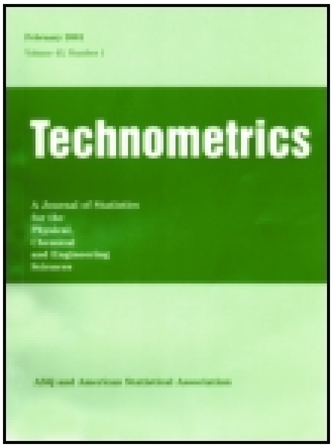

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Operating Window: An Engineering Measure for Robustness

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This article presents a metric for measuring and improving the robustness of engineering systems. Robustness is the ability of the system to avoid failure modes, even in the presence of realistic noises. The metric is the operating window (OW). The OW is the range in some input noise that produces a fixed failure rate in the failure modes. It can be thought of as an inverse method of measuring the ratio of output variance to input variance. The OW is determined while keeping the magnitude of some aggravating noise—the stressing noise—large and controlled. This allows the OW to be measured quickly. This OW approach has proved in practice to be very superior to the traditional ways of trying to develop reliability.

KEY WORDS: Failure-mode avoidance; Noise; Operating window; Reliability; Robustness.

1. INTRODUCTION

Reliability is failure-mode avoidance. A failure mode is any customer-perceived deviation from the ideal function of the product. There are two causes of failure modes: (1) lack of robustness (the ability of the system to avoid failure modes, even in the presence of realistic noises) and (2) mistakes. Reliability and quality are essentially the same thing. Reliability can also be thought of as the time-dependent part of quality. However, this distinction is so slight that it is better to recognize that quality and reliability are the same thing.

The reliability work that could be done during development falls into two types: prediction of field reliability and improvement of reliability. These two approaches tend to be incompatible. Prediction requires holding the product configuration constant and repeating many trials. Improvement requires changing the product configuration and testing each configuration with the minimum set of trials that is just sufficient to point the direction to improvement. Emphasizing improvement is more effective than emphasizing prediction. Improvement means increasing robustness and reducing mistakes early in the development process, when changes are cheap to make.

Effective reliability work during development aims to make the greatest possible early reductions in the occurrence of failure modes, both those caused by lack of robustness and those caused by mistakes. Predictions during the critical early stages of development are best limited to rough ratios with respect to existing products.

The minimization of mistakes is achieved by constraining the normal human tendency to commit errors. This is largely the objective of total quality management. In this article the subject is robustness.

The development of robustness involves two major aspects: (1) the metric used to measure robustness and (2) the search methods used to locate the region of the control-variable space that provides the greatest robustness. The first is far more important to effective development and is the subject of this article.

Traditional reliability engineering has concentrated on such metrics as bathtub curves and mean time to failure. These are useful for business purposes after the product is in the field, but they are not useful for the development of robustness.

There are two requirements for a metric for robustness: (1) that it effectively relate to failure-mode avoidance so that it provides the correct guidance during development, and (2) that it is easy to implement in engineering practice. Such a metric is the operating window (OW). This article describes the basic concepts of the OW.

2. BASICS OF THE OPERATING WINDOW APPROACH

Consider the example of a paper feeder, such as is in a copier and/or printer (Fig. 1). Such a system has two intrinsic failure modes: (1) Misfeed (the top sheet is not fed) and (2) multifeed (the second and sometimes additional sheets are fed along with the top sheet).

Simple consideration of Figure 1 will reveal that these are opposing tendencies. If the stack force is made very small, then misfeeds will be frequent, although multifeeds will be avoided. If the stack force is made large, then the multifeeds will be frequent, although misfeeds will be avoided. Thus it is easy to avoid either failure mode, but difficult to avoid both failure modes at the same time.

The tendency for the failure modes to occur is aggravated by noises. Noises are variations in the magnitudes of the critical functional variables that control the functioning of the system. The designers and producers of the system have limited or no control over these variations. An example of a noise is the friction coefficient between sheet 1 and sheet 2 in the stack of sheets that the feeder must feed. The systems designers and producers cannot control this critical functional variable. They have to accept whatever values are the result of the sheets that the users of the system load into the feeder. In practice, the magnitude of the friction coefficient varies widely. This tends to greatly degrade the performance of the feeder.

The traditional approach to system development has been as follows:

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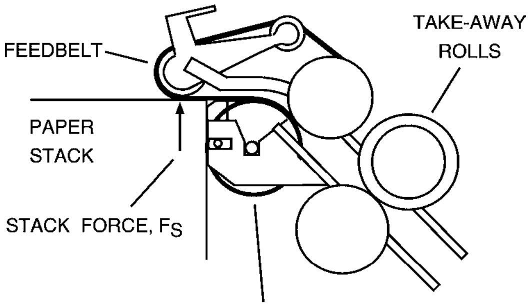

Figure 1. Paper Feeder.

1. Apply very small magnitudes of noises in the early developmental testing.
2. Late in the developmental testing, just before the planned entrance into production, increase the magnitude of the noises to a level intended to be similar to that imposed by the spectrum of users of the system.
3. Measure the failure rate under conditions similar to customer usage. This is driven by a misled desire for prediction. For high-performance systems, the specified upper bound on the failure rate is often 10^{-5}–10^{-4}.

This approach has two severe weaknesses:

1. Problems with lack of robustness are found only very late, when there is little time to do anything about them, and attempts to do so are very expensive.
2. Most of the developmental testing time is spent observing successful trials. This does not provide much information. (In any case, attempts to measure failure rates on the order of 10^{-5} will have little accuracy in a test of feasible duration.)

The improved method for the development of reliability has two key changes:

1. Large magnitudes of noise are applied early in developmental testing. This exposes the robustness problems early, when there is time to address them, with little cost.
2. The tendency to failure (robustness) is measured and improved. This avoids the need to attempt to measure small failure rates.

These two improvements greatly increase the rate of improvement of reliability during development, especially during the critical early phases of development.

2.1 Metric

To improve the robustness a metric is needed. The OW is such a metric. The OW is the range in at least one critical functional variable of the system within which the failure rate is less than some selected value. The range is bounded by thresholds (or a threshold) beyond which the performance is degraded to some selected bad level.

To make this concept more tangible, consider the paper feeder of Figure 1. Its OW is displayed in Figure 2. The following are the critical points about the OW in Figure 2:

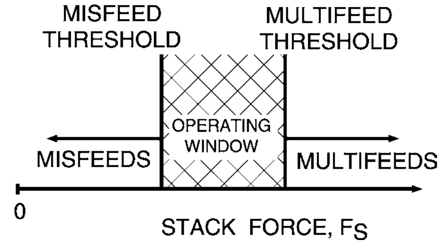

Figure 2. OW for a Paper Feeder.

1. Two thresholds bound the OW, misfeeds and multifeeds. These thresholds are determined for some very high failure rate, such as .1 or .5. This allows them to be quickly determined, avoiding wasting huge amounts of time in observing successful feeds. The precise magnitude of the failure rate that is selected to determine the OW boundaries is not important. The success criterion is the amount of expansion of the OW during development. Usually failure rates in the range .1–.5 are good to use. One might make an information-theory argument that .5 is the best.
2. The OW is determined while the system is subjected to a fixed and large magnitude of noise. In the paper feeder example, the large noise was introduced by using special stacks of paper that were designed and controlled to present great challenges to the system. (A noise that is used to degrade the performance is often referred to as a stress factor or stressing noise; it is said to stress the system.)

When this approach was applied at the Xerox Corporation in the late 1970s, the paper feeder was made very robust. It was then easily integrated into the total system that became the Xerox 1075 copier introduced in 1981. Because this feeder was so robust, it was easily applied to many new Xerox copiers and printers over the subsequent period of more than 15 years. The improvement of this OW approach over the previous traditional methods was dramatic.

2.2 Noise

An essential element of this approach is to make the noise large during early developmental testing so that it can be controlled. If the noise is allowed to be a random variable, as it will be in commercial use, then the number of repetitions for each trial must be large to average out the effect of randomness. By making the noise large and controlled, the number of repetitions to determine the OW thresholds can be small, usually in the range of 10–100.

Usually it is sufficient to select the most important noise, or compound factor of noise. This is done by considering the physics of the system and using knowledge of the magnitude of variations that will be more or less random (at least uncontrolled) during commercial use of the system.

In the paper feeder example, a little consideration of the physics of the system in Figure 1 will give insight into the important noise that tends to cause multifeeds. When the friction coefficient between sheets 2 and 3 is smaller than the friction coefficient between sheets 1 and 2, there is a driving force that tends to drive sheet 2 forward. Armed with this insight, we designed a paper stack that was created by interleaving two different types of paper. This created a large driving force for half of the interfaces. This was used to determine the multifeed threshold (Fig. 2). Of course, a different stressing noise was used when the misfeed threshold was determined.

In the development of a system, the initial configuration of the system concept is frequently of very low robustness. Even though the system concept might have high potential for robustness, the initial values of the critical design variables are often such to make the robustness very weak. If the very large magnitudes of noise are applied to such a system, then the performance can be nonfunctional; that is, not even one successful actuation can be achieved. This makes it difficult to obtain quantitative data, and furthermore is demoralizing to the development engineers.

This leads to the approach of progressive development. Initially the magnitude of the noise is made challenging, but not the maximum that we know how to apply. It is set at a level that will allow the OW to be determined and expanded. After the OW is expanded a satisfying amount, then the magnitude of the noise is increased. This makes the OW small again. Further development again expands it. In some cases a third level of still-greater noise will then be applied and the OW again expanded. After the subsequent improvements, the operating window when the original magnitude of noise is applied will be very wide (see Fig. 3).

It should be obvious that the OW itself is a noise or, more precisely, the "acceptable" range for a noise. Actually, because the OW is determined at high failure rates, the acceptable magnitude of the associated noise is a subrange in the interior of the OW.

Taguchi (1993) classified noises into the following categories:

1. Variations in production
2. Variations as the result of time and use
3. Environmental variations
   3.1 Customer-use profile
   3.2 External environmental variations
   3.3 Interactions with other subsystems.

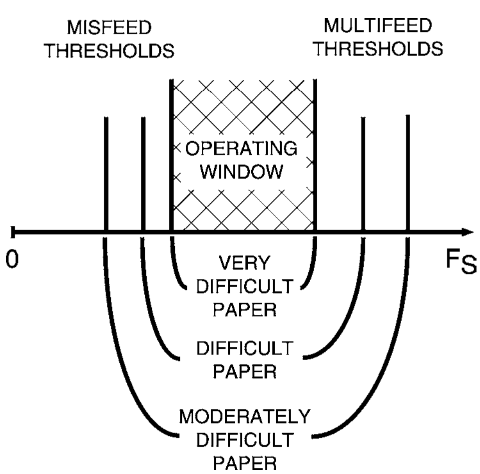

Figure 3. Progressive Development.

The last three subcategories were defined by Davis in 1994 shortly after he was introduced to Taguchi's work, and made operational at the Ford Motor Company at that time (see Davis 2003).

2.3 Noise as the Basis for the Operating Window

As already described, noises have two roles in the OW approach to robustness:

1. A noise is the basis for the OW. The variation in stack force is an example.
2. A noise is used to intentionally degrade the performance. The paper–paper friction is an example. This is referred to as a stressing noise.

In the example of the paper feeder, the OW is based on or associated with a production noise. The stack force will vary in production; thus it is a production noise, the first type of noise in the aforementioned categories. The 6σ range in production might be 1.0 newton. In such a case we might like an OW of 2 newtons.

However, I emphasize that there is not any acceptable magnitude or goal for the magnitude of the OW. The goal is simply to expand the OW as fast as possible during the development time available. That will make the OW as broad as possible (i.e., reliability as good as possible) for the system concept being developed. More than that is impossible to achieve. If more robustness is then desired, then a new system concept will be required that has greater inherent conceptual robustness. The earliest that this could be available is when the next new product is developed.

Any of the types of noise variables can be used as the basis for the OW. In the paper feeder, the OW was based on a production noise, the stack force. In considering the noise to use as the basis for the OW, all of the types of noises should be considered; all can be useful for the appropriate type of system.

Also, it is obvious that some such variables will be nonnegative with 0 as the ideal value. Then 0 is one limit, and only the upper bound of the OW will need to be determined.

2.4 Robustness Improvement

The OW is improved (made wider) by searching through the control-variable space to find the region of best robustness. Control variables have the following characteristic:

1. They control the physics of the system.
2. They can have their nominal value selected by the system engineers, who are therefore said to control the variables.
3. They are often not on production drawings. For example, a force is often a control variable, but forces usually are not on production drawings. Instead the force is the result of several variables that are on production drawings, such as spring rate and geometrical variables.

In the paper feeder example, in the 1970s more than 25 control variables had their values changed to improve the robustness.

2.5 Adjustment

After the OW is expanded, the nominal value is then adjusted to the interior of the OW. If the two failure modes are both equally undesirable, then the set point is midway between the two boundaries of the OW.

Often one failure mode is more detrimental than another. For example, users of copiers and printers are more inconvenienced by multifeeds than by misfeeds. When the quality loss is asymmetrical, then the set point is biased away from the more detrimental failure mode. In the paper feeder example, the stack force is set nearer to the misfeed boundary of the OW. This will cause more misfeeds than multifeeds. Ideally, the set point will minimize the total quality loss caused by both failure modes.

2.6 Improvement With Development Time

The objective of the development work is displayed in Figure 4. Initially (at the left of Fig. 4), the economical manufacturing tolerance cannot hold the critical variable within the OW. As development makes improvement, the situation improves as shown. The OW is made bigger, and the manufacturing tolerance that can be economically maintained during production is made smaller. The economical manufacturing tolerance is reduced by making the production system more robust, as well as by avoiding mistakes and doing design for manufacturability. Typically, the manufacturing tolerance should be approximately half or less of the OW or less. The exact ratio will depend on the failure rate used to determine the OW and on the minimization of the total life-cycle cost.

2.7 Inverse Method

A little thought about the paper feeder will make the following clear. In the OW approach we are holding the variation of the output essentially (or nominally) constant. In this example the variation of the output is the variation of the time of arrival of the sheet at some downstream station of the system. This variation is held "constant" by keeping both the magnitude of the noise and the failure rate at which the OW boundaries are determined constant. Then the OW is made as broad as possible. Basically, the ratio of output variance to input variance is being reduced.

Obviously, this could be done by directly measuring the variance of the output (the sheet time of arrival for the paper feeder) while holding the variation of the input, the stack force in the example, at two fixed values. However, in this example the time of arrival of the sheet at some downstream station is difficult to measure, especially for the second sheet, which is hidden by the first sheet. The use of the OW as described can be thought of as an inverse method for measuring the ratio of output/input variance.

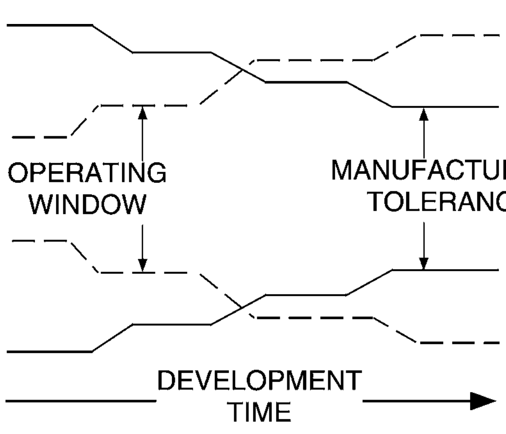

Figure 4. System Improvement With Time. I first drew this diagram at Xerox circa 1979. Subsequently, other people at Xerox smoothed out the two curves so that they had the appearance of two bottles pointing in opposite directions. This came to be called the "bottle model." It should be added that this diagram is relevant only when a production noise is selected as the basis for the OW.

3. IMPORTANT CHARACTERISTICS OF THE OPERATING WINDOW

Now that the basic concept of the OW has been described, two important aspects are discussed: (1) the dependence of the width of the OW on the associated failure rate and (2) multidimensional OWs.

3.1 Failure Rate-Dependent Operating Window

The width of the OW depends on the associated failure rate, as shown in Figure 5. These curves were calculated by Parks (c. 1980). She did this by integrating the probability density function over the appropriate space, with numerical integration used to determine the actual values.

It was my experience that the OW approach tended to worry executives greatly. They initially had great difficulty in comprehending that failure rates of .1 could be relevant to specifications of 10^{-5}. The failure rate-dependent OW of Figure 5 helped to overcome this anxiety.

Figure 5 demonstrates that the OW is determined at a very high failure rate. The assumption is that when the OW is expanded at high failure rates, it is also expanded at the desired low failure rates. Experience certainly verified this assumption in a qualitative way. This could be a good subject for further research.

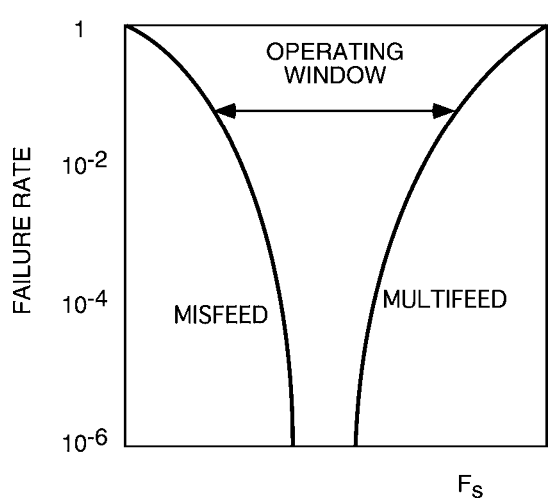

Figure 5. Failure Rate-Dependent OW.

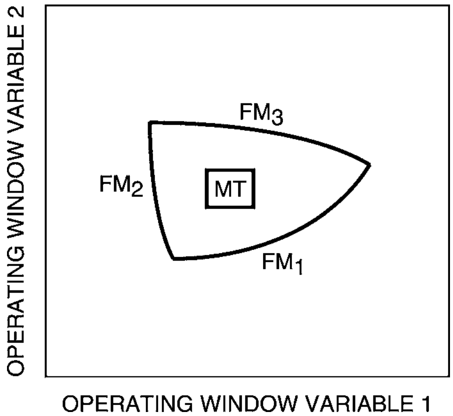

Figure 6. Two-Dimensional OW.

3.2 Multidimensional Operating Window

Although many systems have only one or two intrinsic failure modes, they often have secondary failure modes. For the paper feeder these are, for example, paper jams (the sheet becomes stuck in the feeder, usually by catching on some mechanical part) and paper damage. More than two failure modes usually cannot be characterized by a one-dimensional OW. Therefore, a two-dimensional OW is used. Our robustness development at Xerox in the late 1970s usually used a two-dimensional OW, an example of which is shown in Figure 6.

Two critical noises are used as the basis for the OW, as shown in Figure 6. Figure 6 shows the OW with three boundaries for three failure modes. Also shown is the manufacturing tolerance (MT) within the operating window. Typically a different stressing noise is used for each of the three failure modes.

In principle this approach could be extended to three-dimensional OW, or even more dimensions.

4. SUMMARY

The OW approach comprises the following steps:

1. Select an appropriate noise variable (or variables); use it (or them) as the basis for the OW.
2. Define a fixed, large magnitude of failure rate.
3. Apply a fixed, large magnitude of stressing noise.
4. Determine the range of the defining noise variable (or variables) that produces the fixed magnitude of failure rate; this range (or region) is the OW.
5. Move through the system control-variable space to expand the OW.
6. Adjust the set point to the interior of the OW, using total quality loss as the criterion.
7. Do this early in the system development cycle, and expand the OW as much as possible during the limited time available.

The application of this simple process provides great improvement in system reliability compared with traditional approaches to reliability improvement.

5. PERSONAL HISTORY NOTE

I started using elements of the OW approach during my early industrial career from 1952 until 1961. Then from 1961 until 1972 I took a sabbatical from this type of work to obtain my doctorate and do materials science research. In 1972 I joined the Xerox Corporation, where I did technology development. During the period 1972–1980 I led the development and application of the OW method as described here.

In 1982 I met Dr. G. Taguchi, and after a few months of study I recognized that his highly developed system was doing essentially the same thing as the OW approach. Because his method was highly developed and more sophisticated, no further development of the OW method was done.

6. CONCLUSION

When used with a good understanding of the system's physics, the OW approach is a good way to improve robustness. This, along with mistake avoidance, provides system reliability. A dramatic improvement in product development was achieved when the concepts described in this article were implemented.

The OW approach has the following significant advantages:

1. It is relatively easy to implement in engineering practice, an important consideration for industrial effectiveness.
2. It can readily handle two or more failure modes.
3. It is easily applicable to systems in which one (or more) response is difficult to directly observe and measure.
4. It provides great improvement relative to the engineering system development practices in common use today.

The concepts that are presented in this article are subject to extension and detailed development by the application of mathematics. A start has been made on this by Joseph and Wu (2002, 2004).

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REFERENCES

Davis, T. P. (2003), "Reliability Improvement in Automotive Engineering," in *Global Vehicle Reliability—Prediction and Optimization Techniques*, eds. J. E. Strutt and P. L. Hall, London: Professional Engineering Publishing.

Joseph, V. R., and Wu, C. F. J. (2002), "Operating Window Experiments: A Novel Approach to Quality Improvement," *Journal of Quality Technology*, 34, 345–354.

——— (2004), "Failure Amplification Method: An Information Maximization Approach to Categorical Response Optimization," *Technometrics*, 46, 1–31.

Parks, J. (c. 1980), internal Xerox reports.

Taguchi, G. (1993), *Taguchi on Robust Technology Development*, New York: ASME Press.