variability between 0.5 minutes and 1.5 minutes. Recall the output rate for an 8-hour period as well as the utilization for the two workstations. Before running any simulations in Challenge 2, what do you expect would be the effect of allowing work-in-process inventory to be stored between the two workstations?

Question 1 Answer Choices:

A. No change from Challenge 1, Process 1

B. Workstation A utilization improves, but Workstation B utilization suffers

C. Workstation B utilization improves, but Workstation A utilization suffers

✓D. Both workstations will show improvements in their utilizations

Challenge 2 Question 2

Question 2: The effects of a work-in-process inventory (buffer)

Click on Process 1, which is a 2-workstation line in which the mean processing time is 1 minute, the processing times range from 0.5 minutes to 1.5 minutes, and there is a buffer of size 1 between the two workstations. Now run the simulation. What happens and why?

Question 2 Answer Choices:

A. No change – a buffer of size 1 is insufficient to improve overall performance

B. The buffer improves Workstation A utilization by minimizing blocked occurrences

C. The buffer improves Workstation B utilization by minimizing starved occurrences

✓D. The buffer improves the utilization for both workstations by minimizing blocked and starved occurrences

Solutions to Challenge 2 Questions 1 and 2

After your experience with Challenge 1, it is probably no surprise that even a single-unit buffer between the two workstations noticeably reduces idle time. When the buffer is empty, Workstation A cannot be blocked. When the buffer is full, Workstation B cannot be starved. Hence, the utilization for both increases. Because the buffer can hold at most one unit, this increase is limited: both workstations are still idle 6% of the time, in contrast to 14% for the tightly coupled line. Hourly output rate rises 10% from 51 to 56.[4]

Answers

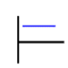
[4] As was pointed out in the discussion of Challenge 1, there is some sampling error inherent in any simulation. Hence, throughout these exercises, your numbers may very well be a bit higher or lower than the estimates presented here.

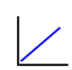
Question 1:	D. Both workstations will show improvements in their utilizations
Question 2:	D. The buffer improves the utilization for both workstations by minimizing blocked and starved occurrences

Challenge 2 Question 3

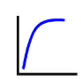
Question 3: Experimenting with buffer capacity
What is the relationship between output rate and buffer size? You have already simulated processes and observed the output rate for a 2-workstation line with either no buffer (per Challenge 1, Process 1) or a buffer of size 1 (per Challenge 2, Process 1). In Process 1, first click Reset Shift. Then, edit the buffer and re-run the simulation with progressively larger buffers. For example, run the simulation with buffer size 2, then 5, then 10, etc. Plotting the hourly output rate on the vertical axis versus the buffer size on the horizontal axis will yield:

Question 3 Answer Choices:

A. A horizontal straight line 

B. An upward sloping straight line 

C. An upward sloping line where the slope is increasing 

✓D. An upward sloping line where the slope is decreasing 

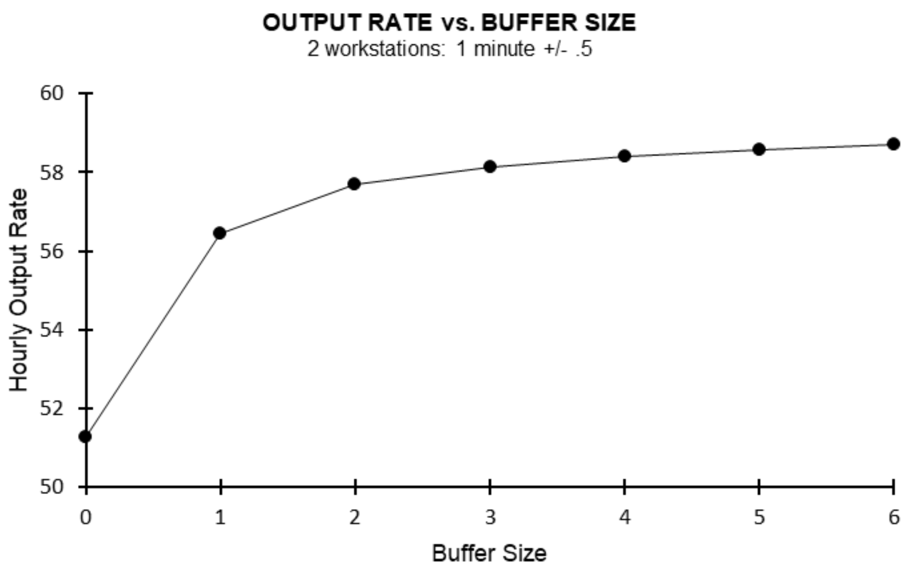
Solution for Challenge 2 Question 3

Figure I depicts the relationship between buffer size and output rate. Output rate continues to increase as buffer size increases, but not surprisingly, with decreasing marginal returns. The speed with which this curve flattens out depends on the processing time distributions. If there were substantially more variability in those times, the curve would flatten out more slowly.[5] In this case, the

[5] For example, instead of the uniform distribution that we have been using, we might more realistically draw process times from a probability distribution shaped like this:

pace of output rate improvement declines rather quickly with each incremental unit of buffer size—increasing buffer size above three or four units has limited impact on output rate.

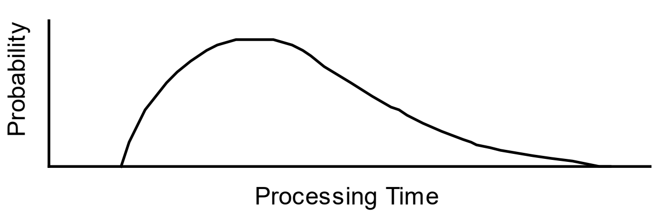
Figure I Effect of Buffer Size on Hourly Output Rate for a Two-Workstation Process



Answer	
Question 3:	D. An upward sloping line where the slope is decreasing

Challenge 2 Question 4

Question 4: The effects of buffers on longer lines
Examine what happens when you include buffers as you move to longer workstation lines. Specifically, investigate the impact of placing buffers in a 6-workstation line.



where the long tail indicates some small probability of a disruption in the process (e.g., machine downtime) that would substantially lengthen the processing time. In this case, the benefit of larger buffers might be significant.

> Click on Process 3, a 6-workstation line with a mean processing time of 1 minute and a range of 0.5 minutes to 1.5 minutes, with buffers of size 1 placed between all successive workstations. Run the process and observe average workstation utilization and total output rate. How do they differ from the results observed in previous processes?

Question 4 Answer Choices:

A. In a 6-workstation line, buffers improve utilization. That is, Challenge 2 Process 3 utilization metrics are better than those in Challenge 1 Process 3

B. A 6-workstation line with buffers has a lower average output rate than a 2-workstation line with a buffer, assuming the buffer sizes are the same. That is, the average output rate of Challenge 2 Process 3 is lower than that of Challenge 2 Process 1

C. As line length grows, installing buffers of a given size between each workstation yields smaller improvements in the average output rate

✓D. All of the above

Solution for Challenge 2 Question 4

The effect of buffers on a 6-workstation line is similar to how buffers affect a 2-workstation line. As we increase the buffer size, we again observe the same decreasing returns. The relationships in all three options are observable by running those scenarios several times in the simulation.

Answer	
Question 4:	D. All of the above

Challenge 2 Question 5

Question 5: Experimenting with buffer location
Now consider a 4-workstation line. If you could create one (and only one) buffer with a size of 4 units, where would you place it? To check your intuition, click on Process 2 and edit the process to vary the size of each buffer. Start by placing a single 4-unit buffer between Workstation A and B, without any other buffers (i.e., edit to set all other buffers to size 0).

Question 5 Answer Choices:

A. Between Workstation A and B, as this will yield a higher average output rate than the other choices

✓B. Between Workstation B and C, as this will yield a higher average output rate than the other choices

C. Between Workstation C and D, as this will yield a higher average output rate than the other choices

D. A buffer in any of the three positions above will yield the same average output rate

Solution to Challenge 2 Question 5

Your analysis above shows that not only is buffer size an important consideration in designing a line, but so is buffer *location*. If we are constrained to using only one buffer, the best place to put it is in the middle of the line, effectively decoupling the line into two smaller lines, each half the length of the original. For the 4-workstation system:

– 4-unit buffer between Workstations B and C: output rate ~ 51 units/hour
– 4-unit buffer between Workstations A and B (or between Workstations C and D; due to the symmetry in the line, the two situations have identical results): output rate ~49 units/hour

The logic behind this result is as follows. Our choice is basically whether to use the buffer to decouple the line into:

i. two 2-workstation lines, or
ii. one 1-workstation "line" and one 3-workstation line.

We have observed that a line is only as good as its worst (i.e., bottleneck) operation. Similarly, a line composed of two decoupled smaller lines is only as good as its worst part. From Challenge 1, we know that in the presence of variable processing times, a tightly coupled 3-workstation line is worse than a tightly coupled 2-workstation line. Hence, alternative (i) above, which should act like a 2-workstation line, is better than alternative (ii), which should act like a 3-workstation line (i.e., its worst part).

Answer	
Question 5:	B. Between Workstation B and C, as this will yield optimal average output rate

Challenge 2 Questions 6 and 7

Question 6: Experimenting with buffer capacity distribution
Following your findings from Question 5, if you could instead create buffers at any or all of the three possible positions in Process 2, subject to the constraint that the total buffer size cannot exceed 4 units, how would you allocate the buffer(s) to maximize output rate?

Question 6 Answer Choices:

✓A. Place a buffer of size 1 between A and B, a buffer of size 2 between B and C, and a buffer of size 1 between C and D

B. Place a buffer of size 2 between A and B, and another buffer of size 2 between B and C

C. Place a buffer of size 2 between A and B, and another buffer of size 2 between C and D

D. Place a buffer of size 2 between B and C, and another buffer of size 2 between C and D

Question 7: Lessons learned
What general lessons can you infer from these observations? Please provide a scenario in which the insights you gained throughout this exercise (Challenges 1 and 2) can help you become a better manager.

Solutions for Challenge 2 Questions 6 and 7

We can now relax the constraint that all four units of buffer size be placed in one location. In this case, we are far better off splitting the four units as equally as possible. Any remaining buffers, by the logic above, should go in the middle. Thus, we place 1-unit buffers between workstations A and B and between workstations C and D, and a 2-unit buffer between workstations B and C. This decouples the line as much as possible. Comparing several alternatives yields the following results. Your results will vary a bit due to the inherent sampling error of the simulation.

Buffer Sizes (e.g., 1st, 2nd, 3rd)	**Weekly Output**[6]
1,2,1	2225
2,1,1 or 1,1,2	2220
2,0,2	2050
3,0,1 or 1,0,3	2045
0,4,0	2030
4,0,0 or 0,0,4	1950

The ranking of these alternatives follows from: 1) the decreasing marginal impact presented in **Figure I** (i.e., the second unit of buffer size is less effective than the first; a fourth unit carries almost no benefit in this case), and 2) the fact that, if buffers of different sizes are to be placed, putting more in the middle of the line is better than putting more elsewhere. These observations are generalizable to longer lines.

Answer	
Question 6:	A. Place a buffer of size 1 between A and B, a buffer of size 2 between B and C, and a buffer of size 1 between C and D

[6] Your results will vary a bit due to the inherent sampling error of the simulation. Outputs are reported as weekly (i.e., 40-hour totals) to illustrate differences between configurations that would be more subtle when measured in terms of hourly output rate. For example, the hourly difference between 1,2,1 (55.6 units) and 2,1,1 or 1,1,2 (55.5 units) is quite small. Nevertheless, over a longer period of time, the first configuration will, in fact, generate a higher output rate than the latter two.