42 Testing and Quality Engineering

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42.1. Introduction

Successful testing is a crucial component of any robust design project. Even if all other related activities are executed flawlessly, poorly conducted testing and evaluation can result in suboptimal results or failure of the project. Despite its critical nature, execution of the experimental design is sometimes considered a "black box" process. Successful execution of a robust design experiment depends on attention to the four "P's" of testing: personnel, preparation, procedure, and product.

42.2. Personnel

Numerous quality methodologies have received considerable attention in the past decade. Robust design, total quality management, six sigma . . . to many engineers these are perceived as nothing more than the latest in a never-ending stream of quick-fix fads adopted by management. Each technique has its proponents, appropriate applications, and case history; each also has its skeptics, misapplications, and

 Taguchi's Quality Engineering Handbook. Genichi Taguchi, Subir Chowdhury and Yuin Wu

anecdotal failures. The interaction between these philosophies and the existing corporate culture of the adopting organization can either lead to empowering synergies or nigh-impenetrable barriers to success. Because of the team-oriented interdisciplinary nature of modern engineering, successful testing in a robust design context cannot ignore the psychology of the people involved in the process.

This issue is of particular importance in organizations that give development responsibility to one functional area and testing and/or validation duties to another. It must also be addressed if the predominant engineering mindset is focused on design-test-fix and testing to targets (or "bogeys"). To obtain full participation and commitment from the team, one must eliminate misconceptions and ensure that each team member has an appropriate level of understanding of robust engineering techniques. It is not necessary for each team member (whether from design, quality, or testing activities) to be an expert in robust design principles; however, each should be familiar enough with the methodology to be able to contribute and apply his or her knowledge and experience to the project.

One positive outcome of the recent attention that quality management has received is that most people in engineering and testing activities are more attentive to quality issues and are somewhat familiar with the associated terms, principles, and methodologies. However, some of this knowledge may be secondhand and not entirely accurate. Although robust design and engineering techniques (Taguchi methods) have received considerable attention in the United States, particularly in the past decade, many engineers and technicians do not have a full understanding of the underlying principles.

One common misconception is that quality is "tested in." This mindset is often found within organizations that separate design and testing activities and use the inefficient design–test–fix cycle to develop products. It is essential to convince engineers in this type of environment that quality is primarily a function of their designs and not something added as an afterthought by testing. Once this hurdle is overcome, one can demonstrate how robust engineering practices can assist them in their design activities.

Another frequent belief is that robust engineering is "just about design of experiments." Although classical and Taguchi experimental design techniques have some similarities, the philosophical differences are considerable. It is important to educate people clinging to this point of view about the underlying conceptual differences between the two methodologies.

Some people may be skeptical of any test plan other than one-factor-at-a-time evaluation. The best way to illustrate the power of robust engineering principles to adherents of this outlook is to share appropriate case studies with them. The ever-growing published body of work available about robust engineering applications should yield a number of suitable illustrations that can be used to educate the team.

Finally, "quality is conformance to specifications" is a mantra that will survive well into the twenty-first century, despite its inherent flaws. People with this type of "goalpost" mentality believe that all product within specification limits is of equal quality; an explanation of the loss function and appropriate case study examples should eliminate this misconception.

Some of the most critical members of the team are those who will be performing the tests. The engineers and/or technicians responsible for conducting the experiment and collecting data must be included in the planning process. Many technicians, particularly within "chimney" organizations that segregate testing and design activities, have a wealth of knowledge about test procedures, instrument capabilities, past design failures, and other institutional knowledge that may not be readily available to the team from other sources. Fostering an inclusive relationship with these people can yield enormous benefits and improve the quality of the test results.

42.3. Preparation

Few oversights will limit the success of a quality engineering project more than that of improper scoping. The focus of the project, whether it is on a component, subsystem, system, or entire product, must be defined clearly at the onset. The development of P-diagrams, ideal functions, and experimental designs is dependent on the boundaries specified by the team. The robust engineering process is also heavily influenced by the nature of the issue: research and development activities validating new technologies will have different needs and requirements than will design engineers creating a product for an end user.

Once the region of interest within the design space has been identified, the team must define the ideal function to be studied and construct an appropriate P-diagram. Existing documents can provide a wealth of information of use in this development: warranty information, failure mode effects analyses (FMEAs), design guides, specifications, and test results from similar products can contribute to the development of a comprehensive P-diagram. It is difficult to develop an exhaustive list of error states, noise factors, and control factors without examining this type of supporting information. Published case studies and technical papers may also yield insights into similar products or technologies.

Although the primary focus during this exercise must be the operating environment and the customer's use of the product, some attention should be paid to the capabilities of the testing infrastructure to be used. Although it is important to specify an ideal function that is energy-based (to minimize the possibility of interactions between control factors), it does little good to select one that cannot be measured readily. Input from the engineer or technician who will perform the trials can assist the team in developing a feasible concept. Many enabling test technologies have been developed (such as miniature sensors, noncontact measuring techniques, and digital data collection and analysis), and the people who use them are best able to accurately communicate their capabilities and availability. If the input signal or output response cannot be measured easily, appropriate surrogates must be selected. These alternative phenomena should be as closely coupled to the property of interest as possible; second- and third-order effects should be avoided whenever possible.

Once the ideal function has been specified and the P-diagram has been constructed, the team can begin development of the experimental design. The control factors to be studied should be selected based on the team's engineering knowledge and data from the sources listed above. Techniques such as Altshuller's theory of inventive problem solving (TRIZ/TIPS), structured inventive thinking (SIT), Pugh's total design, or Suh's axiomatic design can be employed in the development of design alternatives and the specification of control factor levels.

Some consideration should be given to resource constraints at this time. Test length, cost, and facility and/or instrument availability may restrict the magnitude of the overall experiment. It is important to consider these feasibility issues without sacrificing parameters that the team feels are critical. If a meaningful test plan cannot be developed within these limits, it may be necessary to request additional resources or to select an alternative test method.

Testing personnel should be involved in the selection of signal and noise factors. Their insights and knowledge of available test capabilities and facilities can facilitate this phase of test plan construction. Analysis of customer usage profiles and warranty data will also help the team compound appropriate noise factors. Once this phase is complete, the experimental design should be complete, with signal and noise factors identified and the inner and outer arrays established.

42.4. Procedures

As the team develops the experimental design, it must match its expectations with the capabilities of the test facility. Some robust design case studies showcase experiments done on a tabletop with virtually no test equipment; others describe studies that required elaborate measurement devices. Sophistication is not a guarantee of success; appropriate instrumentation maximizes the probability of a favorable outcome.

As the team considers the test procedures to be used, its members should discuss the following questions:

- ❑ What ancillary uses are anticipated for the data?
- ❑ What measurements will be taken?
- ❑ What is the desired frequency of measurements?
- ❑ What measurement system will be used?
- ❑ What test procedure is appropriate?

When establishing the test plan, it is important to consider what other uses may be appropriate for the data collected. For example, the development of useful analytical models depends on correlation with observations and measurements of actual performance. Data obtained by the team in the course of the robust engineering process may be useful in the development of analytical tools that can speed future design of similar components or systems. Therefore, collection of data not directly related to the control and noise factors being studied may be desirable; if this unrelated information can be recorded without disruption of the main experiment, it may be cost-effective to do so.

Once the superset of data has been defined, the team must determine what measurements will be taken. The test plan should clearly define what data are to be collected; it may be useful to develop a check sheet or data collection form to simplify and standardize the recording of information. Parameters such as technician identity, ambient temperature, relative humidity, and measurement time should be considered for inclusion if they are relevant to the experiment.

Measurement frequency must also be established. If the intent of the study is to examine the functions of components that do not degrade appreciably, simple one-time measurements may be appropriate (e.g., airflow through a variety of duct configurations). However, if the system is expected to degrade over its service life, time and/or cycle expectations should be included in the experimental design as noise factors, and the measurement interval must be specified. Some consideration must also be given to the capabilities of the test facility. Will the test run continuously? When are personnel available to make measurements? What data can be captured automatically? The answers to these questions will affect the test plan.

The levels of precision and accuracy necessary for successful completion of the experiments must be also be established. Simple A-to-B performance comparisons may be more tolerant of measurement error than detailed experiments that will also be used to develop analytical models of system behavior. These requirements will drive selection of the measurement technique. It may be necessary to conduct a gauge repeatability and reproducibility study before using an instrument; at the very least, the team should review its calibration records and verify its correct operation by testing a reference standard. It is critical that the team understand the uncertainty that the measurement system will contribute and assure that it is sufficiently small so as not to influence the analysis.

The final consideration is the selection or development of a test procedure. A large number of test methods have been published by organizations such as the American Society for Testing and Materials (ASTM), the Society of Automotive Engineers (SAE), and the Institute for Electrical and Electronics Engineers (IEEE); procedures released by government agencies and included within military specifications also may be relevant. A careful review of available methods will provide the team with guidelines for selecting or establishing an appropriate test technique.

A detailed written test procedure should be provided to the testing activity; it should be an independent document that summarizes all of the test requirements specified by the team. Not only does a complete well-written test procedure serve to eliminate ambiguities, but it also will become an important part of the project's documentation. It must clearly specify what data are to be collected, their method of collection, the frequency of measurement, and any other special instructions. Appropriate images or schematics should be included to clearly illustrate test fixture setups and relevant features of the component or system. Ideally, any person not intimately familiar with the test plan and development of this experiment should be able to conduct the measurements successfully without any instructions other than the written procedure. It may be worthwhile to have a peer review of the document by a person unfamiliar with the process; this will help to identify any assumptions made by the writer that should be defined clearly in the document.

42.5. Product

Once test planning is complete and the procedures have been established, the team must procure the materials to be tested. A number of questions must be addressed:

- ❏ Are surrogate parts appropriate?
- ❏ What adjacent components are required?
- ❏ Is the testing destructive?

The nature of the study and the noise factors involved will determine whether surrogate parts are suitable or design-intent components must be fabricated. For example, if the study is attempting to measure airflow in a duct, a proxy may be appropriate. An existing duct may be reshaped to reflect the desired configurations specified by the experimental design. However, care must be taken not to introduce unintended noise. In this example, if the reshaping process introduced surface finish changes or burrs that affected the airflow, this testing would not accurately reflect the performance of a normally manufactured component. It may be more appropriate to conduct the tests using samples made by stereolithography or three-dimensional printing processes. This would normalize the noise induced, affecting each sample equally and allow the testing to reflect more accurately the impact of each control factor.

Adjacent components may also be required for the testing. Use of nearby components or systems may simplify fixturing and improve the simulation of the test samples' operating environment. If the surrounding items generate heat or electromagnetic interference, for example, omitting them may cause the test to reflect actual performance of the components in service inaccurately. In the case of software testing, processor loading and memory consumption of other executing programs may influence the results. Although the project scope may be limited to a certain subsystem or component, the team must remain aware of those systems with which it interfaces.

If the testing is destructive, the team must consider how to minimize unwanted variability. Certain types of piece-to-piece variation can be compounded into the noise factors; if this is not practical, every effort must be made to make the test samples as uniform as possible to assure test outcomes are a result of changes to control factors and are not due to component variation.

42.6. Analysis

Once testing is complete, the team must analyze the results. Some postprocessing of test data may be necessary: for example, frequency analysis of recorded sounds. All data should be subjected to identical processing to assure that no spurious effects are introduced by these procedures.

Commercial products are available for the calculation of signal-to-noise ratios, main effects, and analysis of variance (ANOVA), or the team may elect to compute these values themselves using spreadsheets or other computational aids. Once the analysis is complete, the team will conduct confirmation and verification of the optimal configuration.

42.7. Simulation

Although they are not considered to be testing in the traditional sense, analytical models and computer-aided engineering (CAE) have their place in the robust engineering process.

If a simulation or model has been correlated adequately to real-world performance and behavior, it can be used to conduct the tests required during the optimization phase of robust engineering. An obvious advantage of this approach is that the use of computational modeling minimizes the costs associated with fabricating test samples, and typically reduces the time to conduct the tests. The sophistication of commercially available modeling software continues to increase, and the power and accuracy of these methods will continue to improve. However, the use of virtual testing does require the engineering team to exercise increased caution and diligence. In *Engineering and the Mind's Eye* [1], Eugene S. Ferguson wrote: "Engineers need to be continually reminded that nearly all engineering failures result from faulty judgments rather than faulty calculations." This adage is particularly appropriate to engineers attempting to use modeling and simulation.

For example, a robust engineering team may need to evaluate the response of a metal part fabricated by stamping. Their analytical model may yield incorrect results if the sheet metal's nominal thickness and material properties are used. To be more accurate, the simulation should reflect the thinning and potential anisotropy of the material due to the stamping operation. Other important factors that might influence the quality of the results are heat treatment, burrs and surface finish, and other artifacts of the fabrication process. In many ways, testing on actual components is more tolerant of oversights and erroneous assumptions; real specimens require fabrication and have intrinsic properties that can be inspected and scrutinized by the team. Virtual test samples are totally dependent on the quality of the parameters entered into the simulation, and it may be difficult to detect errors. For this reason it is important for the team to be just as rigorous in the development of a virtual test plan; all assumptions and boundary conditions should be documented. If no members of the team have experience with the manufacturing of the components tested, a consultant should be queried to ensure that any relevant manufacturing artifacts are considered.

In addition to monitoring the inputs to the model, the team should have some familiarity with the mechanisms it uses to derive its results. Teams that treat the analytical model as a "black box" do so at their peril. Many parameters within modeling software have default values specified that may or may not be appropriate for the team's simulation. Also, whether the software in use is proprietary or available commercially, the possibility of errors in the code does exist. For these reasons, the team should have an intuitive understanding of the experiment and the expected output of the model; this will help to identify unreasonable results due to simulation or input error.

Once the optimization phase has been completed by CAE methods, the team should proceed with actual testing during the confirmation and verification phases. The use of real components during theses steps in the robust engineering process will assure that any errors or oversights inherent in the virtual testing will be detected.

42.8. Other Considerations

External Test Facilities

If the testing is conducted by an external service provider, a number of issues must be considered that do not apply to internal facilities. First, it may be necessary to obtain a nondisclosure or other privacy agreement from the test agency. Many standard contracts include this requirement, but the team should take appropriate steps to assure that any results of their work are retained as a competitive advantage by their organization and not shared with competitors. Second, resource availability and test timing may be less flexible, due to competing demands from other customers. Since the team's influence over the facility's schedule may be limited, it is important that test specimens and other materials be delivered in advance of all scheduling milestones. Finally, extra care must be taken in the development of the test procedure. Technicians and engineers at general test facilities may not be intimately familiar with jargon or nonstandard terminology used by the team's organization. It is important that the team clearly communicate its requirements and expectations.

Documentation

The team should maintain adequate documentation of its project. Meeting minutes, P-diagrams, supporting engineering information, test plans, analysis, and final outcomes should be compiled into a master record maintained by the responsible engineer. This information should become part of the organization's institutional knowledge system; it can also serve as a basis for publication (if appropriate).

Because these documents may ultimately be distributed to an audience wider than the team originally intended, some care should be taken in their development. In particular, engineering documents are subpoenable, and therefore terms that may confuse a jury of nonengineers should be avoided. Inflammatory language and jargon should be minimized; the results of the project should be characterized fairly, in plain language whenever possible. This will minimize the possibility of the content being misconstrued in the event of litigation.

42.9. Conclusions

Testing is the heart of the robust engineering process. It is this fulfillment of the experimental design that allows subsequent analysis to determine optimal configurations and confirm and validate those conclusions. If testing resources are appropriately managed and utilized, a robust engineering team maximizes its probability of success.

Reference

1. Eugene S. Ferguson, 1992. *Engineering and the Mind's Eye.* Cambridge, MA: MIT Press.

This chapter is contributed by Michael J. Vinarcik.