Classroom Exercise Demonstrating Productivity and Quality Relationships

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Introduction

Simple models are often used when teaching operations management courses. These include, but not confined to, the Beer Distribution Game (Sterman, 1989) to illustrate the bullwhip effect of miscommunication through the supply chain, simple MRP models for ordering parts for sub assemblies (Swink, et al., 2011), the Monty Hall game to illustrate risk (Umble, 2001), and Economic Order quantity models for finding the optimal order quantity when placing orders.

Modeling is a specialized art as well as a solely human ability that is used to bridge the gap between a person's innate abilities to simplify and understand their world through an abstraction process (Powell, 2001). In his, *The Search for Solutions (1980)*, Judson notes that "model making is a profound and instinctual human response to understanding the world." He goes on to state that children are modeling when they take on adult roles in their play, adults are modeling when they use maps, political labels such as "Liberals" to describe politicians, or choose an investment based on an informal assessment of risk. Senge (1990) stresses the use of models to facilitate team building.

Models are prescriptive or descriptive. Prescriptive models are used to determine optimality and include a number of models used in operations management. Notable among these are the Economic Order Quantity, Make-or-Buy decision, and decision trees (Swink, 2011). Other models are descriptive models, whose purpose is primarily to describe a process(Powell, 2001).

The exercise described here is basically a descriptive model, part of which is contrived to be prescriptive in a hypothetical situation to be utilized for illustration purposes to suggest a potential application. It should be pointed out, however, that the primary purpose of the model presented here is to demonstrate fundamental concepts through a highly abstracted physical model. Nevertheless, through this abstraction the student might be better able to internalize concepts that have potential application than if they were presented solely in a text or lecture format. This learning process can be an even more powerful tool when the student has the opportunity to tweak the model to see how it responds to varying conditions.

The model presented here is used to demonstrate how productivity and quality can be simultaneously improved. Another concept illustrated by the model is the dynamic nature of optimal solutions. An additional feature of this exercise is the opportunity to enhance students' teamwork skills.

Exercise objectives

The objectives of the exercise are mutually exclusive and can be used on a stand-alone basis:

1. To demonstrate how productivity and quality can be simultaneously improved in an assembly line operation.

2. To demonstrate optimality dynamics

3. To facilitate students teamwork skills

Development of the physical model

If one were to send a group of students to a factory producing goods in a product (assembly line) layout and ask them to develop a mathematical models representing the basic processes, they would probably return rather frustrated with their inability to even know where to begin in developing reasonable mathematical equations representing that process. However, if one were to abstract what takes place in an assembly line to a simple physical model, then that model might more readily be converted to a mathematical model(s) that represents or simulates the simple physical model. As a reality check one could then determine, at least intuitively, whether the mathematical model provides at least a reasonable conceptualization of the original physical phenomena, which in this case would be an assembly line.

In examining an assembly line and abstracting the essence of the process, it might be viewed as a series of work stations where certain processes are performed before the work in process moves to the next work station and so on until the final product emerges. For example, the manufacture of an automobile might begin with the frame, and as it moves through each stage, various components are added, such as the engine, transmission, body, etc. If a defective component is detected at a downstream operation, then sub components from at least some of the previous processes must be removed before the defective components can be replaced with the defect-free sub component. Following this, the other sub components must be then replaced in their designated order. Although this is not precisely what always occurs, it will be considered sufficient here for the purpose of constructing a simple physical model.

The quality aspect of the model is presented in abstracted terms by using the traditional (albeit somewhat archaic in light of some modern manufacturing applications) method in which the product is first produced and then receives a final inspection. It is recognized that more haute methods are ones in which the production and quality processes are often intertwined.

In using the illustration of the hypothetical automobile assembly as a reference, a simple physical model for the assembly process was abstracted to a situation of making a string of beads. The beads are in a container containing about 10% defective beads. Defective beads are those containing a small dab of correction fluid. This can be considered to reasonably represent a defect because it can be detected only upon close inspection from someone looking specifically for defects, such as an inspector. The production worker, who focuses on putting the beads on as fast as possible, is generally likely to overlook these subtle defects as well as occasionally incorrectly keep track of the requisite number of beads to go on each string.

The physical model, then, consists of a production worker making strings of beads followed by final product inspection. Upon finding a defective bead, the inspector must remove all the beads down to the defective bead, put a defect-free bead on the string, and then replace the beads that were removed to result in a defect-free product. The inspector must also count the beads to be certain that the correct number of beads were placed on each string. Although the production worker is also supposed to count the beads, the inspector serves as a final check in this part of the quality assurance process.

To operate the model, there must be a production worker, an inspector, a person to record the production time, and a person to record the time the inspector's time. Although the model usually requires at least four people to conduct the simulation, any additional group members can devote their time toward developing the equations used to calculate the required output from the model.

Simultaneously Improving Productivity and Quality

If one were to ask a typical causal observer about the relationship between productivity and quality, they would most likely state the common sense notion that improving productivity would result in a deterioration of quality. Additionally, they are likely to state that improving quality can only be done at the expense of productivity. Inherent in their association is likely to be the narrow concept of productivity being equal to output per hour. Productivity, as most operations professionals realize, is generally viewed as a ratio of output and input, and in the more general sense is presented as the ratio of these two variables which will present the largest number. This is often done to facilitate ease of interpretation, as numbers greater than one are often more readily comprehended than are decimal numbers. In this exercise, the productivity ratio used is output divided by input because it is more likely to result in numbers greater than one. The sections below will briefly discuss the concept of productivity and quality as used in this exercise:

Productivity

Productivity is typically defined as an index of the ratio of output divided by input (Sink, 1985; Chase et. al. 2006), although sometimes it might be expressed as the ratio of output divided by input in situations where it is more likely to result in a number greater than one. For example, suppose a company produced 25 units of product. The expenses include two hours of labor at $25 per hour and materials cost of $50 for a total cost of $100. The selling price of each unit is $40. The total productivity would be the revenue divided by the total cost, as illustrated below:

$$\text{Productivity} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Revenue}}{\text{Cost}} = \frac{(25\text{ units})(\$40/\text{unit})}{(\$25/\text{hour})(2\text{ hour}) + \$50} = 10 \qquad (1)$$

The above productivity figure is an index and can be interpreted by stating that each dollar of output is *associated* with each dollar of input. It is important for the student to understand that this index is merely an association and should not even imply that a cause and effect relationship exists. Indeed, it is impossible to prove a cause and effect relationship purely on mathematical grounds.

The above illustration is a measure of total productivity, in which total output is compared against total input. Productivity can also be described as a partial measure by using one or fewer input components against the total output. For example, labor productivity in dollars and labor productivity in hours would be as follows:

$$\text{Labor Productivity in dollars} = \frac{\text{Revenue}}{\text{Labor cost}} = \frac{(25\text{units})(\$40/\text{unit})}{(\$25/\text{hour})(2\text{ hour})} = 20 \quad (2)$$

$$\text{Labor Productivity in hours} = \frac{\text{Revenue}}{\text{Labor hours}} = \frac{(25\text{units})(\$40/\text{unit})}{2\text{ hours}} = \frac{\$500}{\text{hour}} \quad (3)$$

In equation (2) the interpretation would be that each $20 of revenue is associated with each dollar of labor cost and in equation (3) each $500 of revenue is associated with each hour of labor.

Both the output as well as input units for productivity in this example could also be expressed in units. For example labor productivity can be expressed as units of output per labor hours, as illustrated below:

$$\text{Labor productivity in units} = \frac{\text{Units of output}}{\text{Units of labor}} = \frac{25\text{ units}}{2\text{ hours}} = \frac{12.5\text{ units}}{\text{hour}} \quad (4)$$

<u>Quality</u>

Although there are numerous ways to measure quality, the method used in this exercise will be on an attribute basis in which a product or sub component is either defective or defect-free. In this exercise, the type of quality assurance pertains to conformance quality. In this manner, the inspector serves not only in an inspection capacity but is further assigned the role of rework as well, and these two activities are subsumed in the role of inspection. The mathematical models in this exercise are derived from the physical bead-stringing model.

The data needed for the model are as follows:

1. Hourly pay for the production worker (HP)
2. Hourly pay for the inspector (HI)
3. Number of minutes to produce 15 strings of beads (PM)
4. Number of minutes to inspect 15 strings of beads (IM)
5. Number of beads per string (BPS)
6. Cost of each bead (CPB)
7. Selling price for each string of beads (SP)
8. Cost of the wire for each string (CPW)
9. Total strings of beads produced (ST)
10. Total units produced in a production run
11. Cost of defect-free beads from supplier (CDFB)

The information produced by the model is presented below:

1. Total Productivity in dollars = <u>Revenue</u> (5)

one containing a white dot that is almost the same color as the bead. Like defects in a real world situation, the inspector must look carefully for the defective beads. The beads used for the stringing contain about 10% defectives. However, the supplier has recently offered to sell beads that are guaranteed to be defect-free for $0.10 each. Would your group accept the supplier's offer?

To enhance their math as well as team skills, it is important that each group learns on their own how to calculate the information needed for the data table below. To do this, only the orientation regarding the measurement of productivity need be given to the class prior to conducting the exercise. The author has found only a very small percentage of groups who were not able to eventually develop the equations upon collaboration among their members. As part of the team building aspect of the exercise, those team members who grasp the logic of the equation must teach the other team members so that every member in the group understands what has been presented. This can be tested by instructor by giving a short quiz to the class in which each class member must individually perform the calculations from a new set of data.

Post Exercise Teaching Points

Upon completion of the exercise, which most groups finish in about 45 minutes, the instructor should have a discussion of the results. To facilitate this, each group can put their results on the overhead. An Excel file has been found useful to do this and a sample tableau is presented in Figure 2 below:

Figure 2 Recap Sheet for Productivity and Quality Exercise

	Container #			
	1	**2**	**3**	**4**
Total Productivity (nearest one hundredth)	**2.10**	**1.88**	**2.25**	**1.54**
Labor Productivity as Revenue/Total Labor Hour Hint: Greater than 100 (Nearest integer)	**$287**	**$225**	**$338**	**$157**
Cost of Quality/String (Nearest cent)	**$1.73**	**$2.17**	**$1.44**	**$3.11**
Cost of Quality/Bead (Nearest cent)	**$.09**	**$0.11**	**$0.07**	**$.16**
Buy defect-free Beads (Yes or No)	**Yes**	**No**	**Yes**	**No**

The three objectives of the exercise are discussed below:

Simultaneous Improvement of Productivity and Quality

The instructor should first determine whether all groups have accurately presented their results. Most groups should have been able to do that within the 45-minute time allotment, and groups that have not can quickly see if their results match the majority of the other teams. When this happens, it usually takes them only a few minutes to see the error of their ways.

The exercise has been carefully calibrated to contain about 10% defects such that some groups would find it economically feasible to accept the supplier's offer while others will not. Adjusting the price at which the supplier would be willing to offer defect-free beads also helped calibrated the exercise to assure that not all groups would accept the supplier's offer. This is important toward explaining that an optimal solution in the real world is usually not static, but is one that depends upon dynamic events which can change rapidly and hence often need to be continuously reviewed and possibly updated.

After viewing the results, the class will generally conclude that there are two ways of getting defect-free beads. One way is for the company to purchase beads with defects and then get strings with no defect beads through their own inspection. Nevertheless, this process is not 100% effective because some strings with defects might manage to get through the final inspection. The other way to get defect-free beads is to purchase them from the supplier but at a higher cost per bead. Implied in this is the fact that the supplier's guarantee will cover any costs incurred by the Bead Stringing Company if any defects get through and are detected by the customer. Upon examining their results, the students can see that the total cost for the company to get defect-free beads internally is to add the cost of inspection per bead to the purchase price of the bead and then compare it to the supplier's offer for defect-free beads. As soon as everyone in the class understands the above points, they should realize (or have it pointed out to them) that if it is cost effective to buy the defect-free beads from the supplier, they should do so because now there is also a guarantee behind purchasing the defect-free beads. They should be able to conclude that purchasing the defect-free beads would improve the quality of the bead stringing process as a result of this guarantee.

In the next part of this part of the discussion, those groups whose results indicate that they would purchase the defect-free beads should now recalculate their total productivity using the cost of the defect-free bead from the supplier and eliminating the inspector. They will not need to conduct the exercise again to do this. After doing this, they should conclude that their total productivity has now increased because it is no longer necessary to have an inspector, even though the cost of the beads has increased. As a result, productivity and quality have simultaneously increased. While making this conclusion, however, some of the more alert students will point out that the beads will still need to be counted and this will incur an expense. Although this should be a point well-taken, it should be mentioned that upon purchasing defect-free beads, acquiring an automatic counting device, such as a used pill counter or simply having the production person use a ping-pong paddle with 20 holes drilled just big enough to keep the smallest bead from falling through, can now be used to quickly and economically count the beads. Further discussion regarding this idea should also conclude that either of these two methods could have been applied even when using beads that contained defects, as individual counting of the beads is likely to be more costly and contains the probability of errors. At the end of this discussion, the instructor should point out that the exercise has also been a demonstration of the lean manufacturing of quality at the source, in which defects should be corrected at the point of discovery whenever possible. (Liker, 2004).

An important feature regarding the use of models that should also be discussed is the effect of tweaking the model. In this exercise, the tweaking of the model does not come from a given group conducting the exercise over a given set of conditions, but instead is the result of comparing different groups' results from the same exercise. Although model construction is important, tweaking the model often results in the best insights into the model processes.

A final consideration of the model is to compare its results to what one might expect in a real world situation under the same basic conditions to determine the practicability of the model. Class discussions have generally concluded that it would, indeed, at least reasonably represent what one might expect in a typical assembly line under the specified conditions. Students are often quick to conclude that suppliers usually know more about their product than the manufacturer, and are often in a better position to be more cognizant of the quality aspects of the products they are providing to their customers. Further, the results of the model have the advantage of helping students think out of the box to conclude that it is possible to simultaneously improve quality and productivity and that there might be even more ways in which productivity and quality can be simultaneously improved.

Dynamics of Optimization

Another point to be brought out in the discussion is for the instructor to ask the class what is the *fundamental driving factor* of the bead stringing process that determines whether or not to purchase the defect-free beads. This usually results in a number of groups needing to huddle regarding this question. Many will observe that groups with lower levels of labor productivity are associated with the willingness to accept the buyer's offer for defect-free beads. This should be logical to them because longer times to inspect each bead will result in higher inspection cost per bead, thus making the supplier's offer increasingly attractive. In this exercise, it should be pointed out that the production worker's productivity and inspector's productivity are intertwined because the rate at which the inspector can inspect the beads will be dependent on the rate at which the strings are produced. In this situation, having a faster inspector might not improve the overall labor productivity because inspection time might to some extent be affected by the speed of the production worker if the inspector inspects each string after it has been produced.

A concluding point that the instructor should make pertains not only to the interaction effect between the inspector and production worker, but should also include the fact that any optimality derived equation should be studied carefully to determine the most significant factors driving that optimality. For example, using a faster production person and or inspector might improve the productivity to the point where it might be more economical to reinstate the inspector if warranted by the increase in labor productivity.

Development of Teamwork

It is generally considered beneficial whenever a class exercise has the potential to enhance student teamwork skills. In order for this exercise to be conducted effectively, all group members must work together as a team. In addition, the group members must pool their math skills to answer the questions. If instructors wish, they can construct a questionnaire for group members to evaluate their group experiences. The instructor can usually get a reasonable idea regarding the effectiveness of the group process by giving the class a short quiz in which each student must perform a set of calculations using different data than that used for their exercise. If the team has followed instructions to be certain that all group members have learned how to perform the calculations of the exercise, then most, if not all, members of that group should do well on the quiz. In this way, the effectiveness of the team has perhaps undergone a more rigorous measure which has been associated with an outcome measure than a self-reporting survey, which is typically done to measure team performance.

Model Enhancements

It is often a more beneficial and perhaps more efficient learning tool if an exercise can be used to demonstrate several concepts. Additional concepts that have been included in the bead stringing exercise pertain to alternate production methods and learning curve. Each of these is briefly discussed below:

Alternate Production Methods

This model might be enhanced by using an additional production method for comparison purposes. In addition to the classical method described in this paper, an alternate method has been one in which the inspector pre-inspects the beads and counts (manually or with a device) the required number of beads prior to the production process. This would correspond more closely with many production processes used today. Doing this would eliminate the need for the production worker to count the number of beads while putting them on the string and would also allow the inspector to work continuously without having to wait for the production worker to finish a string before it can be inspected. Each group can then compare the productivity between these two methods. However, because of the learning curve effect, which will serve to improve both the inspector's as well at the production worker's productivity, it might be best to have the time keepers switch roles with the production workers and inspectors when adding this to the exercise. The author has found about a thirty percent improvement in total productivity and labor productivity using this method to produce the strings.

Learning Curve

The learning curve is a concept often taught in operations management courses but is often not illustrated with hands-on models. This exercise can easily be expanded to demonstrate the learning curve by collecting the specific times to string bead numbers 1, 2, 4, 8, 16, 32, 64, 128, and 256. The learning curve percentage can be determined by trial and error to see which learning curve percentage provides the best fit and then plotting the results. It has been interesting to compare the range of learning curve percentages among the various groups and attendant learning curve percentage with the labor productivity of each group. The author has found that production workers and inspectors with higher learning curve percentages tend to be in groups that found it economically acceptable to purchase the defect-free beads. As discussed above, groups with lower productivity performances expended more time and, therefore, expenses in the inspection process, which resulted in their accepting the supplier's offer for defect-free beads.

Conclusion

References

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