Applying the Continuous Improvement Process to Engineering Design in the Laboratory

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Abstract

One of the contemporary issues in the evolution of engineering curricula concerns Total Quality Management (TQM). In many cases TQM topics are discussed in design seminars, and students are asked to apply and interpret the TQM principles in the context of their design projects. A difficulty emerges when students are asked to apply the principle of continuous improvement. Most students and student teams complete a typical design course when they demonstrate a first prototype, and they seldom engage in further design iterations using a systematic continuous improvement methodology. This paper describes a laboratory integration of engineering design and continuous improvement based on statistical measures of ensemble product performance. An intensive week-long full-time laboratory addresses the iterative design and implementation of a modest electronic instrumentation circuit, seeking improvements in topology and parameter selections which result in improved performance variances.

Introduction

The principles embedded in Total Quality Management (TQM) are having a profound impact on the general conduct of engineering design and product development. As a consequence, most engineering education programs have sought to include aspects of TQM in their curricula and many of these are addressed in the design courses, most notably in the senior capstone project. The various TQM principles are typically covered in seminar or lecture format, and students are asked to interpret these principles in the context of their senior projects, applying some of the ideas where possible. Yet one of the fundamental principles of TQM relates to the continuous improvement of a product, and the rigorous application of this principle in an academic design setting is elusive. For student teams, the endpoint of a design course is usually marked by the delivery of a first working prototype of a product [Webster, 1990]. The complexity of senior projects, together with the timing and logistics of the course, generally prevent student designers from engaging in the systematic and orderly improvement of their designs. As a result, they often leave the course with the impression that a design is complete after its first iteration, and with no meaningful experience in the subsequent process of continuous improvement.

In confronting this issue, I imagined that it could be addressed by an educational experience in the application of continuous improvement to engineering design in a hardware domain. I visualized a setting where students would measure ensemble performance statistics across multiple copies of a product prototype which they had designed and implemented. In conjunction with the Taguchi loss function, these statistics would be used as quantitative indicators of prototype quality. Students would design experiments to explore the consequences of topological and parameter variations in the statistical performance of the prototype. Then they would modify the prototype accordingly, and confirm a quality improvement. They would repeat this process iteratively, observing both continuous improvement in prototype performance and the systematic methodology by which it is achieved.

This idea emerged at a time when we were actively pursuing educational developments to entrench TQM topics into the curriculum at the Colorado School of Mines, under the sponsorship of a grant from Proctor and Gamble. It also emerged at a time when we were getting escalating calls from some of our recruiters, like the semiconductor industry, for graduates to have better preparation in statistical process engineering, and at a time when calls for engineering applications of statistics were being made by our degree accrediting board (ABET).

As a consequence, I have developed and successfully piloted a pre-junior laboratory module in the application of continuous improvement in engineering design, and this paper discusses the main features of this endeavor.

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Pedagogical Objectives and Approach

The general objective of this laboratory module is to develop in the student participants the fundamental competencies relevant to the application of continuous improvement. These include a comprehension of contemporary (Taguchi) representations of quality measures; an understanding of the segmentation of engineering design into synthesis and choice at the topological level, the parameter value level and the tolerance level, and an understanding that choices at each of these levels affect product performance and quality; an interpretation of statistical representations of product performance and an ability to apply elementary statistical methods in the assessment of performance quality; and an appreciation that iterative and experimental approaches are needed for systematic quality improvement. In a collective sense, I wanted these competencies to become intuitive. To foster their development, the pedagogy employed in this module follows a model of the continuous improvement process applied to engineering design, as shown in Figure 1. Of course the framework and flow depicted in this figure forms the intrinsic basis for iteratively achieved product quality improvement [Tribus, 1995].

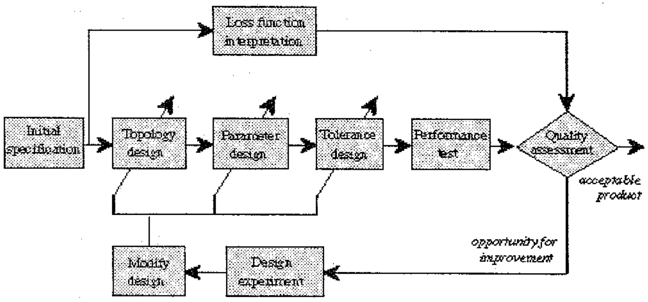


Figure 1. The Continuous Improvement Process in Engineering Design

Beginning with an initial specification, students design a first prototype by successively moving through the determination of a topological architecture, the assignment of parameter values and then the assignment of tolerances on those parameters. Multiple copies of this first prototype are reproduced and individually tested, providing data to derive the statistical performance mean and variance of the ensemble. These statistical measures are contrasted to a Taguchi loss function interpretation of the initial specification, providing an assessment of the performance quality of the prototype. Typically there is opportunity for quality improvement, perhaps in shifting the mean, but almost certainly in narrowing the variance. An interpretation of how shifts in the mean and reductions in variance improve product quality is portrayed in Figures 2(a) and 2(b). When pursuing the opportunity for improvement, the process enters an improvement cycle, where aspects of topology, parameter values and tolerance may be modified in a quest for reducing the penalty imposed by the loss function. Systematic experimental methods are used to search through those design modifications which result in quality improvement, and to implement these modifications in a new prototype. The improvement cycle iterates until quality is deemed to be acceptable.

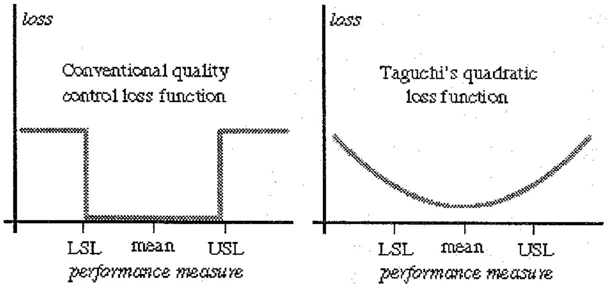
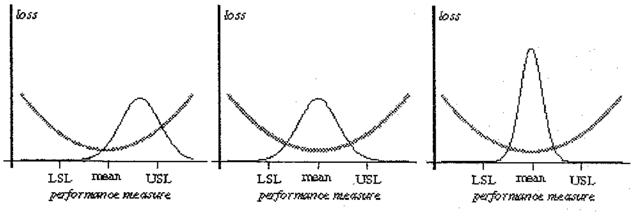


Figure 2(a). Contrasting interpretations of the loss function for conventional quality control and Taguchi methods



Quality improves as mean value is shifted and variance is reduced to minimize area of performance distribution under loss function.

Figure 2(b). Superimposed gaussian performance distributions for successively improving design prototypes on the Taguchi loss function.

Clearly, the laboratory application of this process has to be translated from these abstractions to a physical experience in the context of engineering development. I have used a simple electronic instrumentation circuit as the illustrative vehicle. Electronics offers many logistical advantages over other product embodiments. The component parts are inexpensive, circuits can be prototyped quickly and without the need for machine tools, circuit performance can be measured relatively easily with conventional laboratory instruments, and the component parameter values have an intrinsic statistical spread which ensures that the ensemble distributions will illustrate quality indicators effectively.

Content and Sequencing

This module is delivered as a full-time week-long experiential engineering laboratory to some 35 completing sophomore students at the Colorado School of Mines.

An introductory seminar covers the manufacturing and productivity dogma in the pre-1980's United States and western Europe, and shares the work of Taylor, Shewart and the emergence of traditional quality control processes. Industry and markets in post World War II Japan and the United States are contrasted as a prelude to W. Edwards Deming's philosophy on industrial management, productivity and quality. This motivates further discussion on the quality revolution of the 1980's and 90's, together with an appreciation for quality standards like ISO9000 and a perspective on the evolving NAFTA, European Community and Pacific Rim economic trading blocs. This continues with a contrast between traditional and modern design and manufacturing practices, touching on concurrent engineering and emphasizing the meaning of quality. The compelling case is made for continuous improvement cycles in manufacturing processes and in product design. The work of Genichi Taguchi is introduced as the traditional stepwise loss function is compared to Taguchi's quadratic loss function, and interpreted in the context of gaussian performance expectations (Figure 2). This extends into a brief mathematical review of statistical distributions, the central limit theorem, and computation of statistical measures. Finally, the notion of process signal-to-noise ratio is discussed, and methods for the improvement of this ratio are considered.

Having covered this broad base of contemporary thinking in engineering practice and design, I then pose a design assignment which will exploit these ideas. There are many possibilities on assignments which meet the pedagogical goals of this module. One example of is the following:

Objective: Design an electronic circuit to sense air temperature and turn on an LED at 50°C. (This is typically expressed in the context of an HVAC application).
Constraints: The circuit must operate from a 9V supply, and must be constructed from standard 5% 0.25W resistors, LM1458 operational amplifiers, a supplied NTC thermistor, and an LED.
Performance criteria: The difference between the ensemble mean switching temperature of a population of circuits and 50 °C must approach a minimimum. The variance of the distribution around the ensemble mean must approach a minimum.

Given this assignment, students begin the design of a first prototype by working in small teams to create and then propose topology options. As a large group, we discuss the merits of the submitted options collectively and arrive at a group consensus on the preferred circuit topology. This is followed by another phase of small teamwork, where students size the circuit parameters, essentially specifying resistor nominal values. Each team proposes a different set of parameters, so once again we enter into a consensus discussion on the single preferred set, and like the topology consensus review, this discussion is cast in a context of simple value engineering where students are asked to defend their choices. Since the resistor tolerances are essentially fixed by the given design constraints, the issue of tolerance is partially explored through the statistical assessment of a population of the NTC thermistors in stand-alone mode. The students discover that the thermistors have a broad distribution of terminal resistance at room temperature, and that this is not clearly conveyed in a typical short form data sheet.

Students then work individually to physically construct the first prototype circuit on a breadboard, and take it to a station where its performance is measured. In conjunction with a calibrated temperature probe and a heat gun, the temperature at which each individual prototype circuit switches is determined and logged in a spreadsheet on the personal computer. At the end of this part of the exercise, the ensemble statistics for the performance of the first prototype are shared and reviewed. The discrepancy between the ensemble mean and the target 50 °C, and the breadth of the distribution variance are both considered against the Taguchi loss function. A few initial iterations on obvious or heuristic topological and parameter modifications are performed, and statistical performance data are collected at the end of each iteration.

The next instructional part of the module is a seminar which introduces the principle methods embedded in the design of experiments. Factors which may affect ensemble performance mean and variance are contemplated, as are the relationships between them. The idea of experimenting to search for performance improvement is conveyed, and the issue of exhaustively searching over a number of independent variables emerges. This motivates a discussion of factorial design strategies and especially the two-level factorial approach.

Thus, the next step in the practical implementation of the continuous improvement process is for the class to postulate the set of variables which most strongly influence statistical performance, and then embark on a set of experiments which determines the gradient leading to improved quality. The bulk of the remaining part of the module is taken up iteratively performing experiments, re-designing, and statistically assessing quality improvement. A full statistical record is computed and shared, and the successive improvement in terms of deviation of the mean from 50 °C and the progressive reduction in variance is monitored.

In addition to the seminars and practical activity described above, the week-long module also includes opportunities for pre- and post-module surveys, a short written examination and the development of a team authored report.

Process Review

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This section presents some of the development and performance milestones in the design and continuous improvement of an electronic instrumentation circuit for temperature detection. After some teamwork activities on topology design options, the students reached consensus on a configuration based on a Wheatstone bridge sensing circuit, a differential amplifier, and a voltage comparator. Subsequent activities led to their determination of an initial and plausible set of parameter values. A representation of this version of the circuit is shown in Figure 3.

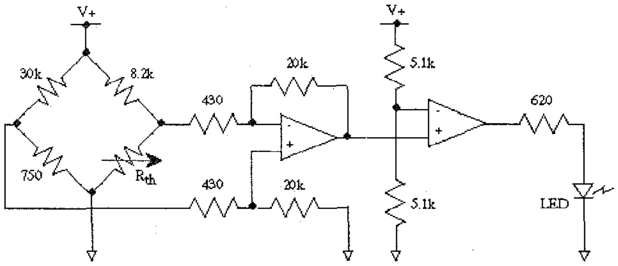

Figure 3. A typical circuit design.

The students each constructed a breadboard circuit based on this design and tested its performance at a measuring station where the actual switching temperature was determined and logged. The statistics of the ensemble of circuit implementations were then reviewed, and the students followed with re-designs which had some intuitive parameter adjustments and topology improvements. The performance for three of these early iterations are shown in parts (a), (b) and (c) of Figure 4.

Having settled on a reasonably good design at this point, represented by the performance in Figure 4(c), the students then embark on a two-level factorial design of experiments process, investigating the independent effects of bridge sensitivity and amplifier gain. The performance variances are determined for the four cases presented by this experiment, and the resulting variance response surface is shown in Figure 5. From this, it is deduced that narrow variance is achieved by reducing the bridge senstivity and raising the amplifier gain, and a new parameter design is developed with modest bridge sensitivity and very high amplifier gain. The statistical performance for this final iteration is shown in Figure 4(d). These examples of performance distributions show how the process has been successful in not only shifting the mean value to the 50 °C target, but also in reducing the variance by some 85 percent over the initial version. These improvements are achieved at no additional cost.

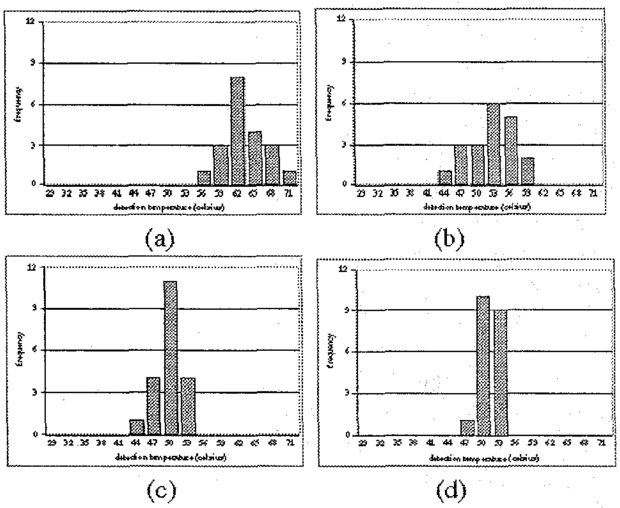

Figure 4. Selected performance distributions for evolving designs. Performance variances (a) - (d) are 14.28, 14.46, 5.33 and 2.13 °C 2 , respectively.

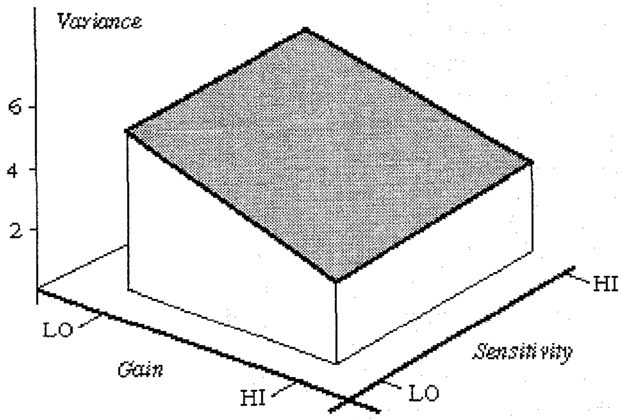

Figure 5. Variance response surface for two-level factorial experiment.

Conclusions

The hypothesis that we could use a practical laboratory experience to give sophomore students the intellectual backdrop and good habits associated with continuous improvement was proven in the delivery of the pilot module. Students not only formulated and exercised these habits, but they also showed that applied continuous improvement works when performance variance is the quality measure. They left the experience with an introductory knowledge of Taguchi methods applied to the engineering design process, and also an intuitive feel on how to apply these methods and what performance quality benefits could be accrued. The students recognized that this style of thinking is increasingly important to them as incumbent engineers, and most of them anticipated electing more advanced coursework to extend their introductory knowledge.

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