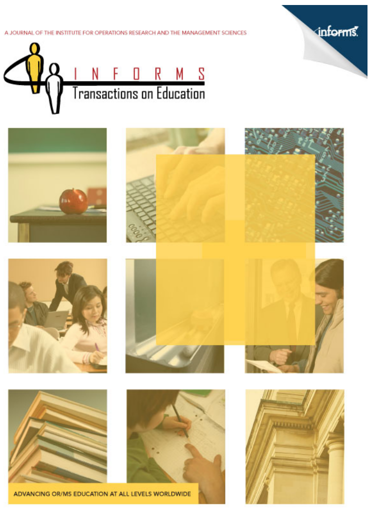

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Case Article

Process Control and Design of Experiments/ANOVA

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Process control and design of experiments are two important concepts that business students must learn, as a proper usage of these techniques can have a significant impact on a firm's bottom line. Moreover, these ideas can be successfully used in a variety of application contexts: Process control applications range from the manufacturing of automobiles to the management of call centers, whereas design of experiments is used for process, product, and policy design. This set of two cases discusses operational improvement initiatives using these methods at a fictitious semiconductor manufacturing company that is being pressured by one of its major customers to improve quality. The first of the two cases covers process control charts, process capability, and a trade-off analysis between product quality improvement and new equipment leasing costs. The second case covers design of experiments and analysis of variance (ANOVA). Both cases require hands-on analysis and can be used in both undergraduate and graduate business programs.

Key words: process control charts; process capability indices; six sigma; design of experiments (DOE); interaction and main effects
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1. Background

Process control and improvement are among the most useful concepts that business students learn in an introductory statistics or an introductory operations management class. In my experience, almost all students, regardless of their career interest, find these topics appealing and want to gain a deeper understanding of these concepts. Students also find the tools needed for implementing these initiatives to be interesting and often ask for additional reading material and practice problems to get a more solid grounding in these concepts. The main reason for developing the first of this set of two related cases was to satisfy these student needs. Another reason was that in 2000, the Katz Graduate School of Business initiated the "Best Practice Partnerships" program. Under this program, to make our courses more rigorous and relevant, each core MBA course was partnered with a leading company globally renowned for its business practices in the topics covered in the course. I was an instructor for the core MBA statistics course when the program was launched and worked with Motorola—one of the companies with which the 1980s quality revolution in the United States is commonly associated. Dr. Skip Weed, formerly of Motorola University (the education arm of Motorola), was the executive faculty for the statistics course. As executive faculty, he lectured on the quality improvement programs at Motorola, Motorola's Six Sigma program, and the use of statistical process control at Motorola. (The best practice program has evolved since that time, and we have a different best-practice partner now.) Two years after the partnership with Motorola began, I thought it might be useful to develop a case related to the talk to better integrate it with the course. Dr. Weed suggested semiconductor manufacturing as the backdrop for a case on control charts and provided a short description of the production process. As I was developing Case 1, I realized that focusing only on control charts might be too limiting. I expanded the scope to also include capability indices and cost-benefit analysis of leasing equipment capable of producing a better-quality product. Keeping the same context, I wrote Case 2 a few years later for discussing analysis of variance (ANOVA) and design of experiments. The data in the cases are fictitious but realistic. Both cases have undergone some changes over the years.

At around the same time as when the Best Practice Program was developed, the Katz School decided to organize the incoming MBA students into Management Learning Organizations (or MLOs). MLOs were groups of 12 students who worked as a team on large projects during their MBA program in some courses (although not in the statistics course). For smaller class projects, the MLOs were split into three teams of about four students each. I assigned these two cases as group projects to these smaller teams. (Later, the school decided to do away with the MLOs and replaced them with smaller Management Learning Teams, MLTs, of about four students each. However, this change did not affect my use of the cases, as I then assigned the cases to MLTs as group projects.) Students seem to have found these cases to be valuable.

2. Description of the Course

I have used these two cases in the full-time and part-time MBA statistics course at the Katz School. This is an introductory three-credit course, required of all students, and is a prerequisite for the management science/operations management course. The full-time students take this course in their first semester, along with economics, financial accounting, and a subset of core courses from organization behavior, finance, marketing, and information systems. The part-time students take the course early in their program, although not necessarily in their first term.

In the statistics course, we study how we can use partial information to draw conclusions about the underlying population. The course can be roughly divided into three segments. First, we learn how to make inferences about the population based on sample data. This segment includes sampling distributions, estimation, and hypothesis testing. The second segment covers simple and multiple regression; forecasting is also covered in this section. The third segment covers statistical process control, design of experiments, ANOVA, and some other miscellaneous topics. The emphasis of this course is on learning the methodologies, seeing their applications, and interpreting computer outputs, rather than focusing on learning a computer package or on studying the underlying mathematical details. I assign two cases in each of the three segments. Some of these cases are individual cases, and others are group cases. I use this set of two cases in the third segment and have assigned them to groups of about four students each.

3. Brief Descriptions of the Cases

As discussed in more detail below, both cases have multiple parts. Some parts are straightforward and help the students review the concepts that have been covered in class. Other parts appear to be simple, but a comprehensive answer requires the students to go beyond what we have covered in class. Unlike Harvard Business School cases, which are usually quite long, are based on real companies, and generally adopt a strategic viewpoint, these two cases are relatively short, have an operational emphasis, are realistic but based on a fictional company, and have very focused learning objectives.

Both cases require hands-on work, where students have to first do the analysis using a computer package and then interpret the results. Both cases involve both quantitative analysis and qualitative thinking.

The two cases associated with this article are as follows.

Case 1. MotoTech Manufacturing Company: Process Control and Improvement: The main actors in this case are the founder of MotoTech Manufacturing (MM), a U.S. semiconductor manufacturing company, and five of his fellow MBA alums, The Famous Five, who have set up a consulting firm. The founder of MM realizes that his dreams of growing his company into a global chip supplier to the consumer electronics industry might be shattered if MM does not take quick steps to improve quality. He places a call to The Famous Five, who visit MM to help in quality-improvement efforts. The case has six parts (questions), sequentially leading the students through MM's quality improvement initiative. As discussed below, depending on the instructor's objectives and the amount of time they want to allocate to the case, instructors may assign only some of the six parts to the students.

Part A. This part asks students the qualitative question of whether MM should ignore a communiqué from one of its major customers requesting an improvement in the quality of MM's products. In particular, the students need to consider whether MM should ignore the customer's requirement in the hope that this focus on quality on the part of the customer is temporary.

Part B. Wafer thickness is a critical characteristic of semiconductor wafers. Given thickness data, students are required to construct $\overline{X}$- and R-charts to check whether the process is in control.

Part C. Following the assessment of the process stability in Part B, the Famous Five consulting company identifies one potential way of improving the process and recommends a course of action. This part provides the data after MM has implemented the change recommended by the Famous Five, and the students are again asked to check for process stability using control charts.

Part D. The students are required to assess the impact of the change proposed by the Famous Five in Part C and propose next steps that MM should take. As discussed in the teaching note, this proposed recommendation must take into account both the conclusion reached from the analysis in Part C and the mindset of continuous improvement.

Parts E and F can be skipped, if necessary. These two parts are independent of each other.

Part E. This part requires students to compute the process capability indices and sigma level for the process. This part also reviews probability concepts such as cumulative probability and highlights the relationship between relative frequency and probability.

Part F. This part requires the financial analysis of investing in new equipment. Capital investment decisions (that the students may learn about in finance or accounting) often overlook the cost of poor quality. The students are expected to account for the cost of poor quality in the capital investment decision. However, not all costs are given, and an understanding of incremental costs is needed for completing this part.

Case 2. MotoTech Manufacturing Company: Design of Experiments/ANOVA: While this case can be used independently of Case 1, both cases have the same application context, and this case is pedagogically most effective if it is assigned after Case 1. The case discusses the use of design of experiments and ANOVA for improving quality. Recall that Part D of Case 1 required the students to propose a course of action, given the impact on quality of stabilizing the temperature. If there is a relationship between temperature and thickness, how does one find the best setting of temperature? Does the optimal temperature setting depend on other factors? The case provides data on two variables and requires the analysis to determine whether they exhibit an interaction or only main effects. The case also describes an approach to heuristically determine the best combination of two continuous input factors.

Part A. The first question requires the students to critique the quality improvement approach outlined in the case. This "local search" approach is intuitive and will lead to the best settings if the response function is concave in the input variables. However, as discussed in the Teaching Note for this case, the approach has several limitations as well. The students are asked to comment on these limitations.

Part B. This part gives the opportunity to the instructor to discuss "bottleneck" analysis. A bottleneck is an activity, stage, equipment, subprocess, or department that constrains the process output. Typically, the concept of bottleneck is used in the context of the output quantity. Here it is used in the context of the quality of the output. (Of course, the quality, along with other factors such as production rate, production time, supplier reliability, etc., will affect the quantity of the output.)

Part C. An important acronym used in industry is critical-to-quality, or CTQ. The objective of this part is for the students to identify some CTQ factors for a manufactured or service product of their choice.

Part D. This, along with Part A, is the main question of this case. For this question, the students use computer software to conduct an ANOVA. They have to comment on the analysis done by another consulting company and explain intuitively the results of their own analysis and conclusion. In doing so, they gain an understanding of interaction and main effects.

4. Objectives of the Cases

The objectives of the two cases associated with this article are as follows.

Case 1. Process Control and Improvement.

- Discuss why a focus on quality improvement is necessary
- Demonstrate the use of control charts for improving a process
- Review basic probability and statistics concepts
- Discuss the difference between a stable process and a capable process
- Examine and compare different measures for evaluating process capability, including C_p, C_{pk}, and sigma level
- Conduct a financial cost-benefit analysis, in a quality setting, of leasing new equipment

Case 2. Design of Experiments/ANOVA.

- Show how a designed experiment can be conducted to identify improved process settings
- Discuss the limitations of a local-search-based approach for finding the optimal process settings
- Demonstrate the use of ANOVA
- Distinguish between main and interaction effects

5. Intended Audience

The intended audience for this set of cases is both graduate and undergraduate students. In an introductory statistics course, Case 1 can be used if process control is covered, and Case 2 can be used if design of experiments and ANOVA are covered. Case 1 can also be used in an operations management course that covers process control. (In my experience, design of experiments and ANOVA are not covered in a typical operations management course.)

I have used the cases several times at the MBA level in the introductory statistics course (with both full-time and part-time MBAs), and the student response has been quite favorable. (Because at our school the statistics course for business undergraduates is taught by the Statistics Department, not the College of Business Administration, I have not taught these cases at an undergraduate level.)

In using the cases, one should be careful in assigning the questions. As far as Case 1 is concerned, most courses covering process control will provide the students with enough knowledge to complete Parts A through D. However, not all courses will emphasize the computation of the process capability indices, or sigma level. If an instructor does not want to cover the computation of these indices, then Part E can be skipped without loss of continuity. Part F requires the students to integrate concepts they may have seen in finance or accounting. In particular, they need to determine whether it is worth investing in new equipment that would help improve quality. To do this, they have to determine the costs with and without the new equipment. Because at our school, all full-time MBA students take accounting and most take finance in the same term as they take statistics, they have the background to handle this part. Otherwise, students who do not have a business background may have difficulty in this part. In particular, undergraduate students may have difficulty in this part, because typically they take statistics in their freshman or sophomore years. If used in an undergraduate operations management course, this problem should not arise because operations management is typically taken by upper-class students.

Case 2 is the easier of the two and can be used in an MBA course that covers design of experiments and ANOVA. Some undergraduate courses may not cover ANOVA, and so this case may not be appropriate. Even though the analysis is not difficult, the case brings out an important issue about why it is important to test for interaction effect before testing for main effects, and how one may arise without the other.

6. Classroom Experience and Teaching Hints

As mentioned above, I have used these cases several times in our MBA program. I assign these cases as group assignments. Some instructors may wish to assign them as individual cases—depending on the profile of the students in the class and on their own judgment about the benefits of individual versus group learning. I feel that assigning the cases in groups helps students learn from each other, especially in the open-ended questions. For example, while the limitations of local search might be obvious to instructors, students discover these as they discuss with their group members the limitations of the methodology outlined in Case 2.

In answering the first few questions for Case 1, the students find constructing the control charts straightforward. Yet, they find the exercise to be quite useful. In discussing the control charts, I emphasize that interpreting the control charts is both a science and an art, in the sense that while there are clear-cut rules for identifying when a process is out of control, including some that we may not have studied in class, we have to exercise our judgment in using them. Existence of periodically occurring patterns (even though they do not violate any of the standard rules) may need investigation. Likewise, an observation close to (but not beyond) the control chart limits may still be a cause for investigation, or at least close monitoring. It is useful to help remind the students that the control chart limits are set so that they are three standard errors on each side of the center line. (In the case of the lower limit of the range chart this comment does not always hold, because range cannot be negative.) The choice of using three, rather than say, 2.5, is a modeling decision that involves a trade-off between the costs of making a Type I versus a Type II error. Recall that the null hypothesis in using control charts is that the process is in control. If the band defining the control chart limits becomes narrower, then the probability of making a Type I error increases, and the probability of making a Type II error decreases. A main point here is that using a multiplier of three for the standard error is a modeling choice—a widely accepted convention—not an optimized, context-specific decision, and so one should use judgment in interpreting the results. Moreover, the conclusions reached, based on control charts, about the stability of the process are probabilistic, not deterministic. Therefore, judgmental criteria might suggest investigating the process when an observation falls close to, but still within, the control chart limits. Likewise, an occasional observation outside the control chart limits may be ignored, as there is a 0.0027 probability that this might happen even when the process is in control.

To assess the process capability in Case 1, the students have to estimate the process standard deviation. In doing so, the students once again see the difference between the process standard deviation, the sample standard deviation, and the standard error of the mean; these are terms they may have seen earlier in the course. I find that while they can generally compute the C_p and C_{pk} values, they find it difficult to determine the sigma level and the corresponding fraction of defectives. However, as they are completing this exercise they may realize (but it is useful to nonetheless emphasize this in the discussion) that the relationship between sigma level and the proportion of defectives is nonlinear. Therefore, a six-sigma level is not twice as good (measured by the proportion of defectives) as a three sigma level.

Answering Part F of Case 1, where the students have to determine whether investing in new equipment is economically viable, requires students to have a good handle on doing incremental cost analysis. Not all the process costs are given, but the ones that are needed for making the decision are. The students need to recognize which costs are relevant, and how to use these costs, for the decision they are making. The costs associated with quality are uncertain, as they depend on the yield of the process, and so the students have to determine various probabilities to compute the expected costs. While the students can do this by hand using normal tables, the calculations become less cumbersome if the students build a spreadsheet model. Instructors may also require the students to compute the net present value of the decision to buy the equipment. (I do not require the students to do so, because not all of them have seen this concept when they take my class. Also, this question would not have anything to do with statistics per se, but would perhaps let the students feel that the statistics course is integrated with the other courses.) Of course, if an instructor decides to add the net present value computation to the assignment, then they may need to specify the discount rate.

Case 2 emphasizes that even though a process may be in control, there may still be a need to further improve the process—the concept of continuous improvement. The students find Case 2 to be easier than Case 1. However, they do grapple with determining why the exploratory approach described in the case may not work. Although students make a decent attempt at discussing the underlying limitations, they generally are unable to identify all of the different limitations of the outlined approach. They are able to answer Part B well and are quite creative in selecting a product and coming up with CTQ dimensions (Part C). Finally, the last part of this case requires students to use a computer package and helps them understand the significance of the interaction effect and how it differs from the main effects. Some students depict the means graphically, as shown in the Teaching Note, but not all teams do this, as Figure TN2 (of the Teaching Note for the second case) is not a standard Excel output. Using this figure, however, helps the students internalize the difference between interaction and main effects.

I assign all six parts of Case 1 as one assignment and all four parts of Case 2 as another assignment. These cases help reinforce the concepts that we have already covered in class. After the students have submitted their reports, I cover some of the main issues in class. At this point, I assume that the students know the mechanics of, say, constructing control charts, and focus on interpreting the results, as discussed in the Teaching Note.

Although the two cases consider different concepts and can be used independently, it is preferable to use Case 1 (Process Control and Improvement) before using Case 2 (Design of Experiments/ANOVA). This also ties in with the sequencing that I believe is most appropriate for an introductory statistics course. In an operations management course, where typically only process control charts are included and design of experiments is not, only Case 1 can be used. I have never used Case 2 without first assigning Case 1—if an instructor wants to do so, it may be useful, although not necessary, to give the description of the context (the first few pages of Case 1—without the questions) to provide students with background information.

While the data files are in Excel, I allow the students to use any statistical package they want to use, but they are responsible for importing the Excel data file.

7. Conclusions

Process Control and Design of Experiments form critical modules of a typical introductory statistics course. Students find these topics to be interesting and recognize the broad-based applicability of the underlying concepts. This article describes the use of the two cases that accompany this article for teaching these concepts. The cases require students to do hands-on analysis, using a computer package (a spreadsheet or a specialized statistical package), and require the students to make both qualitative and quantitative recommendations. Although the cases can be used independently of each other, it is best if the process control case precedes the design of experiments case. The cases, along with the supplements, are available from the journal to potential adopters.

Supplementary Material

Files that accompany this paper can be found and downloaded from http://ite.pubs.informs.orgs/.

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