Teaching Variation Reduction Using a Virtual Manufacturing Environment

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This article describes the virtual manufacturing environment Watfactory (freely available at *http://services03.student.math.uwaterloo.ca:8080/~stat435/login.htm*) and discusses its use in teaching process improvement. Watfactory provides a rich and realistic simulation of a manufacturing process and is accessed through a website requiring no software other than a Web browser. With Watfactory, students select, plan, and analyze the data from a sequence of empirical investigations of many different types, with the ultimate goal of reducing variation in the process output. We have found that using Watfactory addresses many shortcomings in traditional teaching methods for both undergraduate and industrial short courses.

KEY WORDS: Simulation; Six Sigma; Variation reduction; Virtual environment.

1. INTRODUCTION

For mass-produced components and assemblies, reducing process variation can simultaneously reduce overall cost, improve function, and increase customer satisfaction with the product. Excess variation can have dire consequences, leading to scrap and rework, the need for added inspection, customer returns, impaired function, and decreased reliability and durability.

Variation can be reduced by adopting a systematic framework like DMAIC (define, measure, analyze, improve, control) in Six Sigma (Breyfogle 1999), or statistical engineering (SE), as described by Steiner and MacKay (2005). Here we use the term "framework" instead of "process" to describe the series of steps specified by DMAIC or SE to distinguish the problem-solving meta-process from the physical process that we are trying to improve. Without such a framework, inexperienced problem solvers would not know how to proceed.

Most process improvement frameworks are based on the diagnostic and remedial journey of Juran and Gyrna (1980). In this diagnostic journey, we first identify important inputs that cause the variation in a key process output using such methods as brainstorming, statistical process control (SPC), experimentation, and many others. In the remedial stage, we implement a solution that will mitigate or eliminate the effects of the identified causes. Seven broad solution approaches are available (Steiner and MacKay 1997, 2005):

- *Fix the obvious.* Reduce the variation of an important cause by forcing a change on a supplier or reapplying the variation reduction framework.
- *Desensitization.* Specify new levels of one or more process inputs to flatten the relationship between an identified cause and the output.
- *Robustness*. Specify new levels of one or more process inputs to flatten the relationship between an unknown cause and the output.
- *Move process center.* Select new levels for one or more process inputs to shift the center of the process or the centers of parallel subprocesses.
- *100% inspection.* Establish inspection limits on an input or output, and scrap any parts or components with a value outside these limits.
- *Feed-forward control.* Measure an identified cause according to a specified sampling plan, and use an adjustment scheme based on these measurements to reduce the effect of the cause.
- *Feedback control.* Measure the output according to a specified sampling plan, and use an adjustment scheme based on these measurements to reduce the variation.

To apply a variation reduction framework, we carry out a sequence of investigations, each with a different purpose, linked to those that came before by the knowledge gained and the ultimate goal. For example, in the problem formulation step, we may start with an observational study to assess the current pattern and magnitude of the variation in a key output. Next, we search for important causes of the variation using any of a large number of study plans. When looking for a specific solution, we carry out formal experiments to understand the effect of changing process inputs that are normally fixed.

After each investigation, we need to decide what to do next. If another investigation is the way to proceed, then there are always many choices. To help guide these choices and their design, we consider a second framework with the acronym QPDAC (MacKay and Oldford 2000):

- *Question.* Formulate a clear question of what we are trying to learn, taking into account what has been learned already.
- *Plan.* Develop the procedures we use to carry out the investigation to address the question.
- *Data.* Collect the data according to the plan.
- *Analysis.* Summarize and analyze the data to answer the question posed.

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- *Conclusion.* Draw conclusions about what has been learned.

QPDAC helps the user select, plan, and execute each particular investigation within the variation reduction framework.

To teach variation reduction, we have developed a simulated process called Watfactory. Student teams apply the two frameworks to the virtual process to discover how and why the process output varies. They then conduct further investigations to select and implement one of the seven variation reduction approaches described earlier. The context is sufficiently rich that each student team has its own version of the process, with differing causes of variation and multiple solutions.

There is much recent interest in using elaborate simulations (or, in modern parlance, virtual environments) to help students learn statistical concepts and practice. Cobb (2007) provided an elegant, learned, and amusing discussion of the advantages and disadvantages of using simulation compared with traditional textbook exercises on one hand and activity-based data collection on the other. Wild (2007) provided a similar critique, along with an excellent reference list for existing virtual environments, and looked to the future to when there will be a common platform on which to build such objects. Chi, Pepper, and Spedding (2004) described a virtual factory similar in many ways to Watfactory. Other statistical examples have been provided by Nolan and Temple (2007) and Schwarz (2003, 2007). Some other games that focus on operations management include the MIT Beer Game (Sterman 1989, 1992) and Littlefield Technologies (Miyaoka 2005). (See the overview of Wood 2007 for a taxonomy of games, based on pedagogical objective, that are widely used to teach management skills in business programs.) Watfactory is a "capstone" game in this taxonomy.

In the next section we describe Watfactory and how we use it. In Section 3 we discuss some lessons that we have learned while using Watfactory to teach process improvement.

2. WATFACTORY: A VIRTUAL ENVIRONMENT

As you read this section, we suggest that you log in as a "guest" to Watfactory at *http://services03.student.math.uwaterloo.ca:8080/~stat435/login.htm*. You are taken directly to the team home page, which is referenced repeatedly in what follows.

Watfactory is loosely modeled on a manufacturing process that produces camshafts. The process has three major steps (Figure 1). In step 100, five components are assembled. In step 200, the components are welded together. Because of the high volume, three welding lines are operating in parallel. In step 300, the camshaft lobes are hardened using two parallel streams.

The process produces 1,440 parts (camshafts) per day (i.e., one per minute) in three 8-hour shifts, 5 days per week. Two-sided specification limits for $y300$ are used to formulate the problem. Note that $y300$ is measured as the difference from a nominal value, so that the specification has the form $[-L, L]$.

2.1 Output(s) and Inputs

The team can measure the output, a continuous characteristic, after processing steps 100 ($y100$), 200 ($y200$), and 300 ($y300$) but nowhere else in the process. There are no specification limits for $y100$ or $y200$, and these variates are measured on the same scale as $y300$.

The process has 60 varying inputs, denoted by $x1, x2, \ldots, x60$. We define a varying input as an input that may differ from one part to the next; examples include the machine number and stream used at steps 200 and 300, temperatures, fixture numbers, environmental characteristics, and operators. Some varying inputs are continuous, while others are categorical (e.g., operator: Fred, Bob, and Jane). The teams are given partial information about the nature of the variation in these inputs; for instance, some inputs, such as operator change once per shift, while others, such as component dimensions, change haphazardly from one part to the next. Still other inputs drift over time. (See the "introduction" link on the team homepage for the details of the information provided.) A few of these varying inputs are responsible for most of the variation in $y300$.

The virtual process has 30 fixed inputs denoted by $z1, z2, \ldots, z30$. These inputs are normally held constant while the process

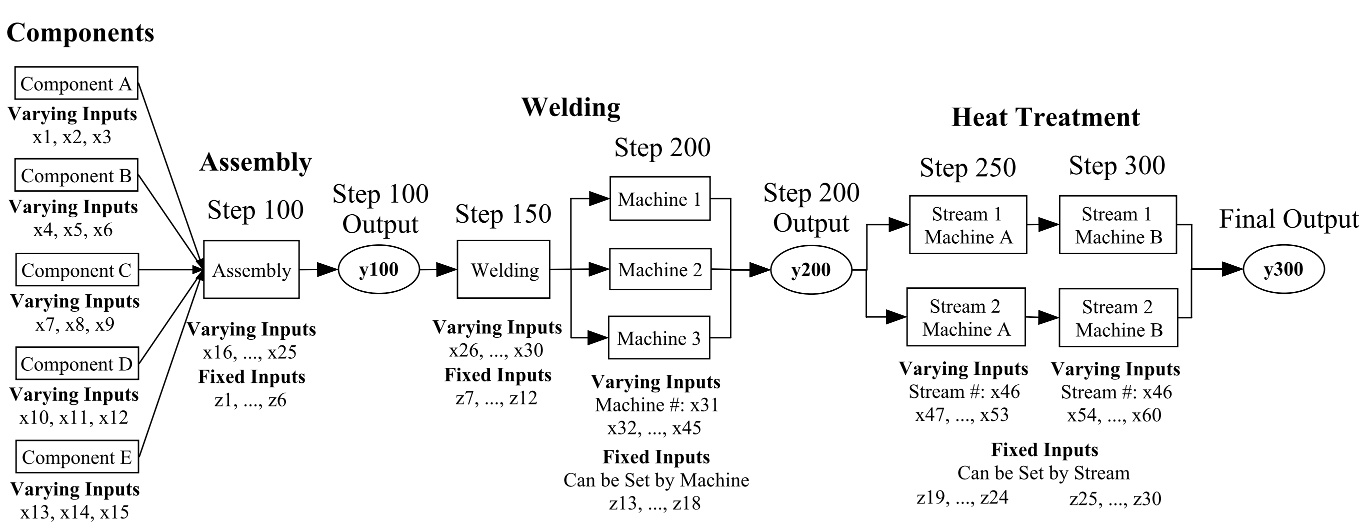

Figure 1. Watfactory process map.

is running, but can be changed by the team. The website provides information about the fixed inputs, such as current values and possible ranges (see the link "Search for a Solution" on the team homepage).

In a real process of this complexity, there likely are many more fixed and varying inputs. We find that the virtual process is sufficiently complex to challenge the student teams to reduce variation in $y300$, but simple enough that they can be successful in their search.

2.2 Empirical Investigations

At any time, a team can choose among several classes of investigations, both observational and experimental:

- *Prospective observational investigation.* Specify a time-based sampling protocol and the varying inputs and outputs to measure.
- *Measurement assessment investigation.* Specify finished parts observed in an earlier investigation or chose from the current process and the number of times to remeasure each selected part.
- *Retrospective observational investigation.* Specify some parts observed in a previous investigation and the varying inputs to be measured on each part. As with a real process, not all inputs can be determined retrospectively.
- *Experiment with varying inputs.* Specify a list of varying inputs to control in an experiment, the output to measure, and the experimental design.
- *Experiment with fixed inputs.* Specify the output to measure, the fixed inputs to change, and the experimental design.
- *Experiment with varying and fixed inputs.* Specify the output to measure, the inputs to change or control and the experimental design.

Note that process step 100 is an assembly operation in which we can disassemble and reassemble components without damage and then remeasure the output $y100$. Two specialized investigations can be conducted at this process step:

- *Component versus assembly investigation.* Specify a number of parts observed in a previous prospective investigation and the number of times each part will be disassembled, reassembled, and remeasured.
- *Component swap investigation.* Specify two parts with $y100$ measured in a previous prospective investigation and one or two components to swap between the two parts.

You can see the interfaces for each class of investigation by double-clicking on the investigation name in the table on the team homepage.

In any investigation, the team must make choices, such as the sample size, what to measure, when to measure, and so on. By giving each team an initial budget of $10,000, we discourage large and complex investigations that would be difficult to implement in practice. Factors that influence the cost include the class of the investigation (e.g., experimental investigations are more expensive than observational ones), which inputs and outputs are measured, whether or not parts are tracked through the process (this can be very expensive), and sample size. We provide tables to describe the cost structure as part of the background information (see the link "quantify problem/check measurement system" on the team homepage). Once a team specifies a plan for an investigation, they can ask Watfactory to calculate the cost of the proposed plan and the time required. The team can then use this information to modify the plan if so desired. Watfactory tracks the total cost and time spent to date for each team.

Once the team clicks on "conduct investigation," Watfactory produces the requested data in row/column format, which can be cut and pasted into analysis software, such as MINITAB (2000). For complex experimental plans such as fractional factorials, the team can copy the experimental design from other software used to build the plan. Watfactory stores the information for each investigation in a database. These data are permanently available to the team for review and further analysis. They also are available to the instructor to help track each team's progress.

2.3 Implementing a Solution

To reduce variation in the final output ($y300$), the team must ultimately implement one or more of the seven approaches described in the Introduction. In Watfactory, these correspond to the following (with the approaches given in parentheses):

- Changing the level of one or more of the fixed inputs $z1, \ldots, z30$ (move the center, robustness, desensitization)
- Adding 100% inspection for one of the inputs or outputs (100% inspection)
- Adding an adjustment scheme to the control plan (feedback or feed-forward control)
- Reducing variation in an important varying input (fix the obvious).

To help the team select a solution, Watfactory provides the cost of running the process (on a $ per part basis) if the process changes defined in the solution are made. Watfactory ignores the one-time cost of changing the set level for any fixed input or adding a processing step. We assume that these one-time costs are similar across all seven variation reduction approaches. Accordingly, Watfactory compares the approaches using ongoing operating costs. The sources of these costs (with the corresponding approach in parentheses) are as follows:

- Cost of reducing variation in one of the varying inputs (fix the obvious)
- Cost of repeated changes to the level of some normally fixed input (feedback, feed-forward)
- Cost of running the process with some new level for a fixed input (move process center, desensitization, robustness, feedback, feed-forward)
- Cost of additional measurements (feedback, feed-forward, 100% inspection)
- Cost of scrapped parts and loss of throughput (100% inspection).

See the link "validate/implement a proposed solution" on the team homepage for details on how these approaches can be implemented and their respective costs.

At this point, we suggest that you play with Watfactory to try to reduce variation in the "guest process." Note that the specification limits are $[-14, 14]$. If you want a real test, go to *http://www.stats.uwaterloo.ca/Faculty/VirtualProcess.shtml* and follow the directions for the 5-cause challenge.

3. LESSONS LEARNED USING WATFACTORY TO TEACH VARIATION REDUCTION

We have used Watfactory several times for a semester-long university course and for 3-day short courses delivered to industry. Although we have not formally evaluated the effectiveness of Watfactory, we believe, based on our experiences and student reactions, that such a virtual environment has many advantages for learning about variation reduction and applying statistics. Our experiences mirror those described by Nolan and Temple (2007) and Schwarz (2003, 2007).

3.1 Increased Interest

One change that we found surprising was the increased interest in the courses. Many industrial and university students view Watfactory as a game (we often refer to the simulation in this way) and, as when playing other games, they view the assignment of reducing variation as a challenge and a competition. Understanding the statistical concepts and tools is seen as a real asset to winning the game. We have also seen, much to our amusement, practicing engineers become so involved with the game that they forget that Watfactory is a simulation designed by statisticians and try to use their engineering knowledge ("Look, I know a lot about assembly, so there is no way that that the assembly process can be the cause of this variation!").

3.2 Better Than Textbook Exercises

Before developing Watfactory, we followed the traditional approach, using textbook-style exercises to give students practice in using the variation reduction framework and QPDAC in the planning and analysis of a wide variety of investigation types. The exercises were rich in issues relating to analysis and interpretation but weak in all other aspects. Watfactory forces the student teams to repeatedly answer important questions for which there is no unique or correct answer:

- What is the goal of the investigation?
- Should we use an observational or experimental plan?
- What sampling protocol should we use?
- What inputs/outputs should we measure or set?
- How should we incorporate the results and uncertainty from previous investigations to help with the current investigation?

All of these and other questions must be answered in light of the overall goal and the cost structures.

3.3 Dealing With Uncertainty

Because Watfactory requires a series of linked empirical investigations, students must learn to deal with the inherent uncertainty. To make this point, we cite a brief anecdote. One team of master's degree students, all with more statistical training and experience than any other team in the class, became quickly paralyzed once the game began. This team could not make decisions about what to do next, because they were focused on the uncertainty of the conclusions from the earlier investigation. We pointed out (helpfully, we thought) that if they were consultants reporting the results of an analysis to a client, then there would be uncertainty in their conclusions, and the client would have to deal with this uncertainty. The team agreed wholeheartedly with this point, but noted that this was the client's problem, not theirs. Watfactory was their first exposure to making real decisions in the face of statistical uncertainty.

3.4 Common Process/Different Settings

In the university course, each team is given a different version of the same virtual process. All versions have the same process map, as given in Figure 1, and background information, as described in Section 2. But the effects of the varying and fixed inputs differ among the versions; that is, the coefficients in the underlying model that drive the simulation are different for each version. Having a common process allows discussion among the teams about their progress without the need to provide extensive background. Plagiarism is not an issue, because the causes and remedies vary from team to team. We use the Watfactory context with yet another version on examinations to exploit the common, well-understood background.

In the short courses, we have found it best to use a single version of the virtual process for all teams. We intersperse lecture segments with team-based Watfactory investigations. Each team is kept at the same place in the variation reduction framework but is free to choose and specify an investigation type. After each team conducts and analyzes its own data, we have a discussion about the various choices that were made and what has been learned. Because of the time constraints, we need to provide much more guidance in this context.

3.5 Advantages Over a Real Process

Before developing Watfactory, we tried class projects for the university course, but the lack of real processes to study doomed these to be toy examples with little interest for the student and a lack of complexity. In the short courses, we tried to incorporate student projects using real processes by spreading the training over several weeks. This approach often failed due to inadequate time and supervision. The projects bogged down or lost priority in the students' busy schedules. In both cases, for many students the lack of practice meant little deep learning was taking place. We know from observation that many of the short-course participants were unable to later apply what we had taught them. Watfactory addresses all of these issues to some extent.

3.6 Flexibility

Watfactory allows the teams to make terrible mistakes with no real damage except to their pride and an artificial budget. We sometimes permit teams to go back and wipe out both the data and the costs of an ill-advised investigation. We always increase budgets when asked, but never announce that we will do so. Especially in the university context, the students are remarkably prudent about using their resources.

3.7 Communication Opportunity

Using Watfactory in the university course provides an excellent opportunity for the students to practice statistical communication. Each week, each team submits a written progress report on its interactions with Watfactory. This report highlights their rationale for the specific empirical investigation(s) that the team conducted, the team's analysis, what the students have learned about their process, and what they plan to do next. We provide feedback as quickly as possible before the team carries out the next investigation.

Twice in the term, each team is the subject of a management review by one its peer teams. In a meeting conducted in front of the entire class, the team's progress to date is formally reviewed. Each team makes a short presentation outlining what it has done and learned so far and what it plan to do next and why. The team assigned to act as the manager questions the decisions made, and also attempts to provide guidance for what should be done next. The purpose of the meeting is to give the students experience in critiquing the decisions made by others and defending decisions they have made. We have been surprised by the enthusiasm shown for these meetings and the excellent presentation skills of many of the teams.

3.8 Instructor/Student Learning

Another advantage of Watfactory over more traditional approaches is that it forces the sequential learning that is essential in process improvement. In our search of textbooks on Six Sigma (e.g. Breyfogle 1999), we found no mention of this important point. All investigations described appear to stand alone, with no discussion of what came before or after. When using a virtual environment such as Watfactory, we as teachers and the students as learners cannot avoid this issue.

Not surprisingly, as instructors, we also have learned from the simulation. For example, we found that our understanding of how the effects of certain interactions would manifest themselves in the process output was incorrect. We also learned how difficult it can be to isolate important causes of variation that occur far upstream of the final output.

4. CONCLUSION

We have listed what we think are the many advantages of using a virtual environment such as Watfactory to teach variation reduction. Watfactory forces the teams to make all decisions necessary to execute a real process variation exercise. The students gain experience in determining when to use what tool and why and generally how to plan, analyze, and draw conclusions from empirical investigations. In addition, we have found that students enjoy the challenge, and we believe that they learn more when using Watfactory. There are no substantive costs, and the overall process is easy to manage.

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