Selection of Quality Characteristics in the Context of Taguchi's Additive S/N Model

The Nature of Additivity in Robust Design

An ***additive model*** is used to predict the influence of the control factors on the response in S/N units of decibels.

For **n** control factors in a design, the optimum predicted S/N Ratio is…

$$S/N_{pred.} = S/N_{avg.} + (S/N_{A\ opt.} - S/N_{avg.}) + \ldots$$
$$\ldots(S/N_{B\ opt.} - S/N_{avg.}) + \ldots$$
$$\ldots(S/N_{C\ opt.} - S/N_{avg.}) + \ldots$$
$$\ldots(S/N_{n\ opt.} - S/N_{avg.})$$

As a consequence, your selection of a measurable response is not to be taken lightly!

This is by far the one area where engineers get into the most trouble – they measure quality instead of **functions**.

So, what is the additive model?

Lets look at a simple example:

If we had the following results for a simple 2-factor experiment:

Run	1 A	2 B	Response S/N
1	-1	-1	1.00 dB
2	-1	+1	4.00 dB
3	+1	-1	7.00 dB
4	+1	+1	10.00 dB

A simple additive model that would describe these result would be:

$$S/N = 5.5 + A*3 + B*1.5$$

- 5.5 represents the average S/N for the entire experiment
- 3 represents the **main effect** of factor A
- 1.5 represents the **main effect** of factor B

This equation is the additive model describing the results of the 4 experiments

The additive model refers to the **sum** of the individual factor effects on the response, without cross-terms (AxB interactions).

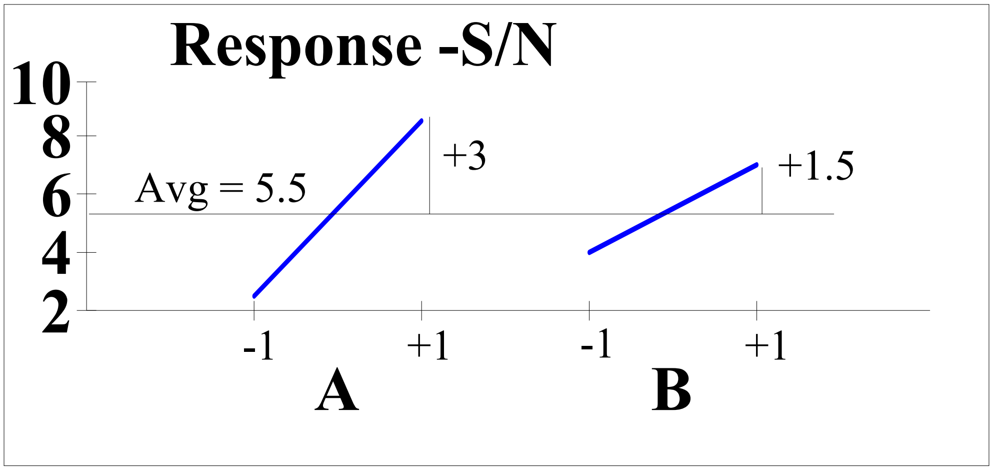
The predicted optimum is given by the levels of A & B that will result in the largest possible value of S/N (*Robustness*).

For the simple equation...

$$S/N = 5.5 + A*3 + B*1.5$$

…we can se by inspection that the optimum value for A is +1 & the optimum value for B is +1.

Graphically this can be represented by a factor main effects plot:



In our simple example, then, the predicted optimum, for the conditions

A = +1 and B = + 1

Is…

S/N = 5.5 + 3 + 1.5 = 10

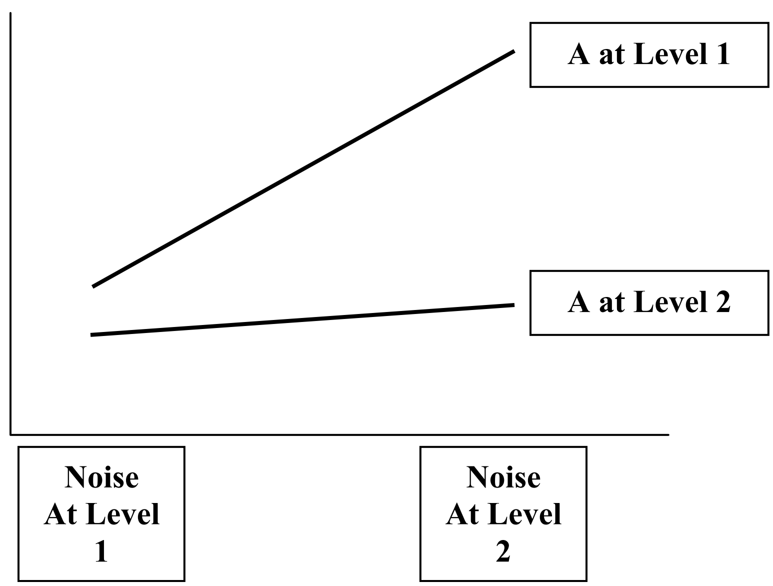
… in this case, the optimum condition is actually run #4, which gave a S/N = 10

Now let's discuss interactions from an engineering perspective by asking:

What is the role of interactions & additivity in parameter design?

(Remember: an additive model describes the response without any interaction terms)

The interactions we are interested in during Robust Design are between Control Factors & Noise Factors…



The interactions we want to suppress and avoid designing into our technology are the type…

...when the effect of one control factor is dependent on the level of another control factor.

Taguchi looks at it this way…

"It is more desirable to treat interaction by including it (sic) in noise. Only a main effect which exceeds the magnitude of the interactions can safely be used in [Robust Design]"

—G. Taguchi

(p 149, System of Experimental Design)

How do we know when we succeed with this approach?

When the S/N ratio behavior follows the additive model,...

...including only the main effects & no interaction terms.

- You should spend a good deal of time assuring & then verifying that the additive model is in effect for your experiments (*engineering focus rather than a statistical focus*)

The Taguchi method focuses our attention on *average control factor main effects*

Robust design assumes that the main effects...

- are strong enough to stand out

- have a greater effect than interactive effects between each control factor

Concept Design is used to develop *additive* Technology (*think Bernoulli's Equation*!!!).

We should not ignore the fact that interactions exist between control factors -- they really are there.

But we are attempting to optimize in spite of the interactions

- we can do this because we know that if the interactions are moderate, the additive model approximates the complex relationships between S/N & the control factors

- **using far smaller experimental designs (cycle time!)**

To rigorously study the math model that relates the S/N ratio to the design parameters A, B, C, D, etc., would be a lengthy process that's not worth our time.

- The additive model allows us to proceed down a very efficient path that depends on orthogonal array-based experiments...

  ... to produce the data that *verifies or denies* the validity of the additive model

That is why we:

- Recognize the interactivity of factors
- Assume that the interactivity is moderate
- Develop designs or processes that force interactivity to be weak (*design for additivity*)

Engineering Analysis in the Planning Stage

The key to minimizing interactions so that the additive model will work is effective engineering analysis & experimental planning.

We try to understand & control the underlying physical principles that drive system performance.

This is why we stress certain concepts such as:

- Main (or ideal) function of a design
- Energy transformations
- Additive factor relationships wrt the response

The closer you are to measuring the simplest act of physics that occur in your design, the better your chance that additivity will be approximated

How do we:

- Suppress interactions?
- Treat interactivity as noise in our analysis?
- Focus our attention primarily on robustness?

Here are the strategies that will help you achieve those objectives:

1. Choose & measure quality characteristics (responses) that reflect ***<u>fundamental functions</u>***

2. Use appropriate transformations such as the S/N ratio (esp. Dynamic Forms)

$$\log(A \times B) = \log A + \log B$$

3. Choose noise levels that overwhelm random error & put the focus on robustness

4. Choose & compound control factors & levels

    - with effects that are **<u>functionally additive</u>**
    - that using **<u>sliding levels</u>** when appropriate
    - logically grouped in energy transform terms

    <u>ADDITIVITY GROUPING</u> of Control Factors

5. Optimize the *<u>elemental subsystems</u>*, using *<u>dynamic</u>* analysis (if possible), before optimizing the *<u>entire</u>* product or mfg. process

Choosing the Quality Characteristic

The quality characteristic, **y**, is the response that is measured at each *combination* of control factors & noise factors.

The S/N ratio acts as a *summary statistic* for the effects of the noise factors on the quality characteristic.

It is calculated from the sample values (data) obtained at compounded noise factor combinations.

In parameter design, the most important job of the engineer is to select an effective characteristic to measure as data...

We should measure data that relate to the function itself and not the symptom of variability...

Quality problems take place because of variability in the energy transformation. Considering the energy transformation helps to recognize the function of the system.

Shin Taguchi, Technometrics, 34, 138 (1992)

You should measure parameters such as:

- Force
- Distance
- Velocity
- Acceleration
- Pressure
- Time

Avoid using indirect measure, such as

- Yield
- Faults
- Voids
- Pass/fail
- Fraction defective
- Number of defects
- Reliability
- Appearance
- Fraction defective
- % Non-Conforming

These are performance indicators, but they are *symptoms* of the underlying physical problems.

- Measure the physical functions, not the aftermath (*leading indicators* of impending failure !!!!)
- Measuring the aftermath will lace your results with interactions, which will only cause confusion & waste time

Dr. Taguchi summarizes the situation with his exhortation to:

DON'T MEASURE RELIABILITY TO GET RELIABILITY

Guidelines for selecting quality characteristics:

- Identify the ***ideal function*** for the product/process
- Characteristics should be ***energy related***
- Select characteristics that are ***continuous variables*** & are measurable through instumentation/tranducers.
- Characteristics should have an ***absolute zero***
- Select characteristics that relate to additive effects of the control factors (non-interactive, also referred to as ***monotonic***)
- Select characteristics that are ***complete*** (cover all dimensions of the ideal function)

  →*A complete response provides all the information required to describe the ideal function.*

- Characteristics should be ***fundamental*** *(basic to functionality)*

A response is fundamental if it...

- does not mix mechanisms together
- is uninfluenced by control factors outside the process being optimized

For more information on choosing quality characteristics see:

- Madhav Phadke, Quality Engineering Using Robust Design, Chapter 6
- R. Leon, A. Shoemaker, and K. Tsui, Technometrics, 35, 21 (1993)

Lets look at some examples to illustrate these concepts

Example 1: Baking Cookies

A baker planned an experiment to improve his cookie making process.

The baker was interested in increasing the number of acceptable cookies produced.

The baker chose to measure *yield* as a larger the better characteristic

Ask yourself:

- Is yield fundamental?
- Is it energy related

The baking team performed tests using time & temperature as control factors.

They generated the following data:

A: Time

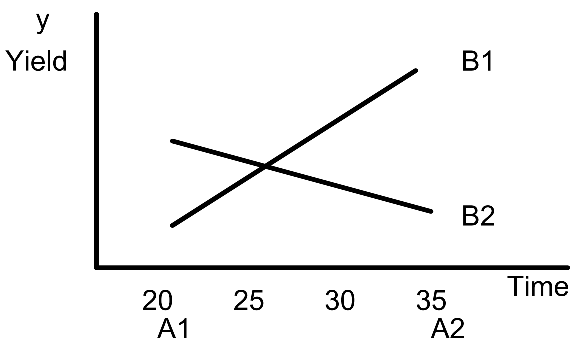
A1 = 20 Minutes

A2 = 35 Minutes

B: Temperature

B1 = 100ºC

B2 = 150ºC



Now ask yourself:

- Is this characteristic free of interactions?

Let's consider another quality characteristic

Cookie Color (Darkness)

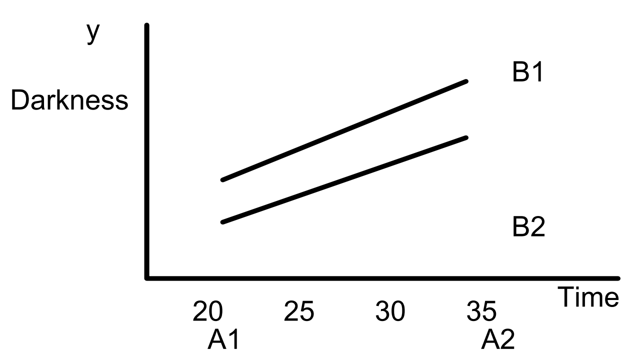
Now ask yourself:

- Is color fundamental?
- Is darkness energy related

The baking team measured the darkness for the same time & temperature test we just saw.

They generated the following data:

A: Time	B: Temperature
A1 = 20 Minutes	B1 = 100ºC
A2 = 35 Minutes	B2 = 150ºC



- Is this characteristic free of interactions?

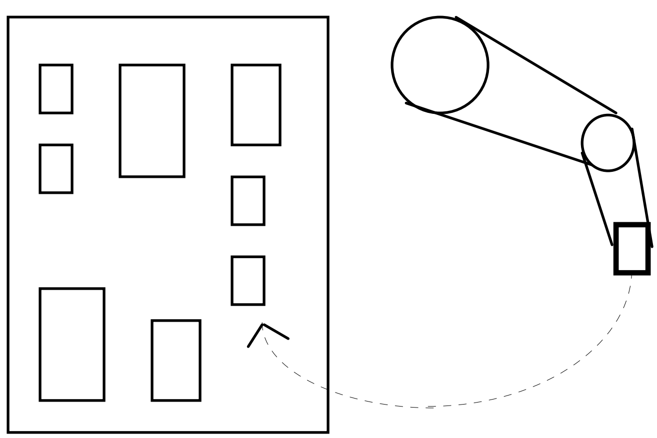
Example 2: Surface Mount Placement

A robot assisted production process is used for circuit board manufacture...

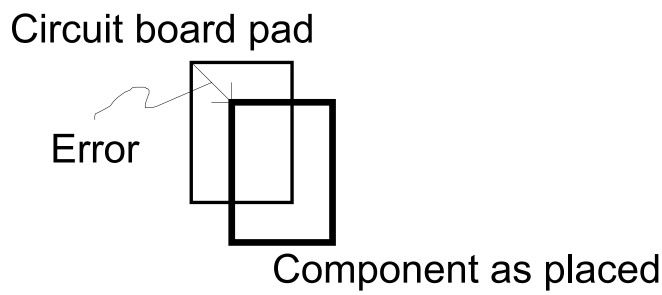
The ideal function is concerned with precision placement of surface mounted components on a circuit board.

The circuit performs reliably only if the components are *precisely located* on the board.

Overall circuit board **yield** is not a good response since there are many processing steps in the manufacture of a board.



The error (*distance*), **r**, between the *actual* location of the component & the *target* location on the board *seems* to be the obvious choice for a quality characteristic.



- Is the error fundamental or does it *mix mechanisms* together

- Would you expect **r** to be free of interactions?

It would also be necessary to consider *skew error*, θ, but that would not change the concerns raised above.

Consider the energy transformations & ideal functions...

The circuit board is *linearly transported* on a conveyer belt.

Ideally it moves only in the **y** direction - with no **x** error & no skew.

The robot transports a component to a position that is *independent of the circuit board*.

A *reference system relating a datum on the robot,* to the component & the board is required to analyze this problem.

Now the problem can be broken up into its *fundamental* aspects:

1. The *location of the board* relative to a datum on the *robot* when the board stops to receive the component.

2. The *location of the component* relative to a datum on the robot when it is placed down by the robot arm.

Note that in the case of the circuit board, **x** and **y** errors are clearly distinct & should be analyzed separately.

The appropriate coordinate system for the robot depends on the positioning mechanism & its *positioning degrees of freedom*.

By measuring the fundamental mechanisms - not the resulting quality...

... a much better (set of) quality characteristics are obtained.

Typically it is not desirable to co-optimize several characteristics simultaneously...

...but in some cases it is necessary.

Example 3: The Fuser

The Wrinkle Case Study…

To be done extemporaneously on a white board.