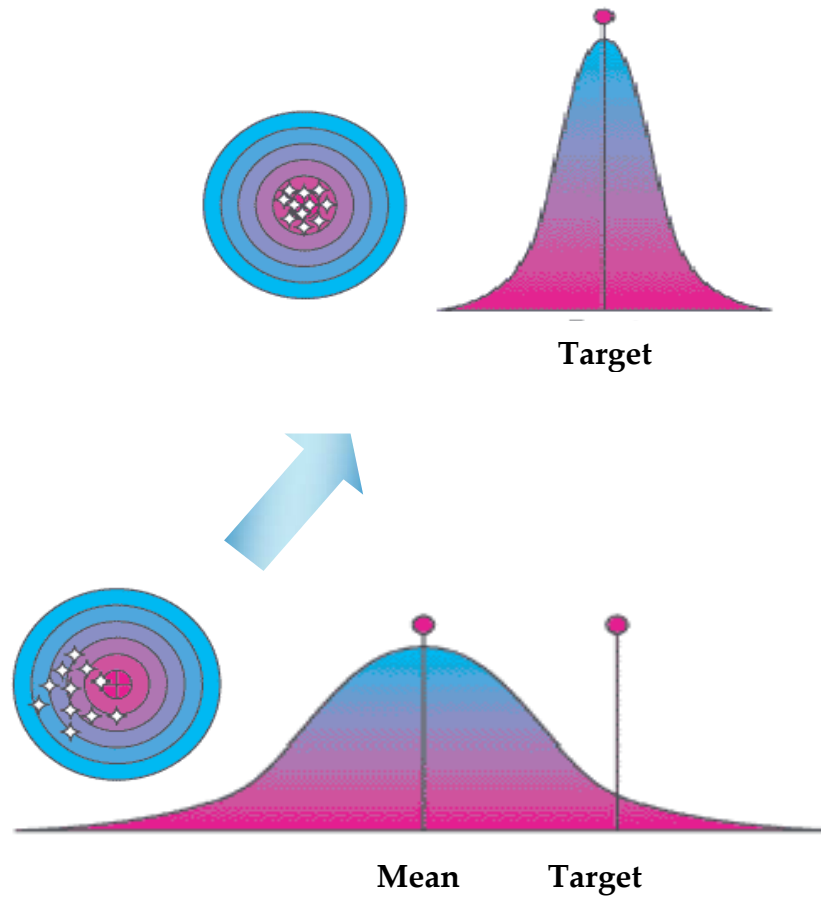


DOE-II. Advanced Experiment Designs for Robust Products and Processes



Nutek, Inc.

Quality Engineering Seminar and Software
Bloomfield Hills, MI, USA. www.Nutek-us.com



DOE-II. Advanced Experiment Designs for Robust Products and Processes

Presented
By

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Course Overview

Manufacturers with established market recognition should strive to build robustness in their products and processes to stay ahead of the competition. To achieve this goal, experienced quality and scientific professionals will need to learn and apply the advanced concepts in design of experiments and robust design strategies. This seminar with hands-on application workshop prepares attendees for immediate applications of the Taguchi experimental design technique for robust product and process designs.

Participants to this session are required to have completed DOE-I or equivalent course content. The topics of discussion in this session will be: *Noise factors, Outer array, Signal-to-Noise, ANOVA statistics, Dynamic characteristics, Loss Function*, etc. The aim of this session is to build a strong foundation among participating application specialists who are looking toward applying the technique to build robustness in new product design and R&D efforts. The last day of the session will be dedicated to hands-on application workshop which utilizes Qualitek-4 software for experiment design and analysis tasks.

Outline

Robust Designs

- Robust design strategy
- Outer array designs & Analysis using Signal-to-Noise ratios

Analysis of Variance (ANOVA)

- Purpose of ANOVA & Sample calculations of ANOVA statistics
- Test of significance & Pooling Technique
- Confidence Intervals & Discussion on Some Key Issues

Loss Function

- Rationale for computation of loss & Sample calculations
- Interrelationships with MSD, S/N, Cpk and Loss
- Improvement in terms of Variation diagram

Dynamic Characteristics

- Process representation of the system
- Ideal function & Objective characteristics (Beta, Sigma, and S/N)
- Experimental setup
- Analysis of results- TWO Step Optimization strategy

Application Workshop using Software

- Experiment Planning, Designs & Analysis tasks
- Group project presentations.

Principal Instructor's Background

Ranjit K. Roy, Ph.D., P.E. PMP (Mechanical Engineering, president of **NUTEK, INC.**), is an internationally known consultant and trainer specializing in the Taguchi approach of quality improvement. Dr. Roy has achieved recognition for his down-to-earth style of teaching of the Taguchi experimental design technique to industrial practitioners. Based on his experience with a large number of application case studies, Dr. Roy teaches several application-oriented training seminars on quality engineering topics.



Dr. Roy began his career with The Burroughs Corporation following the completion of graduate studies in engineering at the University of Missouri-Rolla in 1972. He then worked for General Motors Corp. (1976-1987) assuming various engineering responsibilities, his last position being that of reliability manager. While at GM, he consulted on a large number of documented Taguchi case studies of significant cost savings.

Dr. Roy established his own consulting company, Nutek, Inc. in 1987 and currently offers consulting, training, and application workshops in the use of design of experiments using the Taguchi approach. He is the author of **A PRIMER ON THE TAGUCHI METHOD** - published by the Society of Manufacturing Engineers in Dearborn, Michigan and of **Design of Experiments Using the Taguchi Approach: 16 Steps to Product and Process Improvement** published (January 2001) by John Wiley & Sons, New York. He is a fellow of the American Society for Quality and an adjunct professor at Oakland University, Rochester, Michigan.



SEMINAR SCHEDULE

Design of Experiments Using Taguchi Approach

DOE- I

- **Introduction**
 - The Taguchi Approach to Quality Engineering
 - Concept of Loss Function
 - Basic Experimental Designs
- **Designs with Interactions**
 - Application Examples
 - Basic Analysis
- **Designs with Mixed Levels and Interactions**
 - Column Upgrading
 - Column Degrading
 - Combination Design

DOE-II

- **Robust Design Principles**
 - Noise Factors and Outer Array Designs
 - S/N Ratio Analysis
- **Learning ANOVA through Solved Problems**
 - Computation of Cost Benefits Using LOSS FUNCTION
 - Manufacturer and Supplier Tolerances
 - Brainstorming for Taguchi Case Studies
- Design and Analysis Using Computer Software
- Group Reviews
- Computer Software
(Qualitek-4) Capabilities
- **Dynamic Systems**
- Class Project Applications
- Project Presentations



General Reference

Taguchi, Genichi: *System of Experimental Design*, UNIPUB Kraus Intl. Publications, White Plains, New York, 1987

Roy, Ranjit: *Design of Experiments Using the Taguchi Approach: 16 Steps to Product and Process Improvement*, John Wiley & Sons; ISBN: 0471361011

INTERNET: For general subject references (Taguchi + Seminar + Software + Consulting + Case Studies + Application Tips), try search engines like **Yahoo**, **Lycos**, **Webcrawler**, etc. For Nutek products, services, and application examples, visit:

<http://Nutek-us.com>

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Module - 9

Robust Designs for Dynamic Systems

Although many products and processes we encounter have definite desired level of performance, there are others that are expected to perform at a level in accordance with one or more input parameters. Such expected variable response is called dynamic characteristic and the product or processes that are designed to perform this way are called dynamic systems. The experiments design and Analysis of results from such dynamic systems is more advanced, but makes use of the principles learned so far. This module is dedicated to learning the structure of experiment design, strategy for robustness and analysis method for dynamic systems.

Robust Designs for Dynamic Systems

Things you should learn from discussions in this module:

- What is a dynamic system
- How to determine dynamic characteristics and the signal factors
- What is the nature of the response desired for dynamic system
- How interaction between control and noise factors plays role in robust design selection
- How to set up experiments to study dynamic characteristic

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You will need to have completed DOE-I before attending this session.

You will be able to set up experiments and analyze results for dynamic systems.

9.1 Introduction

The word robust means insensitive. The insensitive refers to the insensitivity of the response to the parameters on the input side of the system, be it a product or a process. On the input side, generally, there are some controllable factors and many uncontrollable factors. Again, the term insensitive implies being insensitive to the influence of the uncontrollable noise factors. When a product or process is robust, its response is less influenced by the uncontrollable factors. A robust design has less variation.

DOE Using Taguchi Approach - It is a special form of DOE practiced and popularized by Dr. Genichi Taguchi of Japan. The Taguchi approach is a relatively simpler and standardized type of DOE. In the Taguchi approach, the goal is to determine optimum design condition, not by seeking the best performance, but by evaluating the design that produce the minimum variation. This approach further employs a formal way to study the effect of uncontrollable factors and relate the effect of variation around the target, quantitatively, in terms of dollars (Loss Function). (Covered in DOE-I)

In robust design, Dr. Taguchi recommends a different approach than the conventional practices to designing products and developing technologies. The differences are pronounced in all aspects of experimental studies. The following leading questions and explanation will give you a brief insight into this approach.

Robustness for Svstems with Dvnmatic	
Dynamic Response Characteristics	<ul style="list-style-type: none"> • Response expected to be different for different inputs • System with such variable response are called dynamic system
Robustness	<ul style="list-style-type: none"> • Build product/process design insensitive to the influence of uncontrollable factors • Determine a combination of the control factor levels such that the response is immune to the influence of the noise factors
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Many systems are designed to perform in direct proportion to the input parameter called signal factor. Such systems are called Dynamic Systems.

**I. What are we after?
What are we to study?**

Conventional approach:

- What's wrong and how can we fix it?

Robust design approach:

- What is the product or process expected to do?
- What is the intended function?
- How can we design it to do the intended job the best way?

Defining Dynamic System Responses	
Dynamic Response Characteristics	<ul style="list-style-type: none"> • Response expected to be different for different inputs • System with such variable response are called dynamic system
Robustness	<ul style="list-style-type: none"> • Build product/process design insensitive to the influence of uncontrollable factors • Determine a combination of the control factor levels such that the response is immune to the influence of the noise factors
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Systems that exhibit variable outputs are said to have dynamic response characteristics.

As with the static system, with fixed desirable output, the strategy for robustness is the same: to make output insensitive to the uncontrollable factor influences.

**II. What do we want to investigate?
What to include in the study?
What to do about he influence of factors we cannot control?**

Conventional approach:

- Study control factors and control or eliminate uncontrollable factors.

Robust design approach:

- Control the controllable factors such that the system is insensitive to the variation of the uncontrollable factors.
- When the system is insensitive, it exhibits reduced variation about the desired



(ideal) performance (function). The ideal function for the system is determined by studying the expected performance before conducting the experiments.

Identification of System Parameters
<p>Questions that would lead to describing the performance of the product/process under study:</p> <ul style="list-style-type: none"> • What would customer want to do? (The intent) • What does customer feel or see as the effect? (Perceived result) [Above two: VOICE OF CUSTOMER] • How is the intent being fulfilled? • How is the intent measured? • How is the result (performance) evaluated? • Is the evaluated result expected to change? <p><i>Nutek, Inc.</i></p>

The most important part in studying a dynamic system is to be able to define the system parameters clearly. Particularly, being able to identify the variable out and the cause for such expected changes in output are important starting steps.

**III. What are the desired objectives?
What are the evaluation criteria?
How do we measure each of the evaluation criteria?**

Conventional approach:

- Measuring symptoms of poor quality and making decision based on it.

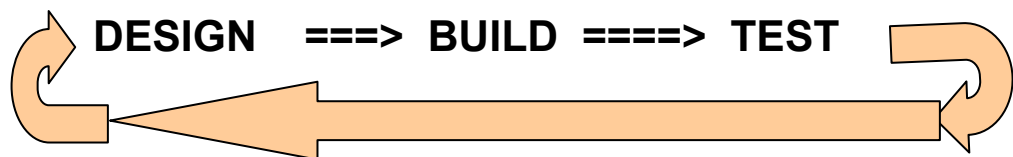
Robust design approach:

- Measuring how well the performance input is transformed into the intended function.

9.2 Why Robust Design?

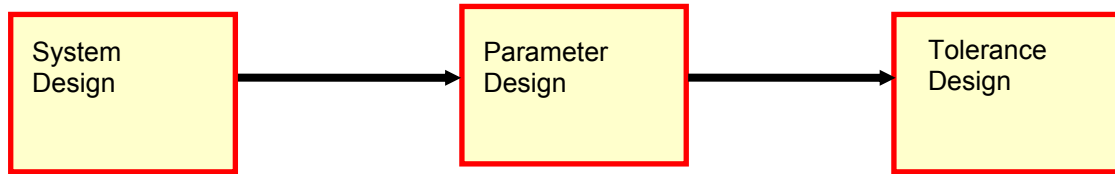
It is a more formal approach than conventional practice.

Conventional practice:

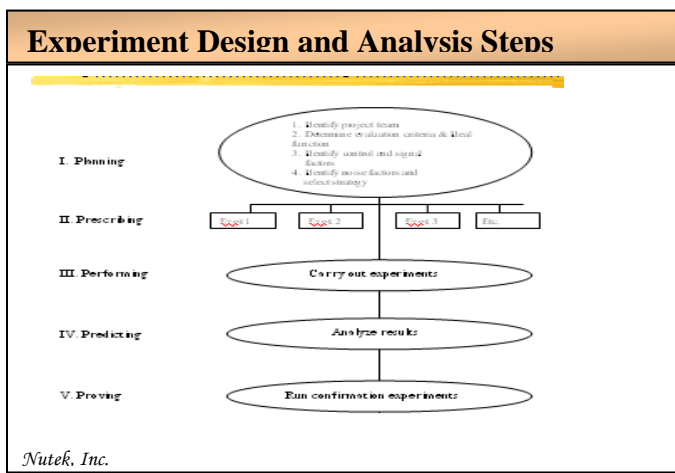


Taguchi quality engineering approach prescribes different forms of experimental efforts for different phases of engineering.





Robust design method is applied in the parameter design phase of the Taguchi's quality engineering recommendation shown above. The application steps for parameter design are shown in the diagram below.



The application steps for experimental studies of dynamic system are same as the five step process followed for the static system with minor difference in planning, design, and analysis of results.

Robust design encourages taking a broader look at the product and process under study. It requires that we look at designing the product to deliver things that the customers would like it to offer. Many in the industry have termed such collection of information as the *voice of the customer*. To collect information along this line, we need to put ourselves in the position of the customer and ask the following questions.

What would customer want to do?

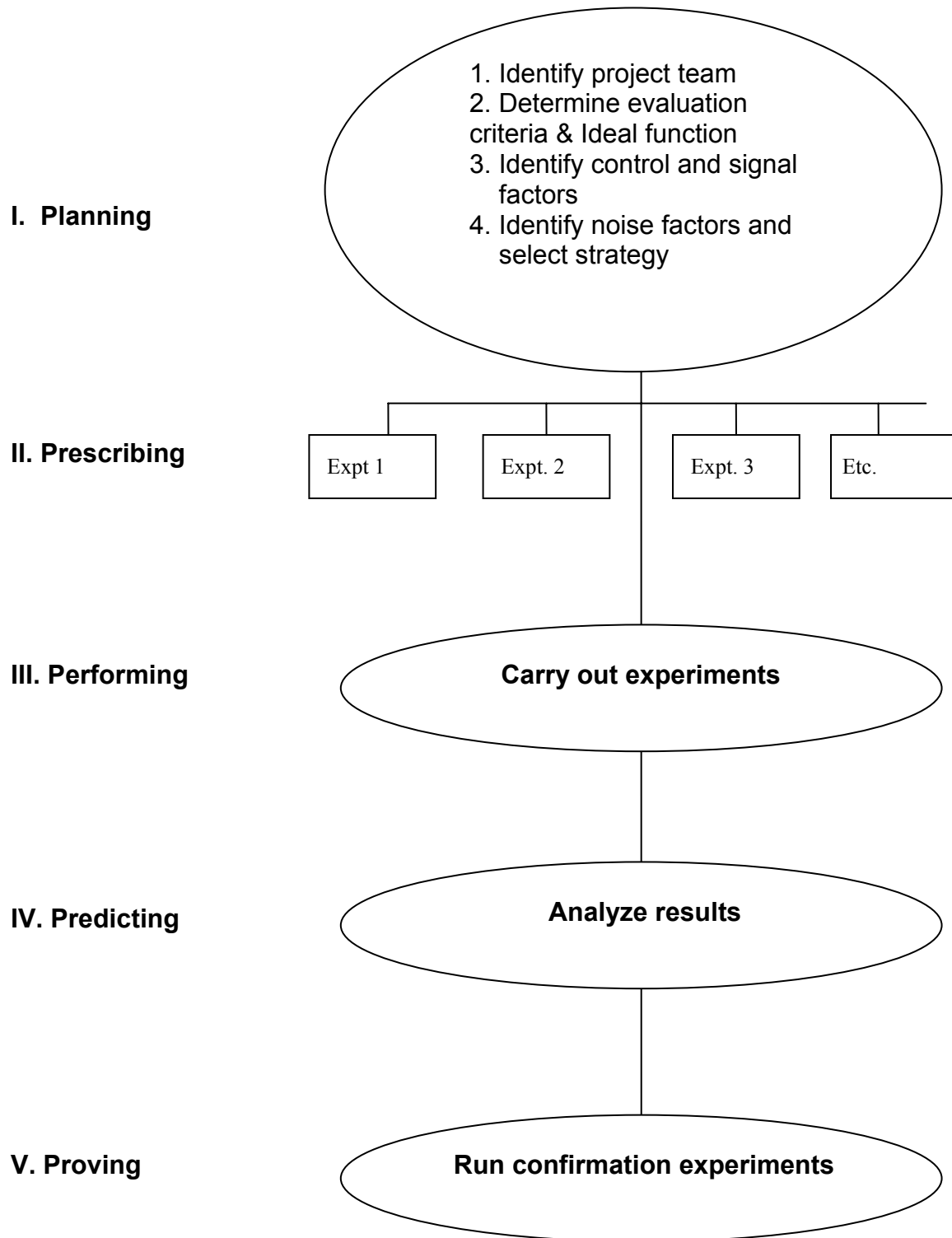
To satisfy what customer wants, he/she is willing to take action (do something). This action, as shown in the figure, is called the *customer intent*. Of course, when the customer takes an action, he/she expects to see some thing happen (some effect to take place).

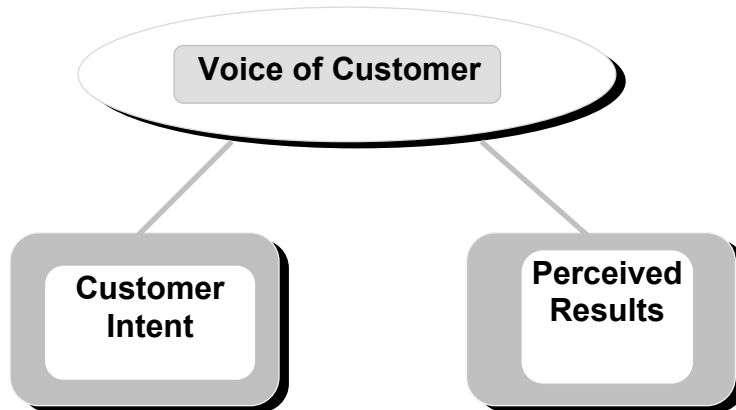
What does customer feel or see as the effect?

It is what the customers see as happening when /he/she takes some action. This effect is called the *perceived result*.



Parameter Design Application Steps





Example		
Intent	Action Taken (SIGNAL)	Perceived Results
1. Slow down vehicle	Apply brake.	Vehicle slows down
2. Turn vehicle to right	Turn steering wheel right	Vehicle turns right
3. Have fuel in tank and minimize running out of gas	Fill up tank with gas.	Fuel gauge shows full tank.
4. Increase air circulation from house fan.	Turn knob to higher speed setting.	Feel that fan blows more air.

Answers to the following questions that reveal more information needed to describe the way the product or process operates.

- How is the intent being fulfilled?**
- How is the intent measured?**
- How is the result (performance) evaluated?**
- Is the evaluated result expected to change?**

The intent is an action on the part of customer. The measured value of the intent in quantitative term is called the SIGNAL.

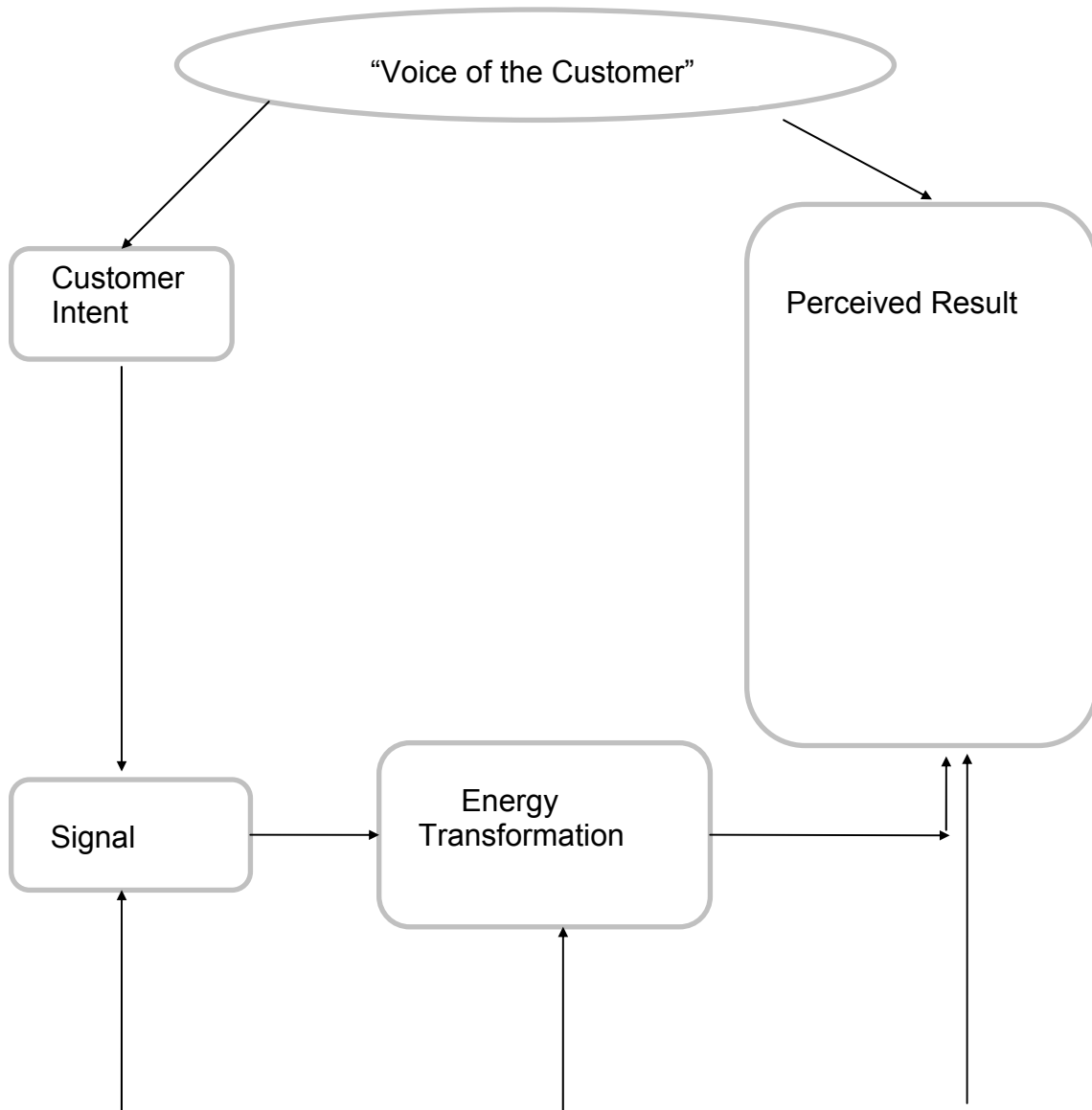
Example: Amount steering wheel is turned, Force applied on the brake to slow down vehicle, etc.

The measured value of the result is generally referred to as the RESPONSE.

Example: The amount vehicle turned, Deceleration of the vehicle when the brake is applied. Etc.



Model of the System Response

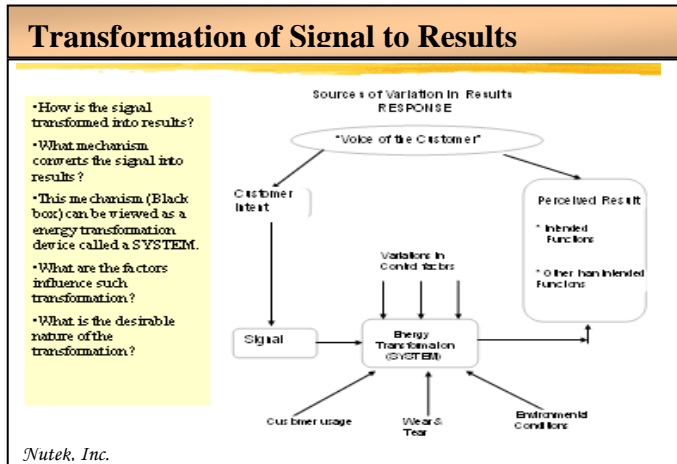


<u>Action by Customer</u>	<u>System – Energy Transformation</u>	<u>Perceived Result</u>
* Push brake pedal	* Fluid pressure Activates brake pads	* Vehicle slows down
* Turn steering wheel	* Steering linkages Turn wheels	* Vehicle turns

Some questions that help define the system are:

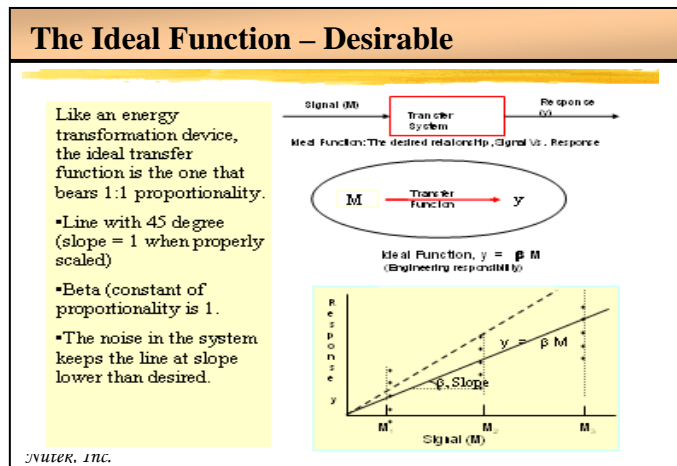


- How is the signal transformed into results?
- What mechanism converts the signal into results?
- This mechanism (Black box) can be viewed as an energy transformation device called a SYSTEM.
- What are the factors influence such transformation?
- What is the desirable nature of the transformation



The things that customer does or the action customer takes to satisfy the intent is converted to result by means of a mechanism/process called the SYSTEM. A system can be viewed as an energy transformer which transforms SIGNAL to RESULT.

9.3 Ideal Function



For most systems, the relationship that the transformation of signal to result follows is guided by laws of physics. The desirable relationship that the signal and response (result) bears is called the IDEAL FUNCTION.

The ideal function is a straight line with a highest slope (maximum = 1, for energy transformation principle)

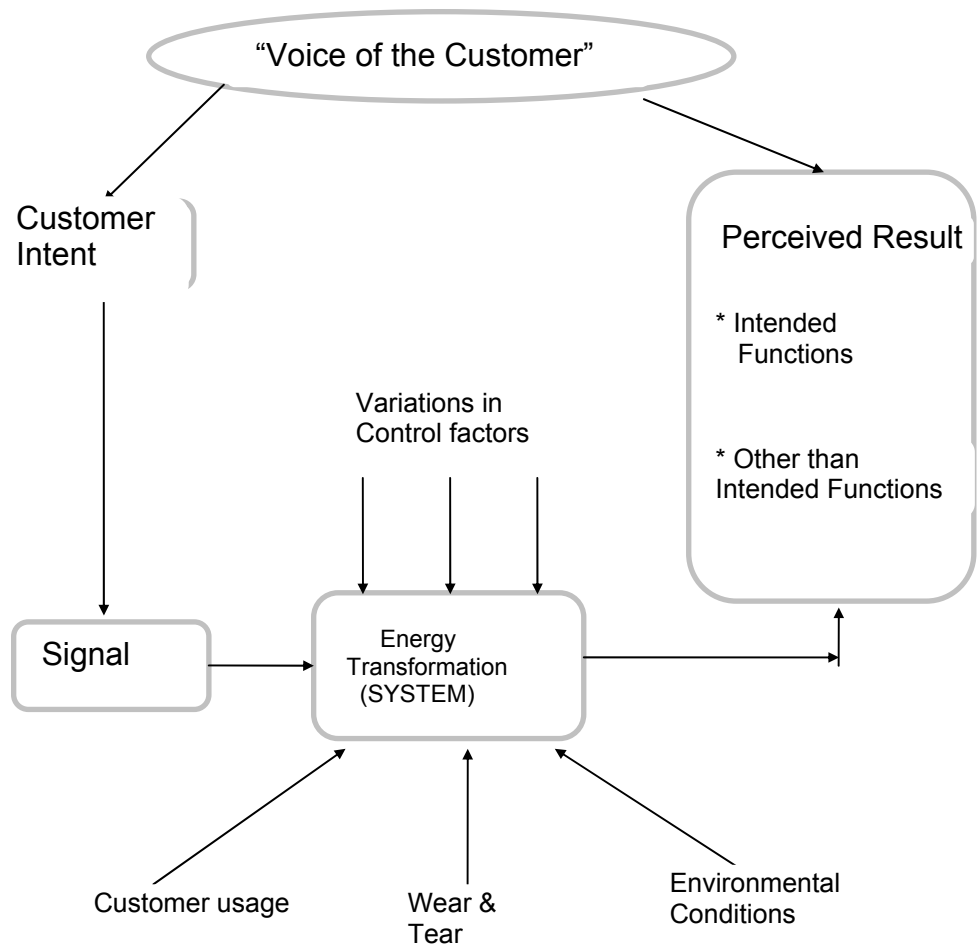
What is a SIGNAL factor?

Signal is an action undertaken to satisfy CUSTOMER INTENT.

1. Signal, Noise and Control factors produce RESULTS.
2. Unlike Control factors, Noise and Signal values are expected to vary during applications.
3. Response bears a direct relationship with Signal: this relationship is desired to be LINEAR. (This is not desired from noise)

Not all systems have SIGNAL.

Sources of Variation in Results



Ideal function is the mathematical relationship of transformation between response and the signal.



Ideal Function: The desired relationship, Signal Vs. Response

$$M \xrightarrow{\text{Transfer Function}} y$$

In mathematical terms, the transfer function is the constant of proportionality between response, y , and the signal, M .

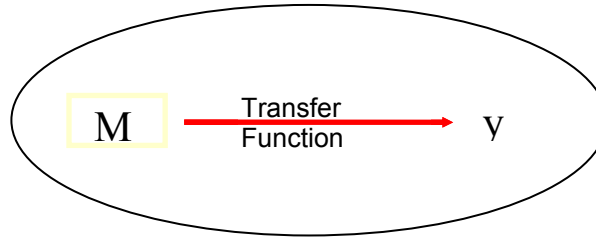


$$y \propto (\text{proportional to}) M$$

or $y = \beta M$ (linear relationship)

where

β = Constant of proportionality which establishes the constant relationship between the signal and the response.



Ideal Function, $y = \beta M$

(Engineering responsibility)

What Does an Ideal Function Do?

It defines a mathematical model of the system performance based on physics. The engineer can use this model to evaluate the system performance by comparing the closeness of the data to the model and adjust the control factors that produce results closest to the ideal function.

Note:

In contrast to the traditional approach where system performance is represented by a math model (analytical simulation, FEM model, distribution equation, etc.), the robust design approach starts with idealized behavior representation and attempts achieve that by adjusting the system parameters.

A number of common examples of systems (mechanism, product, or process) are shown below. In each example, common signal and response characteristics have been identified. Often there are other signals and multiple responses are applicable. The response as a linear function of the signal is theoretically desired behavior and is often supported by the physics applicable to the system.

Examples of Dynamic Systems and Ideal Functions

Example Case 1: Fuel Gauge Reading

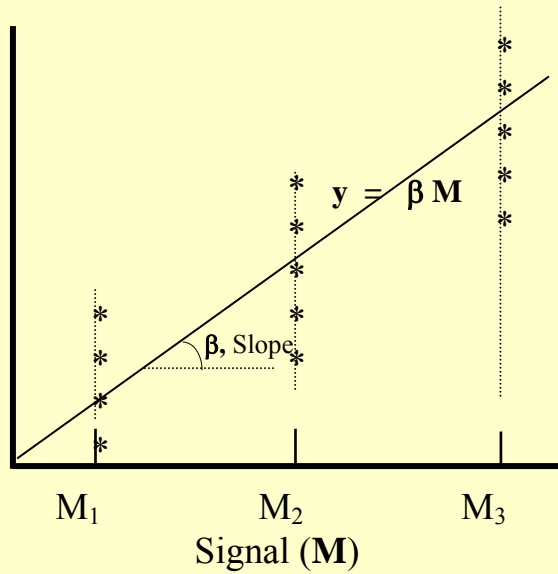
Signal Factor (M):
Amount of gas in the tank

Response (y):
Displayed fuel reading

Notes:
Displayed reading is expected to be same as the fuel content.



Response
(y)



Example Case 2: Faucet Water Flow Control Mechanism

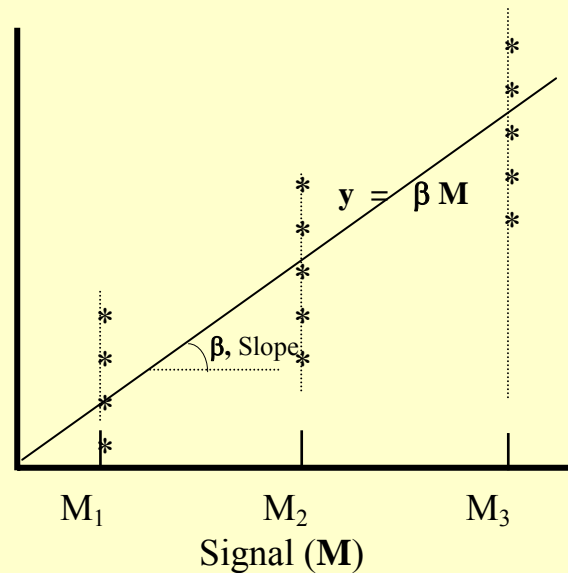
Signal Factor (M):
Faucet opening (turn)

Response (y):
Flow rate

Notes:
Flow rate expected in proportion to the Opening.



Response
(y)

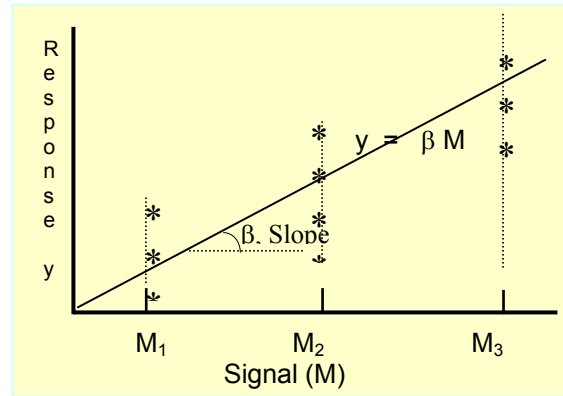


Example Case 3: Blower Fan Speed Control

Signal Factor (M):
Fan speed

Response (y):
Air flow control

Notes:

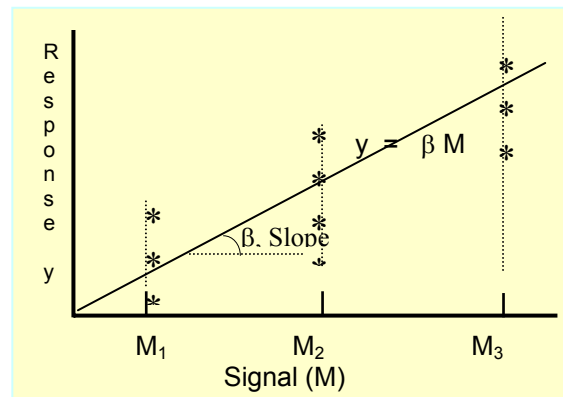


Example Case 4: Automotive Engine Acceleration Mechanism

Signal Factor (M):
Accelerator pedal depression

Response (y):
Engine RPM

Notes:

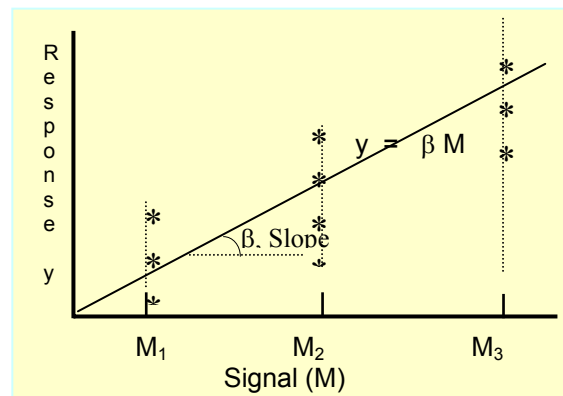


Example Case 5: Microwave Cooking Time

Signal Factor (M):
Energy level

Response (y):
Cooking time

Notes:

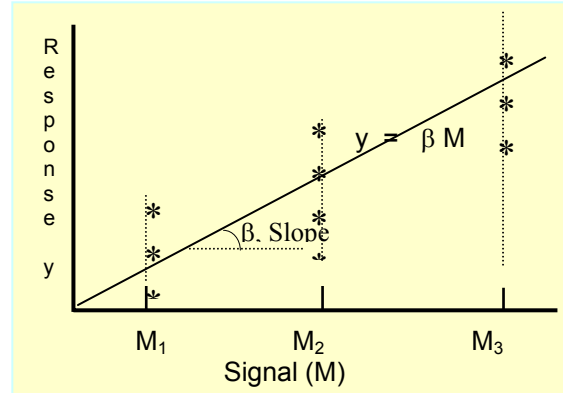


Example Case 6: Automotive Steering Wheel Turning Mechanism

Signal Factor (M):
Steering wheel turn angle

Response (y):
Wheel turn angle

Notes:

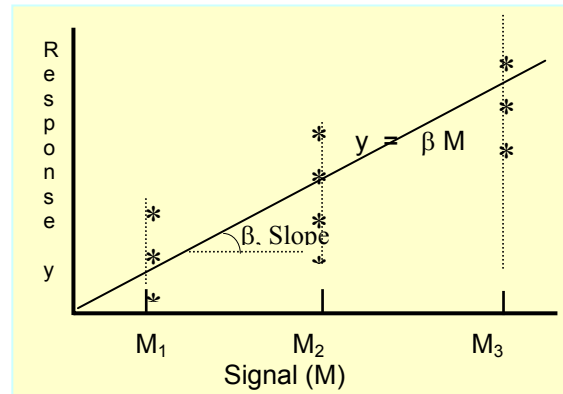


Example Case 7: Weighing Scale Design

Signal Factor (M):
Weight of subject

Response (y):
Indicated weight

Notes:
Weight indicated should be the same as weight of the subject.

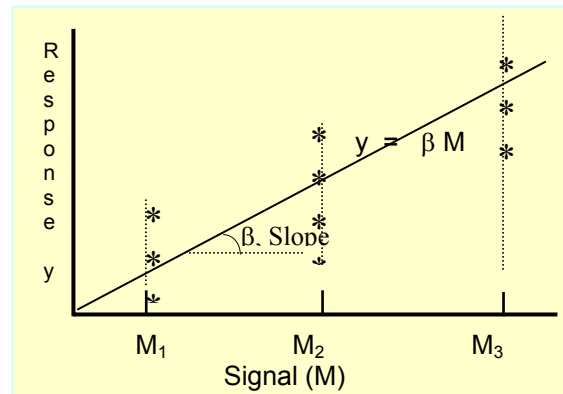
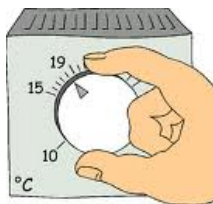


Example Case 8: Air-conditioning Control

Signal Factor (M):
Knob setting

Response (y):
Temperature change

Notes:

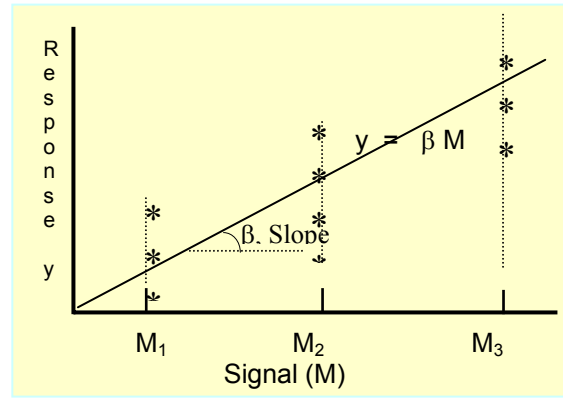


Example Case 9: Bill Changing Vending Machine

Signal Factor (M):
Bill type

Response (y):
Changes received

Notes:

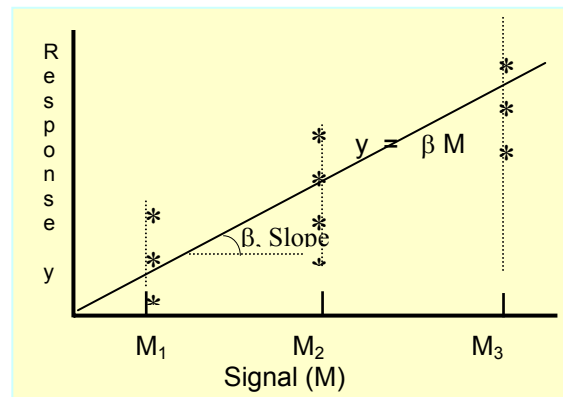
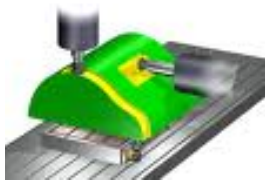


Example Case 10: Machining of Dies

Signal Factor (M):
Part sizes/dimension

Response (y):
Machined dimension

Notes:

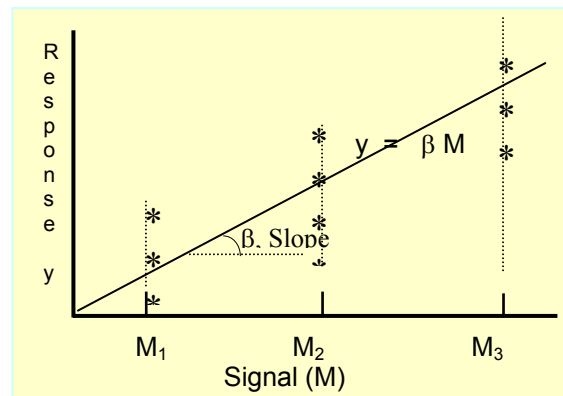


Example Case 11: Voltage Measuring Instrument

Signal Factor (M):
Battery voltage

Response (y):
Voltage reading

Notes:

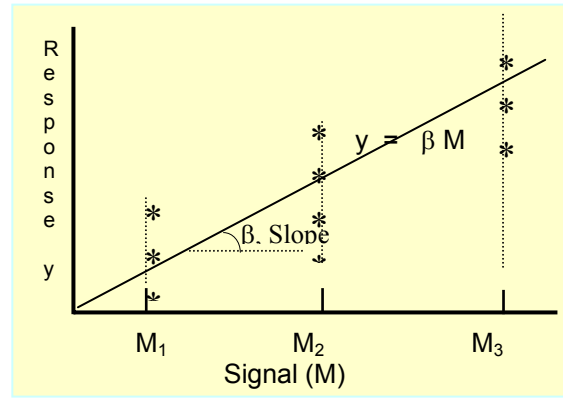


Example Case 12: Airbag Deployment Pressure

Signal Factor (M):
Elapsed time

Response (y):
Pressure generated

Notes:

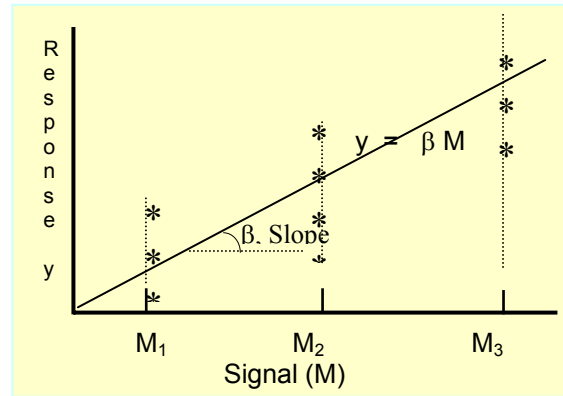


Example Case 13: Test of Material Elasticity (Hooke's Law)

Signal Factor (M):
Extension/Displacement

Response (y):
Axial force

Notes:
Stress/Strain = Constant (E)

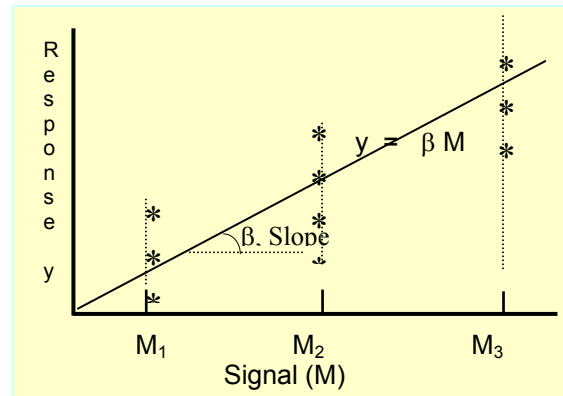


Example Case 14: Door Sealing Rubber Design

Signal Factor (M):
Bulb displacement

Response (y):
Closing pressure

Notes:

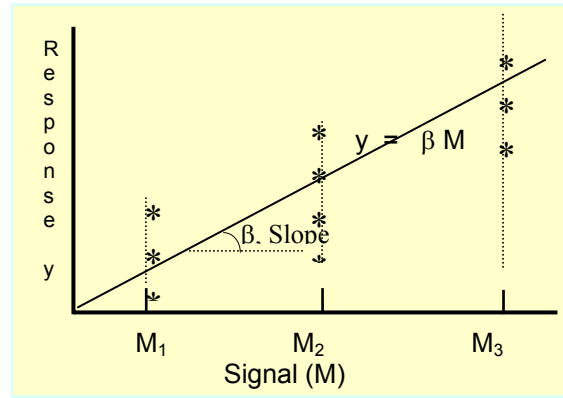


Example Case 15: Hydraulic Pump Performance

Signal Factor (M):
Speed

Response (y):
Generated pressure

Notes:



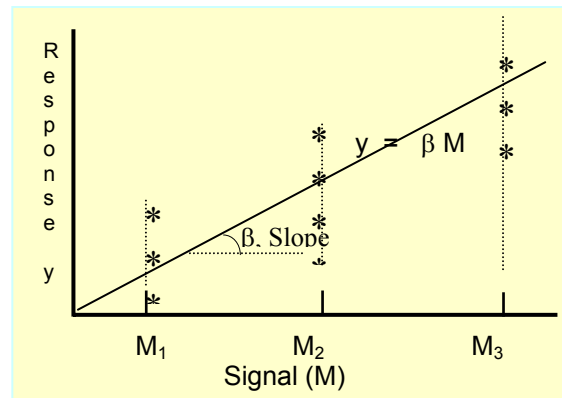
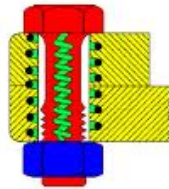
Example Case 16: Threaded Fastener Joint

Signal Factor (M):
Torque

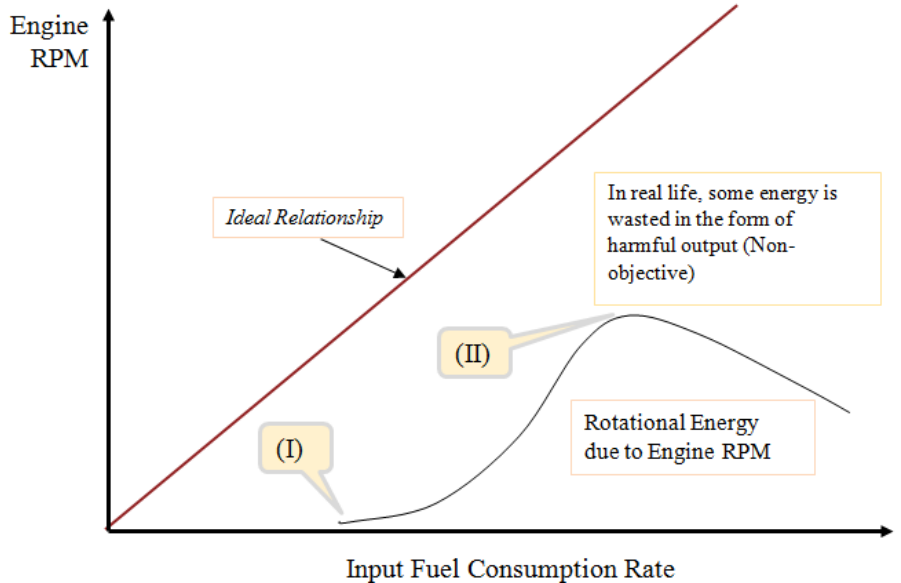
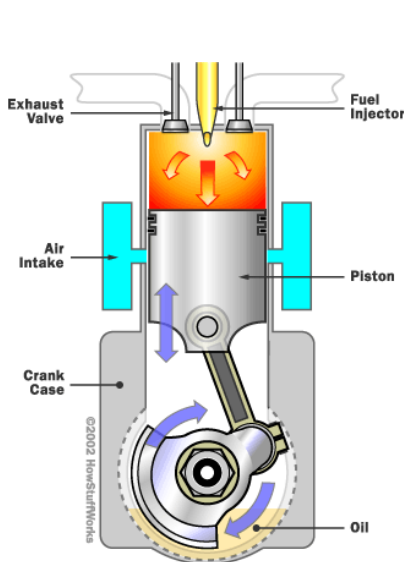
Response (y):
Fastening force

Notes:

The force generated is proportional to the Applied torque within the elastic range



Example Case 17: Internal Combustion Engine



Typical research objectives: improvement of internal combustion engines such as combustion efficiency, reduction of carbon monoxide, oxidized nitrogen compounds, or carbon particles, etc.

Taguchi Approach: Improve overall objectives by optimizing energy transformation .

The ideal condition between fuel rate and engine RPM is the straight line as shown , under which all chemical energy is converted into mechanical rotational energy of the engine.

- In real operating condition, chemical energy of fuel is used to overcome mechanical loss of the engine; thus, the engine RPM is zero if the fuel rate is lower than (I). As fuel rate is increased, RPM slowly increases and reaches its peak value at condition (II). If you keep increasing the fuel rate, however, the RPM may go down, indicating that the increased fuel energy is converted into harmful side effects such as vibration, audible noise, thermal loss in the exhaust pipe, residual fuel, carbon monoxide, nitrogen dioxide, etc.
- When the engine performance and fuel consumption are improved and the harmful side effects are reduced, the real operating condition moves closer to the IDEAL CONDITION which results:
 - Reduced deterioration and wear of the engine
 - Increased reliability & life.

Signal (M): Fuel Consumption Rate

Response (Y): Engine Rotation

Desirable output – Mechanical mobility energy (Y)

Unwanted outcome

- Mechanical loss (Vibration, friction, wear, audible noise)
- Thermal (Exhaust, radiator,..)
- Incomplete combustion reaction (Residual Fuel, Monoxide, Nitrogen Dioxide, Carbon Particles)

System: Internal Combustion Engine

Factors: Fuel, air-fuel mixing, combustion chamber, exhaust system, cylinder-piston design parameters, etc.

Noise Factors:

fuel impurities, temperature distribution variation of the engine, fuel octane values, and lubrication oil viscosity.

A good engine is robust against all kinds of noise factors.

(Noise factors are introduced into the experiment by compounding the them into two extreme noise conditions)

The goal of robust design is to minimize the unwanted effects which can be obtained when the performance resembles the ideal function.

9.4 Desirable Performance from Robust Design of Dynamic Systems

Robustness for Static System – a Model

Static System: Tiger Woods putting golf balls
August 11, 2004
Top spot: Tiger Woods' hold on the world number one ranking is more tenuous now.

"Vijay Singh has been on Tiger's heels for some time now, and if either Singh, or Ernie Ells were to win the PGA Championship, Woods would relinquish his spot atop the rankings."



Nutec, Inc.

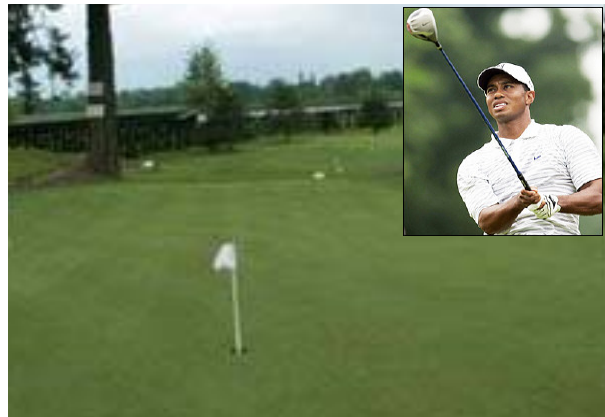
For static systems (DOE-I) where the target is fixed (at a point, zero, or higher), the objective is same as for an expert golfer: putting the ball in the hole or being as close to the hole as possible, most of the time.

Comparison of Solution Strategies for Static and Dynamic System

Static System: Champion player like *Tiger Woods putting golf balls*
August 11, 2004

Top spot: Tiger Woods' hold on the world number one ranking is more tenuous now.

"Vijay Singh has been on Tiger's heels for some time now, and if either Singh, or Ernie Ells were to win the PGA Championship, Woods would relinquish his spot atop the rankings."





Lance Armstrong rides into Paris, collects record sixth consecutive Tour title (Tour de France).

Sunday July 25, 2004 5:39PM

PARIS (AP) -- Lance Armstrong raced onto the crowd-lined Champs-Elysees as a yellow blur, bathed in the shimmering light of a 24-carat, gold-leaf bike, a golden helmet and the race leader's yellow jersey.



Dynamic System: *Lance Armstrong biking for Tour de France*

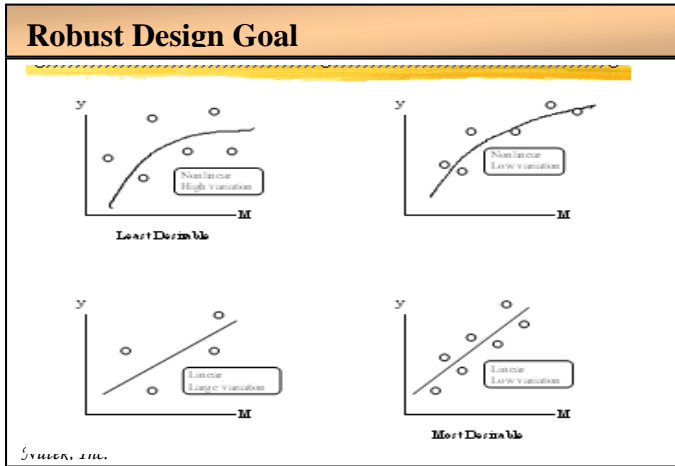
Robustness for Dynamic System – a Model

A thumbnail version of the news article about Lance Armstrong's Tour de France win. It includes the same three images: Lance Armstrong on his bike, the road through the forest, and the silhouette of the cyclist. The text is smaller but follows the same structure as the main article above.

Lance Armstrong rides into Paris, collects record sixth consecutive Tour title (Tour de France)
Sunday July 25, 2004 5:39PM
PARIS (AP) -- Lance Armstrong raced onto the crowd-lined Champs-Elysees as a yellow blur, bathed in the shimmering light of a 24-carat gold-leaf bike, a golden helmet and the race leader's yellow jersey.

For dynamic systems on the other hand, the objective is same as for an expert biker who wishes to ride the bike close to a fixed path most of the time.



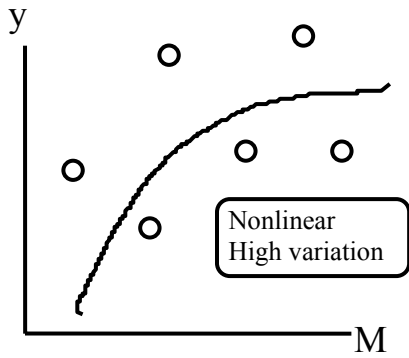


The actual performance, however, could be nonlinear of some degree and may display much higher variability than desired. The combination of nonlinearity and variability can be depicted by the four extreme conditions shown below.

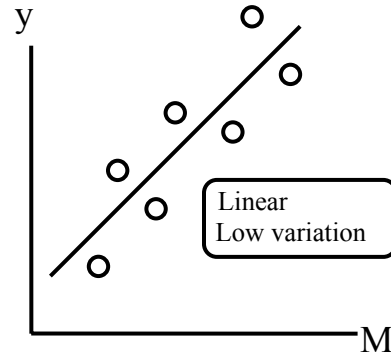
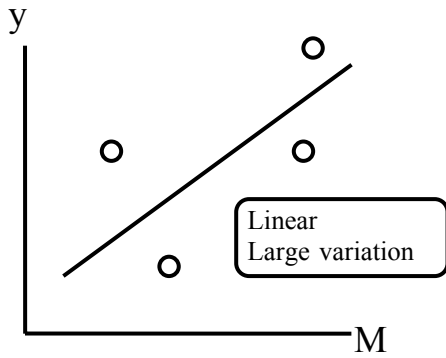
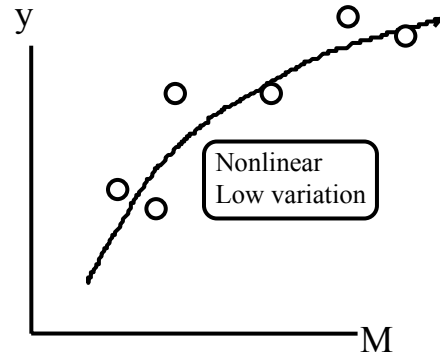
Human perceptions accept and comprehend only linear relations.

For robustness, least variation around the linear response is preferred.

The most desirable performance is where the response is linear with minimum variation around it.



Least Desirable



Most Desirable

The most desirable ideal function is the one which is linear and the one that has minimum variation at any point.

[Optimizing **Static System** is like a proficient golfer putting for the hole in the green. Optimized **Dynamic System**: Equivalent to an expert biker biking uphill always close to center line of the road.]

What if the ideal function is not linear?

If the ideal function is not linear, then the function can be transformed such that the plot becomes linear. Generally this can be accomplished by plotting the ideal function in a Log or semi-Log paper.

Suppose that

$$y = \beta M^n$$

which is polynomial of nth order. By taking Log of both sides,

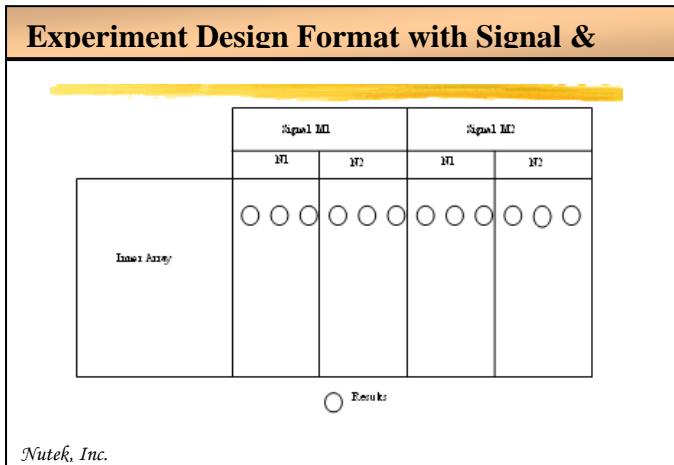
$$\text{Log}(y) = \text{Log}(\beta) + n \text{Log}(M)$$

or $Y = C + n M'$ (a linear equation)

where $Y = \text{Log}(y)$ and $M' = \text{Log}(M)$

9.5 Robust Design Strategy

- Define ideal function
- Determine control and noise factors for the system
- Design and run experiments
- Compare how close the results are to the ideal function
- Consider closeness to the Ideal Function as the criteria to determine the best control factor settings.

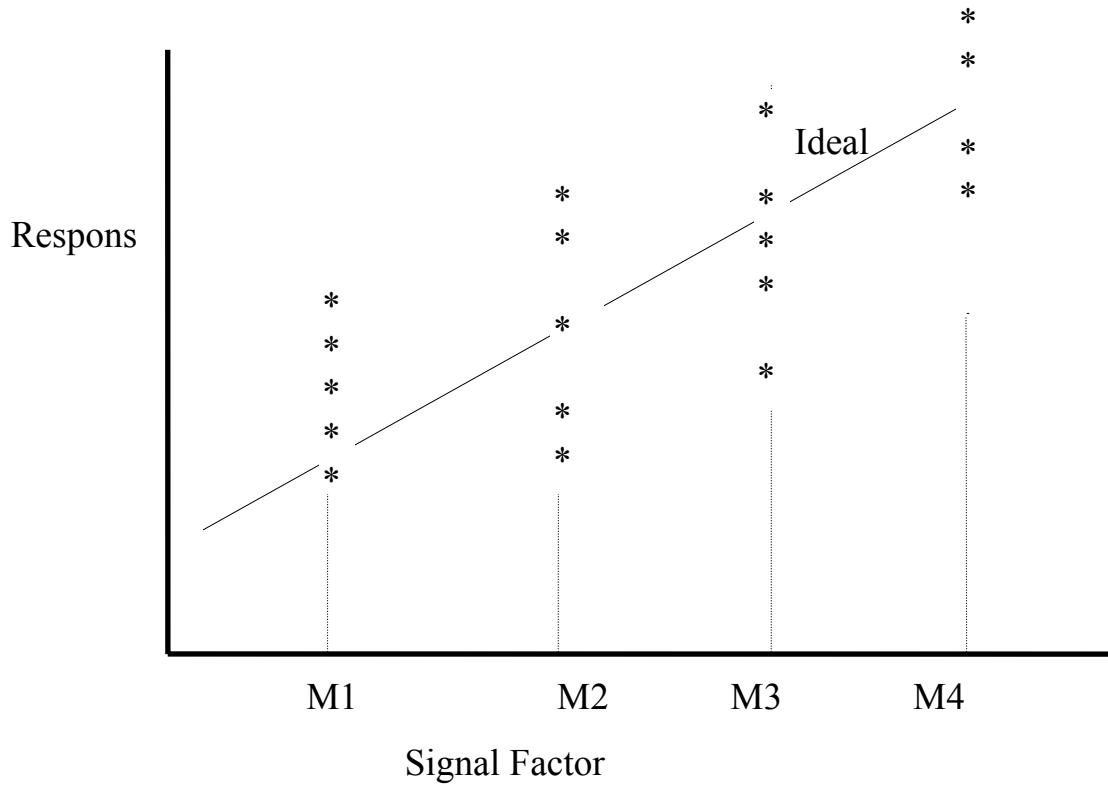
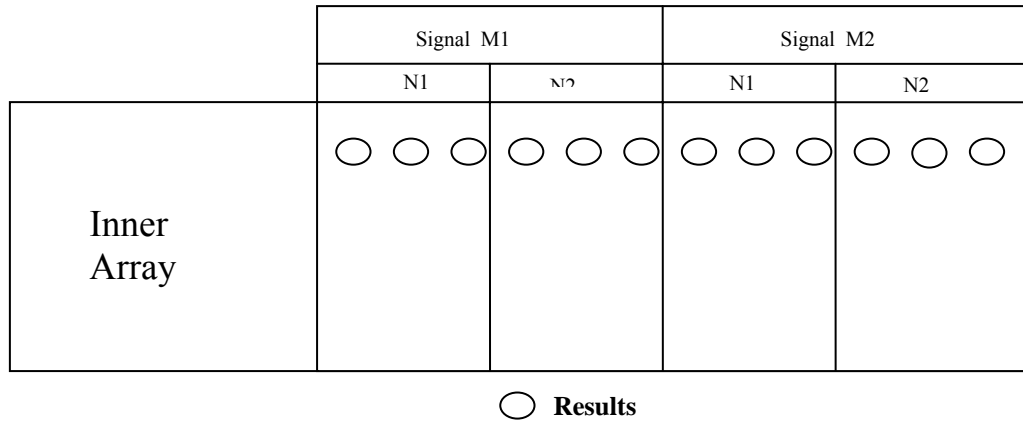


Unlike for static systems, no orthogonal is commonly utilized to configure the noise factor. Signal levels and noise levels are combined in the format shown to create unique conditions under which the experiments with control factors are conducted. Multiple samples under each of these unique conditions can be tested.

Experiment Layout Strategy

- Select inner array based on control factors
- Run experiments at various levels of signal and with different noise factor setting at each trial condition. Repeat samples at each combination of signal and noise (cell).

The number of test samples required per trial condition depends on the signal & noise combination, and the number of repetitions for each combination. If three samples are tested for each combination of two levels of signal and two levels of noise, then there will be 12 samples necessary for each trial condition, as shown below.



Analysis Approach

- Determine how all data for each trial condition deviate from the ideal function.
- Express the variation of the data in terms of a single number (S/N ratio).
- Use these numbers to carry out analysis of the experiments and determine the optimum condition.



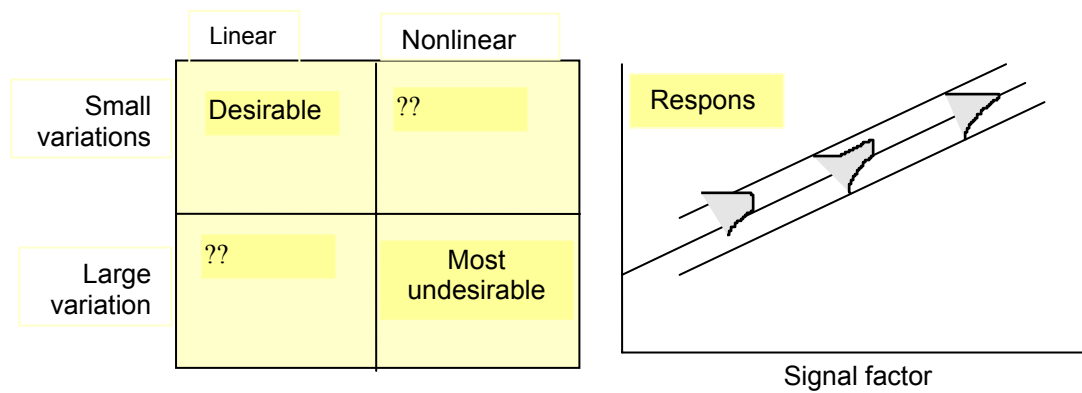
DOE application projects are of two types; Static and Dynamic. In Static system, response does not change with time, nor is it dependent on a specific factor. Such systems always function at about the same performance level. Dynamic systems, on the other hand, have variable performance depending on a specific factor, called the Signal Factor.

Examples of Dynamic Systems

1. Brake system
2. Steering control mechanism
3. Water faucet control system
4. Variable speed electric fan
5. Diving board Structure design

Ideal Function - How should the system behave?

Response Control - What is desirable behavior?



Goal - Design the system such that the response follows a straight line with the least amount of variation around it.

Analogies:

Robust **Static System** - performs like a golfer who has a consistent putting record.

Robust **Dynamic System** - is like a good biker who always steadily rides on a straight line up and down the hill.

Dynamic Characteristic



Reference texts:

1. Taguchi Methods by Glen S. Peace, Addison Wesley Publishing Company, Inc. NY, 1992, Pages 338-363
2. Quality Engineering Using Robust Design by Madhav S. Phadke, PTR Prentice Hall, Englewood , Cliff, NJ. Pages 114 - 117.
3. "Taguchi's Quality Engineering Philosophy and Methodology" by Shin Taguchi, American Supplier Institute, Inc. Allen Park, MI.
4. "Robust Technology Development" by Yuin Wu, American Supplier Institute

What is Dynamic Characteristic?

A system is considered to exhibit dynamic response characteristic when the strength of a particular factor has a direct effect on response under investigation. Such a factor with a direct influence on the result is called a SIGNAL factor.

SIGNAL FACTOR - is an input to the system. Value/level may change

CONTROL FACTOR - is also an input to the system. Values/level is fixed to the optimum level for the best performance.

NOISE FACTOR - is an uncontrollable factor. Its level is random during actual performance.

STATIC SYSTEM GOAL - is to determine combination of control factor levels which produces the best performance when exposed to the influence of the varying levels of noise factors.

DYNAMIC SYSTEM GOAL - is to find the combination of control factor levels which produces different levels of performances in direct proportion to the signal factor, but produces minimum variation due to the noise factors at each level of the signal.

Step 1. Design experiment with control factors using option F1 from main menu (manual or automatic design).

Step 2. Print description of trial conditions using option F5.

Step 3. Select option F8, the F5 to describe (*) DYNAMIC CHARACTERISTICS and print description of test conditions (noise and signal).

* You will need to describe signal and noise factors and their levels. You will also have to decide on the number of levels of signal and noise factors. BUT MOST IMPORTANTLY, you will have to choose the nature of the ideal function (Straight line representing the behavior Response vs. Signal) applicable to your system.

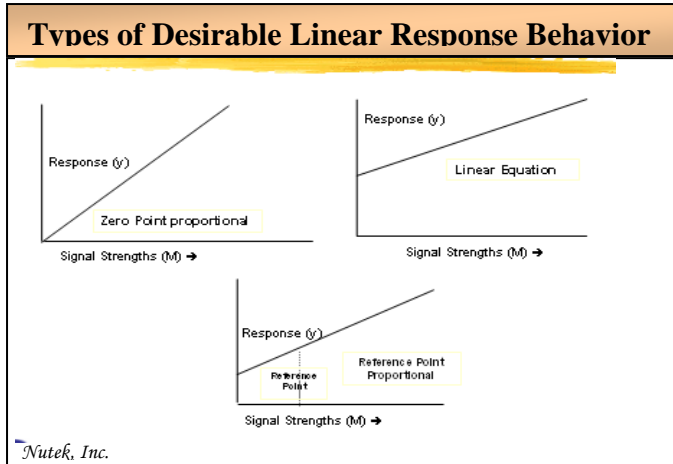
Step 4. Strictly follow the prescribed test conditions.

Step 5. Enter results in the order and locations (run#) prescribed in step 4 using option F1 from analysis menu.

Signal-To-Noise Ratio Equations (alternate dynamic characteristic equations)
 Signal factor may not always be clearly defined or known. For common industrial experiments, one or more attributes may be applicable:

- true value known
- interval between factor levels known
- factor level ratios known
- factor level values vague

Depending on the circumstances of the input signal values and the resulting response data, different signal-to-noise (S/N) ratio equations are available.

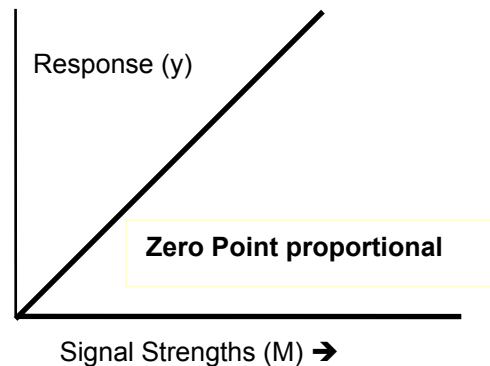


The simple straight-line can be of three different types:

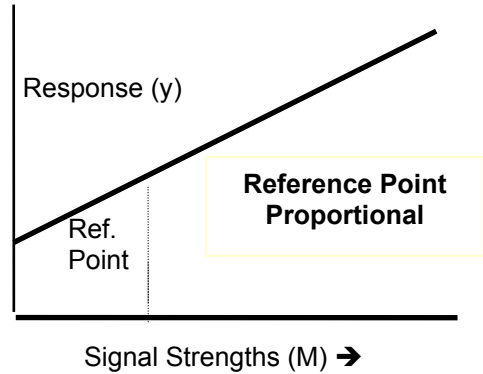
1. Line passing through the origin (most common).
2. Line with arbitrary slope and intercept.
3. Line passing through a fixed point.

All straight –line can be described with two parameters, a slope and an intercept.

Zero Point proportional - Select this type of equation when response line passes through the origin. The signal may be known, unknown or vague.

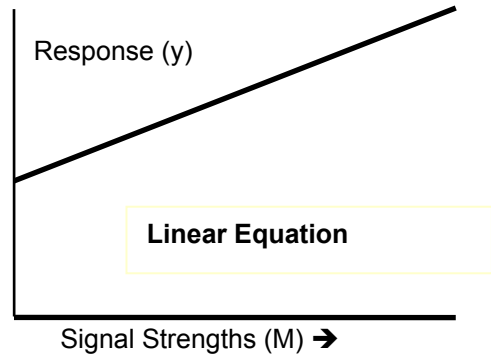


Reference Point proportional - this type of equation should be the choice response line does not pass through the origin but through a known value of the signal or when signal values are wide apart or far away from origin.



When the signal values are known, zero point or reference point proportional should be considered first. If neither is appropriate, the linear equation should be used.

Linear Equation - is based on the least squares fit equation and should be used where neither zero and reference point proportional equation are not appropriate. Use it when signal values are close together and response does not pass through the origin.



When in Doubt - plot the response as a function of the signal factor values on a linear graph and examine the magnitude of y-intercept. If it passes through origin, use ZERO POINT. If the intercept is not through origin but the line passes through a fixed point, use REF.POINT. In all other situation use LINEAR EQUATION.

Zero Point Proportional: $y = \beta M$

$$r = r_o (M_1^2 + M_2^2 + \dots + M_k^2)$$

Sum of response under each signal level (l=1, 2, ..., k)

$$y_i = \sum_{j=1,2,..} y_{ij} \quad r_o$$

Where

- y = response of the system (QC), M = Signal factor strength
- β = slope of the (ideal) response line, k = number of signal levels
- r_o = number of samples tested at each signal level
- M₁, M₂, etc, are strength of the signal levels
- y₁₁, y₁₂, etc, are response from sample 1 and 2 under signal level 1.
- y₁, y₂, etc., are totals of responses under signal levels 1, 2, .. k, etc.

Slope $\beta = (M_1 y_1 + M_2 y_2 + \dots + M_k y_k) / r$ and $S_t = Y_{11}^2 + Y_{12}^2 + \dots + Y_{kro}^2$



Variation caused by linear effect:

$$S_{\beta} = 1/r (M_1y_1 + M_2y_2 + \dots M_ky_k)^2 = r \beta^2$$

Variation associated with error or non linearity	
	$S_e = S_t - S_{\beta}$
Error Variance:	$V_e = S_e / (Kr_o - 1)$
S/N:	$\eta = 10 \log \frac{1}{r} \frac{(S_{\beta} - V_e)}{V_e}$

Ref. Point Proportional: $y - y_s = \beta(M - M_s)$

$$y_s = 1/r_o(y_1 + y_2 + \dots y_{r_o})$$

where r_o = no. samples for each signal level

M_s = reference signal strength

$$r = r_o [(M_1 - M_s)^2 + (M_2 - M_s)^2 + \dots (M_k - M_s)^2]$$

Adjusted sum of response for each Signal factor strength

$$y_i = \sum_{j=1}^{r_o} (y_j - y_s)$$

$$\beta = [y_1(M_1 - M_s) + y_2(M_2 - M_s) + \dots + y_k(M_k - M_s)] / r$$

$$S_t = \sum_{i=1}^k \sum_{j=1}^{r_o} (y_{ij} - y_s)^2$$

$$S_{\beta} = [y_1(M_1 - M_s) + y_2(M_2 - M_s) + \dots y_k(M_k - M_s)]^2 / r$$

Variation associated with error or non linearity	
	$S_e = S_t - S_{\beta}$
Error Variance:	$V_e = S_e / (Kr_o - 1)$
S/N:	$\eta = 10 \log \frac{1}{r} \frac{(S_{\beta} - V_e)}{V_e}$



Linear Equation: $y = \bar{m} + \beta (M - \bar{M}) + e$

where

$$\bar{m} = \bar{y}, \quad e = \text{error}$$

$$\bar{M} = (M_1 + M_2 + \dots + M_k) / k$$

$$r = r_o[(M_1 - \bar{M})^2 + (M_2 - \bar{M})^2 + \dots + (M_k - \bar{M})^2]$$

$$y_i = \sum_{j=1}^{r_o} y_{ij}$$

$$\beta = 1/r [y_1(M_1 - \bar{M}) + y_2(M_2 - \bar{M}) + y_k(M_k - \bar{M})]$$

$$S_T = y_{11}^2 + y_{12}^2 + y_{kro}^2 - \left(\sum_{i=1}^k \sum_{j=1}^{r_o} y_{ij} \right)^2 / k \cdot r_o$$

$$S_\beta = [y_1 (M_1 - \bar{M}) + y_2 (M_2 - \bar{M}) + y_k (M_k - \bar{M})]^2 / r.$$

$$S_T = y_{11}^2 + y_{12}^2 + y_{kro}^2 - \left(\sum_{i=1}^k \sum_{j=1}^{r_o} y_{ij} \right)^2 / k \cdot r_o$$

$$S_\beta = [y_1 (M_1 - \bar{M}) + y_2 (M_2 - \bar{M}) + y_k (M_k - \bar{M})]^2 / r.$$

Variation associated with error or non linearity	
	$S_e = S_t - S_\beta$
Error Variance:	$V_e = S_e / (K_{r_o} - 2)$
S/N:	$\eta = 10 \log \frac{1(S_\beta - V_e)}{r \quad V_e}$

9.5 Examples of Dynamic Systems

Discharge of water from water faucet: The rate of discharge is a function of valve opening. The position of the valve is the signal factor. A well designed valve system will discharge in direct proportion of the opening.

Design of a golf club: The club must be designed such that the distance is strictly a function of the angle of the swing, which is the signal factor.



Example calculations:

Case of LINEAR EQUATION (Expt. file: ASI400.QT4)

The results of samples tested for trial#1 of an experiment with dynamic characteristic. There are three signal levels, two noise levels, and two repetitions per cell.

	M1				M2				M3			
	Noise 1		Noise 2		Noise 1		Noise 2		Noise 1		Noise 2	
Tri#1	5.2	5.6	5.9	5.8	12.3	12.1	12.4	12.5	22.4	22.6	22.5	22.2

Signal strengths: M1 = 1/3, M2 = 1, M3 = 3

CALCULATIONS FOR S/N:

$$M_{avg} = (1/3 + 1 + 3) / 3 = 1.444$$

$$r_o = 4 \text{ (2 sample/cell x 2 noise levels)}$$

$$r = 4 [(1/3 - 1.444)^2 + (1 - 1.444)^2 + (3 - 1.444)^2] \dots (L)$$

$$= 4 (1.2343 + 0.1971 + 2.421)$$

$$= 15.41$$

$$y_1 = 5.2 + 5.6 + 5.9 + 5.8 = 22.5$$

$$y_2 = 12.3 + 12.1 + 12.4 + 12.5 = 49.3$$

$$y_3 = 22.4 + 22.6 + 22.5 + 22.2 = 89.7$$

$$\text{Beta} = (1/r)[22.5 \times (1/3 - 1.444) + 49.3 \times (1 - 1.444) + 89.7 \times (3 - 1.444)]$$

$$= (1/15.41) [-24.9975 - 21.692 + 139.5732]$$

$$= 92.8842/15.4101$$

$$= 6.01$$

$$S_{\text{beta}} = r \times \text{Beta}^2 = 15.4101 \times 6.0274^2 = 556.82$$

$$y_{\text{avg}} = [5.2 + 5.6 + \dots + 22.2]/12 = 161.5/12 = 13.46$$

$$S_t = (5.2 - y_{\text{avg}})^2 + (5.6 - y_{\text{avg}})^2 + \dots + (22.2 - y_{\text{avg}})^2$$

$$= 68.23 + 61.78 + 57.15 + 58.67 + 1.346 + 1.85 + 1.123 + .921$$

$$+ 79.92 + 83.54 + 81.72 + 76.387$$

$$= 572.65$$

$$S_e = S_t - S_b = 572.65 - 556.82 = 15.83$$

$$V_e = S_e / (12 - 2) = 15.83 / 10 = 1.583$$

$$\text{Eta} = 10 \text{ Log } (S_{\text{beta}} - V_e) / (r \times V_e) \quad \dots \quad \text{for all Eqns.}$$

$$= 10 \text{ Log } [(556.82 - 1.583)/(15.41 \times 1.583)]$$

$$= 10 \text{ Log}(22.76)$$

$$= 13.572 \quad (\text{S/N for the trial\# 1 results})$$

Likewise, S/N for all other trial conditions in the experiments are calculated. The analysis of results is then carried out just the same way as done for the static S/N case. The optimum condition determined by selecting the higher average factor effects as DYNAMIC CHARACTERISTIC is nothing but a special case of NOMINAL IS THE BEST quality characteristic. The optimum so determined, represents the control factor level combination which is expected to produce linear response with the least variation along the straight line. The exact value of the response, of course, is dependent on the strength of the signal and may be estimated by the *ideal function* of the S/N equation.

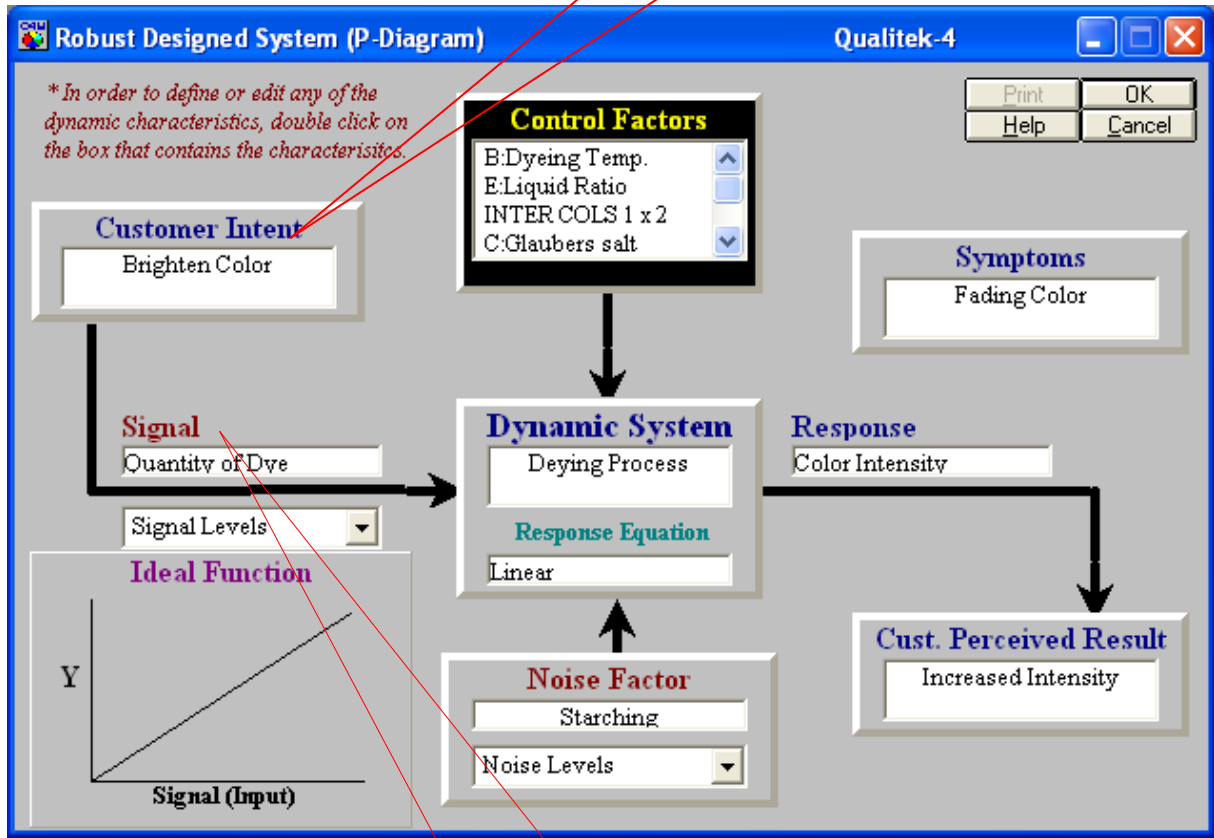
Sample Screens from Software

(Experiment: Dc-As400.q4w)

The parameters for dynamic characteristics (DC, Outer Array) in Qualitek-4 software are defined after first defining the control factors using the Inner Array. To describe the DC parameters, you will select *Dynamic Characteristic* option from *Manual Design* in *Design* menu option. Then, double click on Customer Intent to start describing the DC parameters. A few sample screens are shown below.

Double-click here to start defining DC parameters (shows first screen below).

System Configuration or Process Diagram (P-Diagram)



Double-click on Signal to define Signal and Noise factors and levels (next three screens)



Interaction between Control and Noise Factors

Since all factors, whether controllable or not, have influence on the output, it is possible that interaction exists between factors as well as between control factors and the noise factors. As a matter of fact, it is only when the interaction between the noise and control factors exists, than the robustness in designs is possible. The strategy for robust design, which seeks a combination of the levels of the control factors that is least sensitive to the variation of the uncontrollable noise factors, lies in picking the levels of the control factors based on the interaction with the noise factors.

The key to understanding how robustness can be achieved while multiple control and noise factors are studied simultaneously, is to understand how the interaction between the two types of factors are analyzed and decisions about the optimum levels is made.

The basic concept of factor interaction with noise for robustness has been introduced in Module 5 under discussions of robust design strategy for static system. The discussion there involved one control factor interaction with a single noise factor. Here we will consider how levels of multiple factors can be selected based on interaction with a noise factor.

Example Case Study 1

Factors: A, B, C, D, and E
 Noise Factor N (two levels, N1 and N2)

Trial No.	A	B	AxB	C	D	BxC	E	NOISE	
								N1	N2
1	1	1	1	1	1	1	1		
2	1	1	1	2	2	2	2		
3	1	2	2	1	1	2	2		
4	1	2	2	2	2	1	1		
5	2	1	2	1	2	1	2		
6	2	1	2	2	1	2	1		
7	2	2	1	1	2	2	1		
8	2	2	1	2	1	1	2		



Example Experiment with Five Factors and Noise

Trial No.	A	B	AxB	C	D	BxC	E	Noise Factor						\bar{y}		
								N1			N2				$\bar{N1}$	$\bar{N2}$
1	1	1	1	1	1	1	1	42	40	38	65	67	63	40	65	52.5
2	1	1	1	2	2	2	2	26	25	24	44	45	46	25	45	35
3	1	2	2	1	1	2	2	31	32	33	58	56	54	32	56	44
4	1	2	2	2	2	1	1	44	43	42	57	54	60	43	57	50
5	2	1	2	1	2	1	2	38	36	34	60	59	61	36	60	48
6	2	1	2	2	1	2	1	45	39	42	62	65	68	42	65	53.5
7	2	2	1	1	2	2	1	49	51	50	71	72	73	50	72	61
8	2	2	1	2	1	1	2	33	36	39	52	54	53	36	53	44.5

Average Factor Effects and Noise Effects

Trial No.	A	B	AxB	C	D	BxC	E	Noise Factor						\bar{y}		
								N1			N2				$\bar{N1}$	$\bar{N2}$
1	1	1	1	1	1	1	1	42	40	38	65	67	63	40	65	52.5
2	1	1	1	2	2	2	2	26	25	24	44	45	46	25	45	35
3	1	2	2	1	1	2	2	31	32	33	58	56	54	32	56	44
4	1	2	2	2	2	1	1	44	43	42	57	54	60	43	57	50
5	2	1	2	1	2	1	2	38	36	34	60	59	61	36	60	48
6	2	1	2	2	1	2	1	45	39	42	62	65	68	42	65	53.5
7	2	2	1	1	2	2	1	49	51	50	71	72	73	50	72	61
8	2	2	1	2	1	1	2	33	36	39	52	54	53	36	53	44.5

Factors	A	B	C	D	E	Average Values:	38.0	59.12	48.5
Avg 1	45.37	47.25	51.375	48.62	54.25	Effect of Noise = 59.125 - 38 =			
Avg 2	51.75	49.87	45.75	48.5	42.875				
Effect	6.375	2.625	-5.625	-.125	-11.375				



Average Factor Effect Calculations – A1

Trial No.								Noise Factor						$\bar{N1}$	$\bar{N2}$	\bar{y}
	A	B	AxB	C	D	BxC	E	N1			N2					
1	1	1	1	1	1	1	1	42	40	38	65	67	63	40	65	52.5
2	1	1	1	2	2	2	2	26	25	24	44	45	46	25	45	35
3	1	2	2	1	1	2	2	31	32	33	58	56	54	32	56	44
4	1	2	2	2	2	1	1	44	43	42	57	54	60	43	57	50
5	2	1	2	1	2	1	2	38	36	34	60	59	61	36	60	48
6	2	1	2	2	1	2	1	45	39	42	62	65	68	42	65	53.5
7	2	2	1	1	2	2	1	49	51	50	71	72	73	50	72	61
8	2	2	1	2	1	1	2	33	36	39	52	54	53	36	53	44.5
Factors	A	B	C		D	E	Average Values:			38.0	59.12	48.5				
Avg 1	45.37	47.25	51.375		48.62	54.25	Effect of Noise = 59.125 - 38 = 21.125									
Avg 2	51.75	49.87	45.75		48.5	42.875										
Effect	6.375	-5.62	-5.625		-.125	-11.375										

Average Factor Effect Calculations – A2

Trial No.								Noise Factor						$\bar{N1}$	$\bar{N2}$	\bar{y}
	A	B	AxB	C	D	BxC	E	N1			N2					
1	1	1	1	1	1	1	1	42	40	38	65	67	63	40	65	52.5
2	1	1	1	2	2	2	2	26	25	24	44	45	46	25	45	35
3	1	2	2	1	1	2	2	31	32	33	58	56	54	32	56	44
4	1	2	2	2	2	1	1	44	43	42	57	54	60	43	57	50
5	2	1	2	1	2	1	2	38	36	34	60	59	61	36	60	48
6	2	1	2	2	1	2	1	45	39	42	62	65	68	42	65	53.5
7	2	2	1	1	2	2	1	49	51	50	71	72	73	50	72	61
8	2	2	1	2	1	1	2	33	36	39	52	54	53	36	53	44.5
Factors	A	B	C		D	E	Average Values:			38.0	59.12	48.5				
Avg 1	45.37	47.25	51.375		48.62	54.25	Effect of Noise = 59.125 - 38 = 21.125									
Avg 2	51.75	49.87	45.75		48.5	42.875										
Effect	6.375	2.625	-5.625		-.125	-11.375										



Average Factor Effect Calculations – B1

Trial No.	A	B	AxB	C	D	BxC	E	Noise Factor			N1	N2	N1	N2	y	
								N1	N2							
1	1	1	1	1	1	1	1	42	40	38	65	67	63	40	65	52.5
2	1	1	1	2	2	2	2	26	25	24	44	45	46	25	45	35
3	1	2	2	1	1	2	2	31	32	33	58	56	54	32	56	44
4	1	2	2	2	2	1	1	44	43	42	57	54	60	43	57	50
5	2	1	2	1	2	1	2	38	36	34	60	59	61	36	60	48
6	2	1	2	2	1	2	1	45	39	42	62	65	68	42	65	53.5
7	2	2	1	1	2	2	1	49	51	50	71	72	73	50	72	61
8	2	2	1	2	1	1	2	33	36	39	52	54	53	36	53	44.5

Factors	A	B	C	D	E	Average Values:	38.0	59.12	48.5
Avg 1	45.37	47.25	51.375	48.62	54.25	Effect of Noise = 59.125 - 38 = 21.125			
Avg 2	51.75	49.87	45.75	48.5	42.875				
Effect	6.375	2.625	-5.625	-.125	-11.375				

Average Factor Effect Calculations – B2

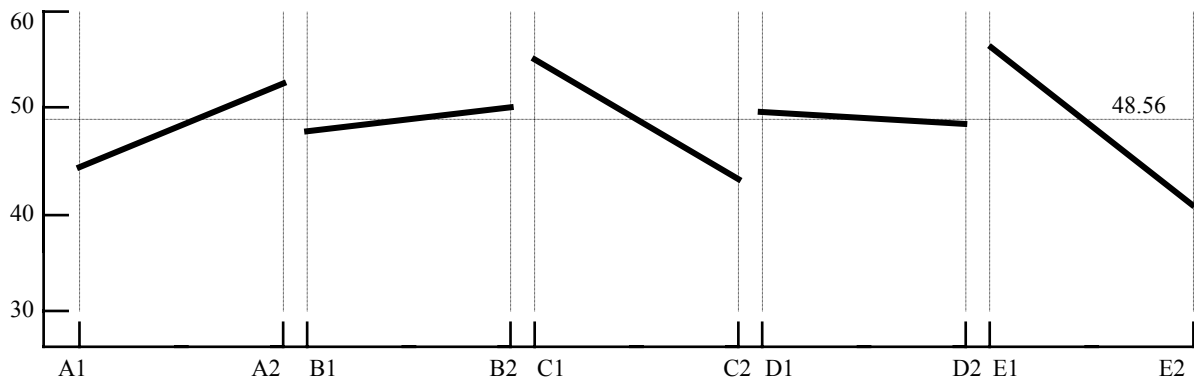
Trial No.	A	B	AxB	C	D	BxC	E	Noise Factor			N1	N2	N1	N2	y	
								N1	N2							
1	1	1	1	1	1	1	1	42	40	38	65	67	63	40	65	52.5
2	1	1	1	2	2	2	2	26	25	24	44	45	46	25	45	35
3	1	2	2	1	1	2	2	31	32	33	58	56	54	32	56	44
4	1	2	2	2	2	1	1	44	43	42	57	54	60	43	57	50
5	2	1	2	1	2	1	2	38	36	34	60	59	61	36	60	48
6	2	1	2	2	1	2	1	45	39	42	62	65	68	42	65	53.5
7	2	2	1	1	2	2	1	49	51	50	71	72	73	50	72	61
8	2	2	1	2	1	1	2	33	36	39	52	54	53	36	53	44.5

Factors	A	B	C	D	E	Average Values:	38.0	59.12	48.5
Avg 1	45.37	47.25	51.375	48.62	54.25	Effect of Noise = 59.125 - 38 = 21.125			
Avg 2	51.75	49.87	45.75	48.5	42.875				
Effect	6.375	2.625	-5.625	-.125	-11.375				



Plot of Average Factor Effects

Factors	A	B	C	D	E
Avg. 1	45.375	47.25	51.375	48.625	54.25
Avg. 2	51.75	49.875	45.75	48.5	42.875
Effect	6.375	2.625	-5.625	-0.125	-11.375



Combined Factor & Noise Effects Calculations – A1N1

Trial No.	Factor							Noise Factor						\bar{y}		
	A	B	AxB	C	D	BxC	E	N1			N2				$\bar{N1}$	$\bar{N2}$
1	1	1	1	1	1	1	1	42	40	38	65	67	63	40	65	52.5
2	1	1	1	2	2	2	2	26	25	24	44	45	46	25	45	35
3	1	2	2	1	1	2	2	31	32	33	58	56	54	32	56	44
4	1	2	2	2	2	1	1	44	43	42	57	54	60	43	57	50
5	2	1	2	1	2	1	2	38	36	34	60	59	61	36	60	48
6	2	1	2	2	1	2	1	45	39	42	62	65	68	42	65	53.5
7	2	2	1	1	2	2	1	49	51	50	71	72	73	50	72	61
8	2	2	1	2	1	1	2	33	36	39	52	54	53	36	53	44.5

Average Values:	38.0	59.12	48.5
Effect of Noise =	59.125 - 38 =		

Factors	N1	N2		N1	N2		N1	N2
A1	35.0	55.75	B1	35.75	58.75	C1	39.5	63.25
A2	41.0	62.50	B2	40.25	59.50	C2	36.5	55.0
Effect	6.0	6.75		4.50	0.75		- 3.0	- 8.25



Combined Factor & Noise Effects Calculations – A2N1

Trial No.	A	B	AxB	C	D	BxC	E	Noise Factor			N1	N2	N1	N2	y	
1	1	1	1	1	1	1	1	42	40	38	65	67	63	40	65	52.5
2	1	1	1	2	2	2	2	26	25	24	44	45	46	25	45	35
3	1	2	2	1	1	2	2	31	32	33	58	56	54	32	56	44
4	1	2	2	2	2	1	1	44	43	42	57	54	60	43	57	50
5	2	1	2	1	2	1	2	38	36	34	60	59	61	36	60	48
6	2	1	2	2	1	2	1	45	39	42	62	65	68	42	65	53.5
7	2	2	1	1	2	2	1	49	51	50	71	72	73	50	72	61
8	2	2	1	2	1	1	2	33	36	39	52	54	53	36	53	44.5

Average Values:	38.0	59.12	48.5
Effect of Noise = 59.125 - 38 =			

Factors	N1	N2		N1	N2		N1	N2
A1	35.0	55.75	B1	35.75	58.75	C1	39.5	63.25
A2	41.0	62.50	B2	40.25	59.50	C2	36.5	55.0
Effect	6.0	6.75		4.50	0.75		- 3.0	- 8.25

Combined Factor & Noise Effects Calculations – A1N2

Trial No.	A	B	AxB	C	D	BxC	E	Noise Factor			N1	N2	N1	N2	y	
1	1	1	1	1	1	1	1	42	40	38	65	67	63	40	65	52.5
2	1	1	1	2	2	2	2	26	25	24	44	45	46	25	45	35
3	1	2	2	1	1	2	2	31	32	33	58	56	54	32	56	44
4	1	2	2	2	2	1	1	44	43	42	57	54	60	43	57	50
5	2	1	2	1	2	1	2	38	36	34	60	59	61	36	60	48
6	2	1	2	2	1	2	1	45	39	42	62	65	68	42	65	53.5
7	2	2	1	1	2	2	1	49	51	50	71	72	73	50	72	61
8	2	2	1	2	1	1	2	33	36	39	52	54	53	36	53	44.5

Average Values:	38.0	59.12	48.5
Effect of Noise = 59.125 - 38 =			

Factors	N1	N2		N1	N2		N1	N2
A1	35.0	55.75	B1	35.75	58.75	C1	39.5	63.25
A2	41.0	62.50	B2	40.25	59.50	C2	36.5	55.0
Effect	6.0	6.75		4.50	0.75		- 3.0	- 8.25



Combined Factor & Noise Effects Calculations – A2N2

Trial No.	A	B	AxB	C	D	BxC	E	Noise Factor			N1	N2	N1	N2	y	
								N1	N2							
1	1	1	1	1	1	1	1	42	40	38	65	67	63	40	65	52.5
2	1	1	1	2	2	2	2	26	25	24	44	45	46	25	45	35
3	1	2	2	1	1	2	2	31	32	33	58	56	54	32	56	44
4	1	2	2	2	2	1	1	44	43	42	57	54	60	43	57	50
5	2	1	2	1	2	1	2	38	36	34	60	59	61	36	60	48
6	2	1	2	2	1	2	1	45	39	42	62	65	68	42	65	53.5
7	2	2	1	1	2	2	1	49	51	50	71	72	73	50	72	61
8	2	2	1	2	1	1	2	33	36	39	52	54	53	36	53	44.5
Average Values:											38.0	59.12	48.5			
Effect of Noise = 59.125 - 38 =																

Factors	N1	N2		N1	N2		N1	N2
A1	35.0	55.75	B1	35.75	58.75	C1	39.5	63.25
A2	41.0	62.50	B2	40.25	59.50	C2	36.5	55.0
Effect	6.0	6.75		4.50	0.75		- 3.0	- 8.25

Combined Factor & Noise Effects Calculations – D1N1

Trial No.	A	B	AxB	C	D	BxC	E	Noise Factor			N1	N2	N1	N2	y	
								N1	N2							
1	1	1	1	1	1	1	1	42	40	38	65	67	63	40	65	52.5
2	1	1	1	2	2	2	2	26	25	24	44	45	46	25	45	35
3	1	2	2	1	1	2	2	31	32	33	58	56	54	32	56	44
4	1	2	2	2	2	1	1	44	43	42	57	54	60	43	57	50
5	2	1	2	1	2	1	2	38	36	34	60	59	61	36	60	48
6	2	1	2	2	1	2	1	45	39	42	62	65	68	42	65	53.5
7	2	2	1	1	2	2	1	49	51	50	71	72	73	50	72	61
8	2	2	1	2	1	1	2	33	36	39	52	54	53	36	53	44.5
Average Values:											38.0	59.12	48.5			
Effect of Noise = 59.125 - 38 =																

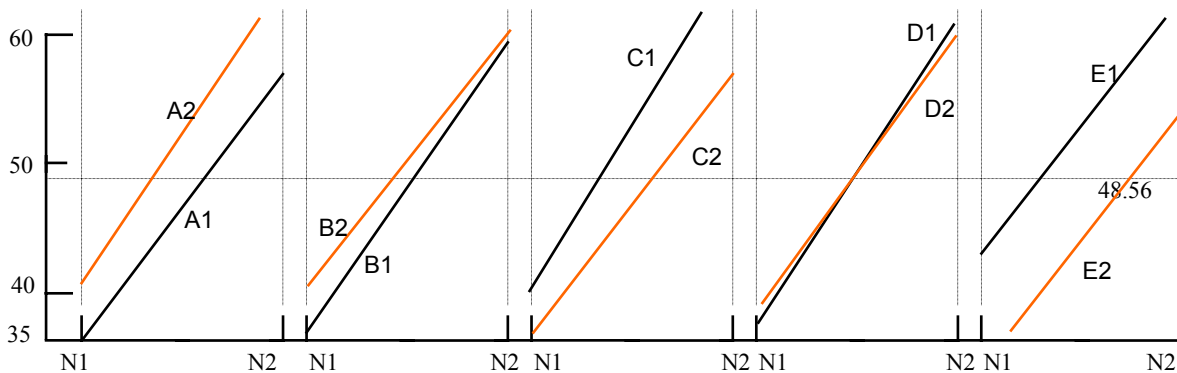
	N1	N2		N1	N2
D1	37.5	59.75	E1	43.75	64.75
D2	38.5	58.5	E2	32.25	53.5
Effects	1.0	- 1.25		- 11.5	- 11.25



Plots of Interaction –Between Noise and Control Ffactors

Factors	N1	N2		N1	N2		N1	N2
A1	35.0	55.75	B1	35.75	58.75	C1	39.5	63.25
A2	41.0	62.50	B2	40.25	59.50	C2	36.5	55.0
Effect	6.0	6.75		4.50	0.75		- 3.0	- 8.25

	N1	N2		N1	N2
D1	37.5	59.75	E1	43.75	64.75
D2	38.5	58.5	E2	32.25	53.5
Effects	1.0	- 1.25		- 11.5	- 11.25



Based on shallower plots, control factor levels least sensitive to noise factors are: A1B2C2D2E1

Observations and analysis strategy:

1. Plot of effects of noise (noise factor along x-axis) allows selection factor level most desirable for least in influence of the noise factor.
2. Influence of noise factor, which is the reason for variation, is captured when S/N ratio of the result is used for analysis instead of the original trial results for analysis.
3. Therefore, selection of the optimum condition based on S/N analysis indeed produces the factor levels robust against the influence of the noise factors.
4. To avoid plotting noise effects and selecting factor levels for robust design, analysis should be performed using S/N ratios of the trial results.



Sample Qualitek-4 Screens (Experiment Designs)

Dynamic System Description

Symptom
Fading Color

Response
Color Intensity

Customer Intent
Brighten Color

Customer Perceived Results
Increased Intensity

System Description
Deying Process

Please note that only the first 20 characters of each description will be used for display purposes in the response digram.

Description of Signal and Noise factors

Select the number of signal levels: 3
Previous 3

Select the number of noise levels: 2
Previous 2

Select the number of results per cell: 2
Previous 2

OK
Cancel
Help

Reset values for DC

Signal and Noise Factor and Level Descriptions

DC Factor Descriptions And Levels Qualitek-4

Signal Factor

Description
Quantity of Dye

Levels (numeric values only)

Level 1	Level 2	Level 3
0.333	1	3

Noise Factor

Description
Starching

Levels (alphanumeric/numeric)

Level 1	Level 2
Not Starched	Starched

Expected Ideal Function

Dynamic Response Equation Selection Qualitek-4

Dynamic Response Equation:

Zero Point Proportional

Reference Point Proportional

Linear Equation

Select:

Zero Point Proportional - when the output response line passes through
*Equation: $Y = b \times M$

Reference Point Proportional - when the response is known for a fixed signal value (reference point).
*Equation: $Y - Y_{ref} = b \times (M - M_{ref})$

Linear Equation - when none of the above are appropriate.
*Equation: $Y = m + b \times (M - M_{avg})$

Help

9.6 Theory and Derivation of formulae (Reference 2. Page 114)

Notations: Equations apply to one row of results under dynamic characteristic (any trial)

k = number of signal levels

r_o = number of results under each signal level (noise level x repetitions per cell)

K = a constant (cost of processing one piece, page 113, ref. 2)

When both the signal factor (M) and the quality characteristic (y) are continuous, the quality loss (Q) can be expressed as

$$Q = \frac{1}{kr_o} \sum_{i=1}^k \sum_{j=1}^{r_o} \{y_{ij} - M_i\}^2$$

The quality loss comprises of two components: a) Deviation from linearity (error e), b) The slope (β) being other than one. The slope can be estimated by minimization of the loss (estimated by least squares criterion).

$$y_{ij} = \beta M_i + e_{ij}$$

$$\frac{d}{d\beta} \left[\sum_{i=1}^k \sum_{j=1}^{r_o} (y_{ij} - \beta M_i)^2 \right] = 0$$

That is

$$\sum_{i=1}^k \sum_{j=1}^{r_o} (y_{ij} - \beta M_i) M_i = 0$$

Which yields

$$\beta = \frac{\sum_{i=1}^k \sum_{j=1}^{r_o} (y_{ij} M_i)}{\sum_{i=1}^k \sum_{j=1}^{r_o} (M_i^2)}$$

The quality loss after adjustment is given by

$$Q_a = \frac{K}{kr_o} \sum_{i=1}^k \sum_{j=1}^{r_o} (y_{ij} - M_i)^2$$

$$\begin{aligned}
&= \frac{K}{kr_o} \sum_{i=1}^k \sum_{j=1}^{r_o} \left[\frac{y_{ij}}{\beta} - M_1 \right]^2 \\
&= \frac{K}{\beta^2} \cdot \frac{1}{kr_o} \sum_{i=1}^k \sum_{j=1}^{r_o} (y_{ij} - \beta M_1)^2 \\
&= K \cdot \frac{(kr_o - 1)}{kr_o} \cdot \frac{\sigma_e^2}{\beta^2} \\
&= K \cdot \frac{\sigma_e^2}{\beta^2}
\end{aligned}$$

Where the error variance (square of Sigma) is given by

$$\sigma_e^2 = \frac{1}{(kr_o - 1)} \sum_{i=1}^k \sum_{j=1}^{r_o} (y_{ij} - \beta M_i)^2$$

Minimizing the quality loss is equivalent to maximizing S/N given by

$$S/N = \eta = 10 \log_{10} \frac{\beta^2}{\sigma_e^2}$$

Note:

Slope (Beta) is the change in y produced by unit change in signal strength (M). Thus the square of slope quantifies effect of signal. The denominator (square of Sigma) represents the effect of noise. Hence the quantity (Eta) is called S/N ratio.

In case where there is a target, we must make adjustments to both slope and the intercepts. This leads to response equation of Reference Point Proportional type as shown below

$$y = a_o + \beta_o M$$

Simplified Formulas (Zero-Point Proportional)

For each run calculate $\hat{\beta}$:

$\hat{\beta}$ = slope of the 'best fit' line using the 'least squares' method

$$\beta = \frac{\sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^r M_i y_{ijk}}{r n \sum_{i=1}^m M_i^2}$$

Where m = number of signal levels
 n = number of noise levels
 r = number of replication (1 or more)

$$\beta = \frac{\sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^r M_i y_{ijk}}{\sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^r M_i^2}$$

For each run calculate σ^2 :

σ^2 = Mean Squared Error (MSE)
 = variation around the 'least squares' line

$$\sigma^2 = \frac{\sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^r (y_{ijk} - \beta M_i)^2}{mnr - 1}$$

Where m = number of signal levels
 n = number of noise levels
 r = number of replication (1 or more)

Design and Analysis Using Qualitek-4 Software (Dynamic Systems)

Step 1: Design *inner array* (after planning experiment) first as you will do for any other situation.

Step 2: Design *outer array* by selecting *dynamic characteristic* from *Manual Design of Design* menu option.

- a. Double-Click on *Symptom* in the P-Diagram and describe system characteristics. Complete all items as best as you can.
- b. Double-Click on *Signal* in the P-Diagram and describe the number of levels for signal and noise factors. Click OK when done. Describe the signal and noise factors and their levels. Note that the levels of the signal factor MUST be numeric form. Click OK to proceed. Check the box for *Zero Point Proportional* and click OK.

Step 3: To print test conditions under *dynamic characteristic*, select *Dynamic Test Condition* from *Condition* menu option. Print or highlight text, *copy and paste* to a Word document for future use.

Step 4: Upon completion of tests and entering test results, you are ready for analysis. To analyze, select *Dynamic Characteristic* from Analysis menu option. Review P-Diagram and click OK to proceed.

Step 5: At ANOVA for Dynamic System screen, review and click OK to proceed with S/N analysis. If you prefer to analyze results using the slope (Beta), click on the button labeled 'Select S/N or Beta Analysis' and check box for Beta. Perform rest of the analysis just like any other experiment.

Review Topics and Q&A

How to determine if a system has dynamic characteristic and how to define the system parameters?

Approach

- Define system boundaries first. The system should contain, preferably, only one energy transformation device with input (signal) and output (response)
- Establish intent and perceived results. Intent is what we wish to achieve. The action executed to satisfy the intent is the input or signal.
- To determine if the system is has dynamic characteristic, answer the following questions.
 - How is the intent satisfied? What action needs to be executed before the desired objective can be satisfied.
 - Is there more than one signal strength to satisfy the intent? What are the signal values? In other words, could there be different values of the signal (input factor) in actual application? If the answer is yes, the system could be dynamic.
- Determine factors and their levels.
- Identify noise factors
- Define responses and how they are measured.

9.6 Considerations for Formulating Robust Design Case Studies

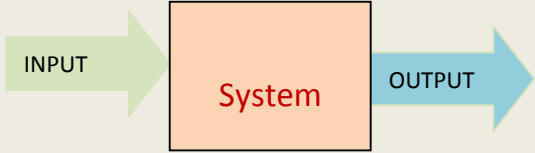
Application Steps

1. Define project scope (System to study)
2. Define *Ideal Function* (Signal and Response relationship)
3. Determine signal levels
4. Identify noise and their practicable levels for the study
5. Select control factors and their Levels
6. Select array, assign factors, and describe experiments
7. Conduct experiments
8. Analyze experimental results
9. Perform confirmation test
10. Document and incorporate recommended design changes

These steps are discussed in more details below.

- (1) **Define project scope:** Identify the system or sub-system to study and define its boundaries. Helpful thoughts in this process are:
- What is the system?
 - Can it be broken into subsystems and what are they?
 - Can the subsystem be studied economically?
 - Is the output of the system definable and measurable?
 - Can the system be studied by analytical means to save hardware cost?

Does your system possess dynamic characteristic?

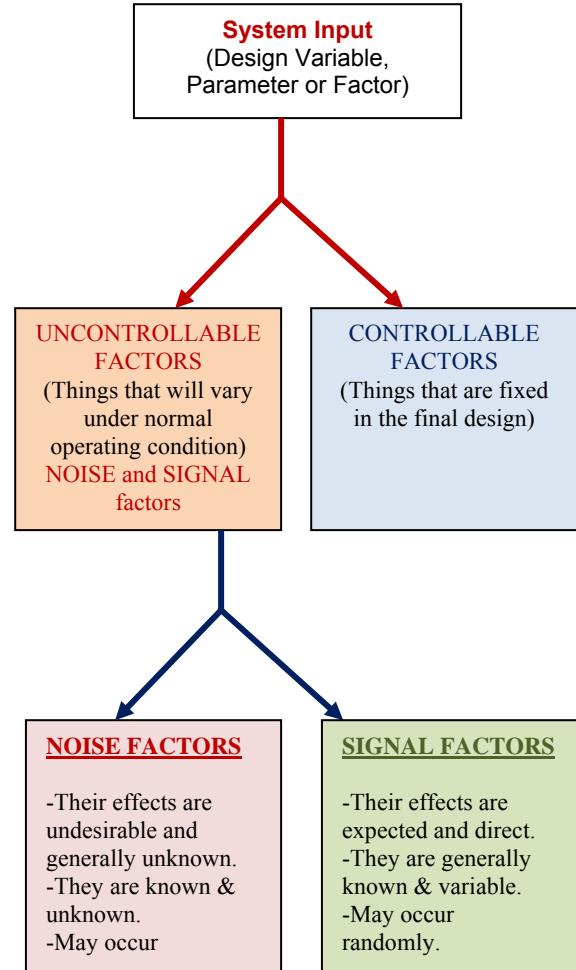


- All systems have INPUT and OUTPUT
- Most systems also have many inputs and multiple outputs (results/response)
- INPUTS are of different kinds as shown in the diagram.
- Careful examination of inputs help identify SIGNAL factor for the system.

DYNAMIC SYSTEM:
Signal factor is present and is a variable.

STATIC SYSTEM:
Signal factor fixed or absent.

Response:
Do you expect a fixed level of response always?
If so, it may not be a dynamic system.



(2) **Define Ideal Function:** Identification of *Ideal Function* is a critical step. Here you establish the basic functions of the system that help you define the applicable input/signal and output/response. Consider examining the system in terms of the following function.

- **Objective Function:** This is what the customer/user will see or experience as the results. It is a description of system output function in non-technical language (use a verb and a noun). Example – Slow down vehicle (in case of automotive brake application system)
- **Basic Functions:** These are descriptions of input (Signal, M) and output (Response, y), that bears a relationship based on physics of the system. Ideally, some sort of energy transformation is to take place to convert signal into response. Example: M = Weight of a person, y = Weight indicated by the scale.
- **Ideal Function:** It represents a relationship (desirably linear) between signal and the response (result/output).

Some examples of above functions in common systems are shown in the table below.

Example Systems and Their Ideal Functions				
System	Subsystem	Objective Function	Basic Function	Ideal Function
(1) Automotive Dashboard	Fuel Guage	Show fuel content	M = Fuel in tank y = Guage reading	$y = \beta M$
(2) Automotive Steering mechanism	Steering Wheel	Turn vehicle	M = Turn of steering Y = Rotation of wheel	$y = \beta M$
(3) Bathroom Sink	Faucette	Control water flow	M = Knob rotation Y = Water flow	$y = \beta M$
(4) Cooling System	Blower fan	Blow air	M = Motor speed Y = Air flow	$y = \beta M$
(5) Joint Assembly	Bolted fastener	Attach parts	M = Turn of bolt Y = Axial force	$y = \beta M$

Helpful guidelines and thoughts to determine input signal and output response functions (answer these questions).

- (a) What is the system expected to do (intent)? How does it do that?
- (b) What action needs to take place to satisfy the intent (Signal)?
- (c) When the action is taken, what is the observed result (response)?
- (d) What is the desirable relationship between the action (signal) and the result (response)?

Note: From user perception and human feel, the most desirable relationship between the signal and response is linear. This means that, a 1:1 relationship, with response (y) scaled properly (a straight line with slope 1), is most desirable.

Most systems, naturally, do not behave this way. The goal of studies with *dynamic characteristic* is to find line of *least-square fit* that offer behavior close to the desired slope.

DO's

Look for **system functions** that are ENERGY, PHYSICS or CHEMISTRY related and can be defined like:

- To transfer torque
- To transfer force
- To transfer heat
- To indicate measured specimen true value
- To convert chemical energy to heat energy
- To distribute load
- Etc.

Don'ts

Avoid selecting **systems with functions** like:

- To reduce (symptom like SCAP from happening)
- To prevent (symptom from occurring)
- To shield (effect of undesirable factors)
- To meet/qualify (performance requirements)
- Etc.



Symptoms that prompts (validate studies) selection of system input & output functions are of nature:

- Undesirable or negative result
- Results display loss of energy, efficiency, utility or performance
- Creates problem
-

Common examples of such symptoms are: Movement, vibration, audible noise, shrinkage, leakage, heat loss, rattles and squeaks, pollution, etc.

(3) **Determine signal levels:** The signal level should be expressed in numeric terms. The number of levels should be between 2 and 4 that cover the entire working range. The levels should:

- Represent extremes of usage
- Family of products utilizing the system
- Future products that may be developed using the system

Example: M = Signal, M1, M2 and M3 are three levels of signal.

(4) **Identify noise and their practicable levels for the study:** Utilize the brainstorming and documented output from static design. Examine the list of noise factors identified and determine important ones. Find ways to identify 2 or 3 levels of the noise (combination of levels of several noises) for the study. When multiple important noise are present, consider performing small experiment (L-4 array with three 2-level noise factors) to determine the compound noise levels.

Example: Suppose that from an experiment (L-4) with three important noise factors, two extreme noise conditions, N1 and N2 were identified. To capture variability better, 3 test samples exposed to each of these noise levels were tested (3 x 2 x 3 = 18 samples in each trial condition).

The outer array for carrying out experiments with signal and noise as described in (3) and 4(0 above will be as shown bellow.

	M1				M2				M3			
	N1		N2		N1		N2		N1		N2	
Trial#1												
Trial#2												

... etc.

(5) **Select control factors and their Levels:** To select control factors for the study, follow the experiment planning steps recommended under discussion of static system earlier.

(6) **Select array, assign factors, and describe experiments:** To design experiments, follow the experiment planning steps recommended under discussion of static system earlier. Prefer to utilize L-8, L-9, L-12 or L-18 arrays for experiment design. Utilize method to modify orthogonal array (upgrade & downgrade columns) to accommodate mixed-level factors.



- (7) **Conduct experiments:** Run experiments by selecting Trial Conditions in random order.
- (8) **Analyze experimental results:** Analyze results using Slope (Beta) and S/N ratio. Follow either Two-step Optimization approach (Identify levels based on variability first, and slope next).
- (9) **Perform confirmation test:** Run Confirmation Tests to verify recommendations.
- (10) **Document and incorporate recommended design changes:**

Recommendations: Carefully follow the steps above to formulate project. The success of your robust design study will depend on how well you identify signal, noise and control factors.

Example Case Study 2

In an experiment with design of outlet valve for a pressure chamber, four 3-level factors (A, B, C, and D) were studied using an L-9 array. The ideal function was defined in terms of measured torque (Response, Y) required for valve opening as a function of internal pressure (Signal, M). The results measured at two noise conditions of three different signal values are shown in the table below. Determine the factor influence, optimum design condition, and the improvement expected (express it as GAIN in S/N).

Calculations of Slope, Variance, and S/N ratios for each trial results follows.

Number of signal levels, $m = 3$, $M_1 = 0.1$, $M_2 = 0.3$, $M_3 = 1.0$
 Number of noise level, $n = 2$, N_1 and N_2
 Number of repetitions, $r = 1$ (one sample tested in each unique test condition)

There are six ($=3 \times 2$) results in each trial condition. In the example case, results $y_{11} = 5.4$, $y_{31} = 18.8$, $y_{32} = 28.8$, etc. Note that the third subscript of y in this case dropped as the value of $r = 1$. Also, the formulas shown below apply to an individual trial results at one time.

Trial# 1:
 Slope equation:

$$\beta = \frac{\sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^r M_i y_{ijk}}{r n \sum_{i=1}^m M_i^2}$$



$$\beta = \frac{(0.1 \times 5.4 + 0.1 \times 12.1) + (0.3 \times 7.5 + 0.3 \times 24.6) + (1.0 \times 18.8 + 1.0 \times 28.8)}{(0.1^2 + 0.1^2) + (0.3^2 + 0.3^2) + (1.0^2 + 1.0^2)}$$

$$= [1.75 + 9.63 + 47.6] / 2.20 \quad \text{or} \quad \beta = 26.809$$

Variance Formula:

$$\sigma^2 = \frac{\sum_{i=1}^m \sum_{j=1}^n \sum_{r=1}^r (y_{ijk} - \beta M_i)^2}{mnr - 1}$$

$$\sigma^2 = \frac{[(5.4 - 26.809 \times 0.1)^2 + (12.1 - 26.809 \times 0.1)^2 + (7.5 - 26.809 \times 0.3)^2 + (24.6 - 26.809 \times 0.3)^2 + (18.8 - 26.809 \times 1.0)^2 + (28.8 - 26.809 \times 1.0)^2]}{(3 \times 2 - 1)}$$

$$\sigma^2 = [(2.7191)^2 + (9.4191)^2 + (0.5427)^2 + (16.5573)^2 + (8.009)^2 + (1.991)^2] / 5.0$$

$$\sigma^2 = [7.393 + 88.719 + 0.2945 + 274.144 + 64.144 + 3.964] / 5.0$$

$$\sigma^2 = [438.6585] / 5.0$$

$$\sigma^2 = 87.73 \quad \text{or} \quad \sigma = 9.366 \quad (\text{Shown at right of results for first Trial})$$

$$S/N = 10 \times \text{Log}_{10} (\beta^2 / \sigma^2)$$

$$S/N = 10 \times \text{Log}_{10} (26.809^2 / 9.366^2) \quad \text{or} \quad S/N = 9.134$$

S/N for Trial # 1

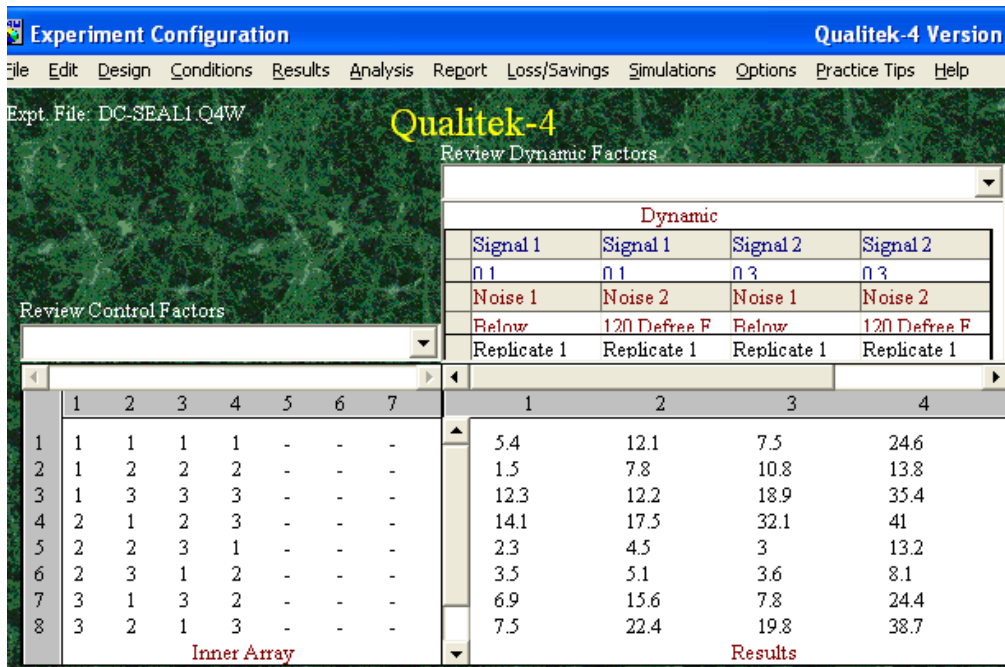
Case Study Example: Pressure Camber Sealer Design Study
 Signal (M): Pressure Noise (N): Outside Temperature Result: Opening Force
 Control Factors: A, B, C and D (3-level)

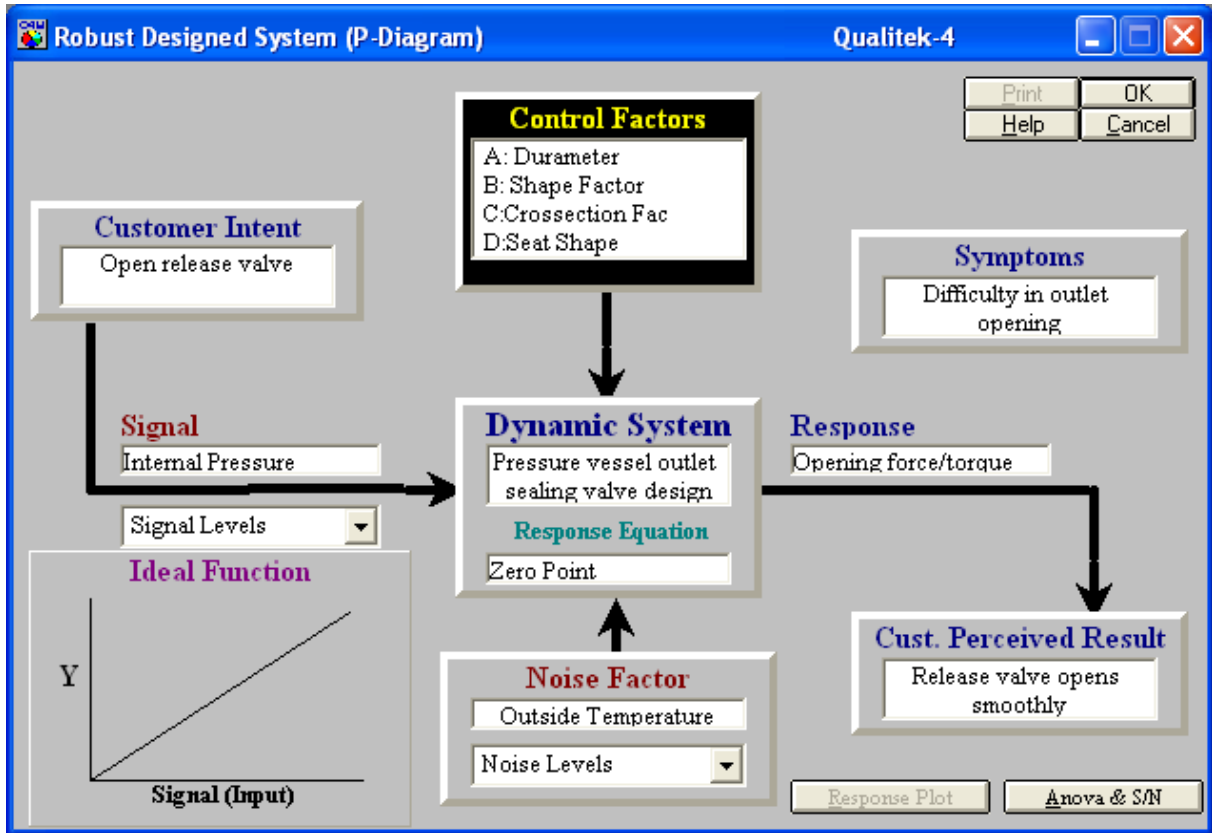
Trial#	A	B	C	D	M ₁ = 0.1		M ₂ = 0.30		M ₃ = 1.0		β	σ	S/N
					N ₁	N ₂	N ₁	N ₂	N ₁	N ₂			
					R ₁	R ₁	R ₁	R ₁	R ₁	R ₁			
1	1	1	1	1	5.4	12.1	7.5	24.6	18.8	28.8	26.81*	9.37*	9.13*
2	1	2	2	2	1.5	7.8	10.8	13.8	10.2	14.1	14.82	6.16	7.63
3	1	3	3	3	12.3	12.2	18.9	35.4	22.3	20.1	27.79	14.92	5.40
4	2	1	2	3	14.1	17.5	32.1	41.0	20.1	32.7	35.40	19.66	5.11
5	2	2	3	1	2.3	4.5	3	13.2	8.7	13.8	12.74	4.85	8.39
6	2	3	1	2	3.5	5.1	3.6	8.1	10.2	14.7	13.30	3.08	12.67
7	3	1	3	2	6.9	15.6	7.8	24.4	20.2	34.4	30.23	10.27	9.37
8	3	2	1	3	7.5	22.4	19.8	38.7	34.3	61.8	53.02	15.87	10.48
9	3	3	2	1	8.3	11.4	24	40.5	33.4	28.5	37.83	15.46	7.77

* The detail calculations of these values for Trial # 1 are shown above

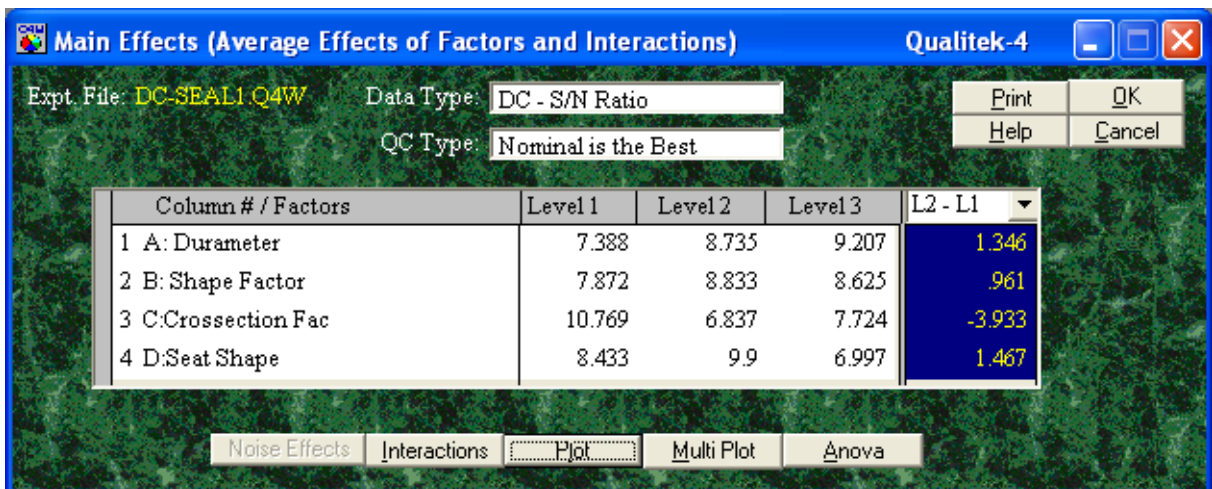
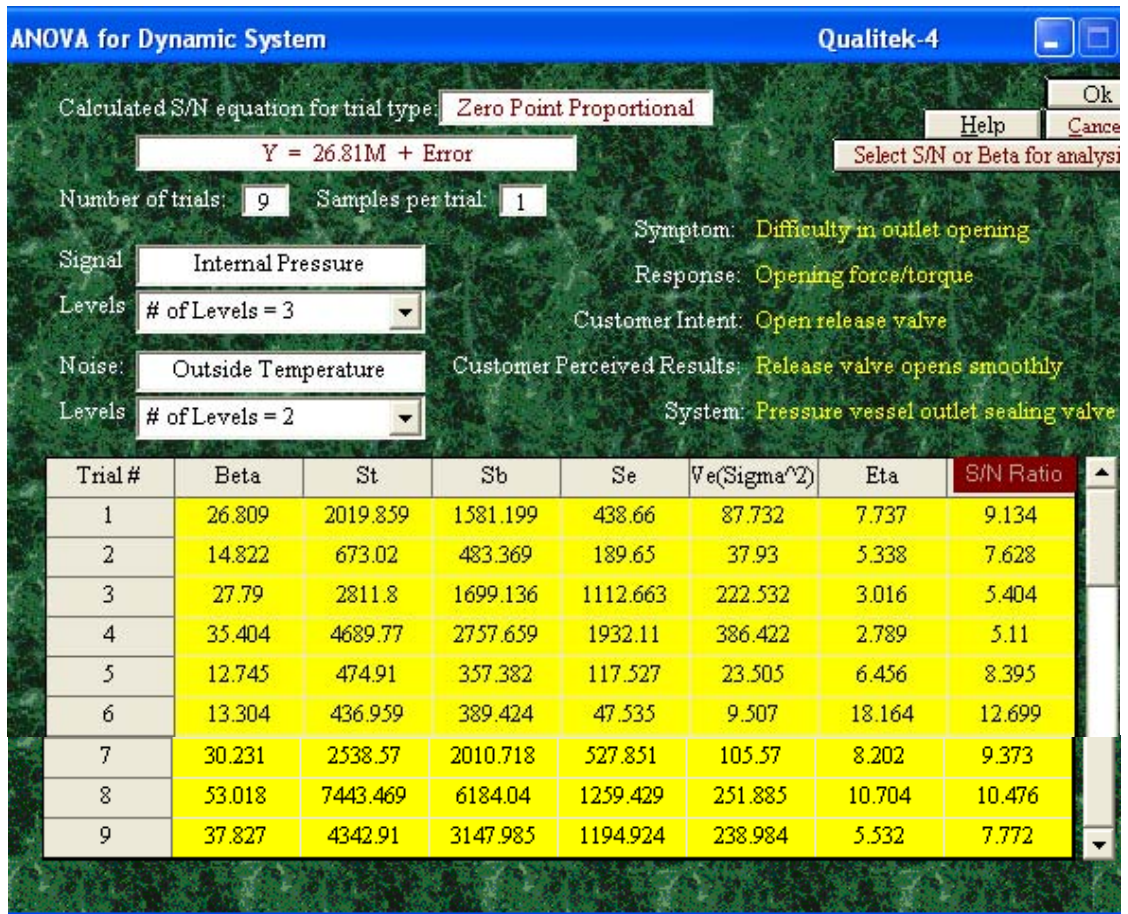
In the same manner, the slope, variance, and S/N values can be calculated for the remaining eight trial results (Trials 2 – 8).

When you use the software, your experiment design would look like the one shown below. You will be able to view the P-Diagram as you proceed with analysis by selecting *Dynamic Characteristic* option from the *Analysis* menu option.

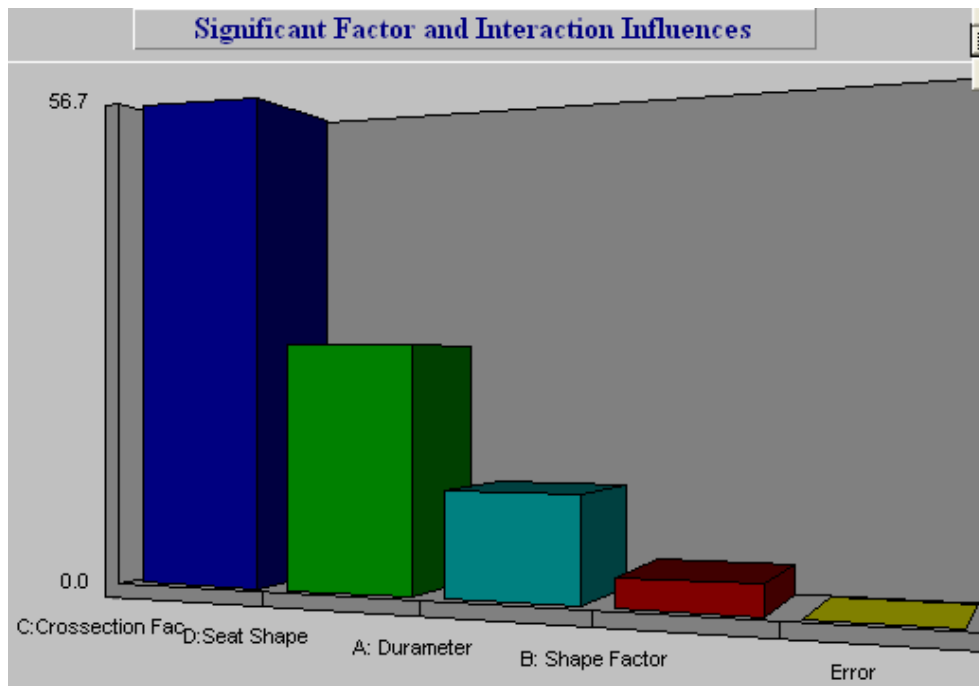
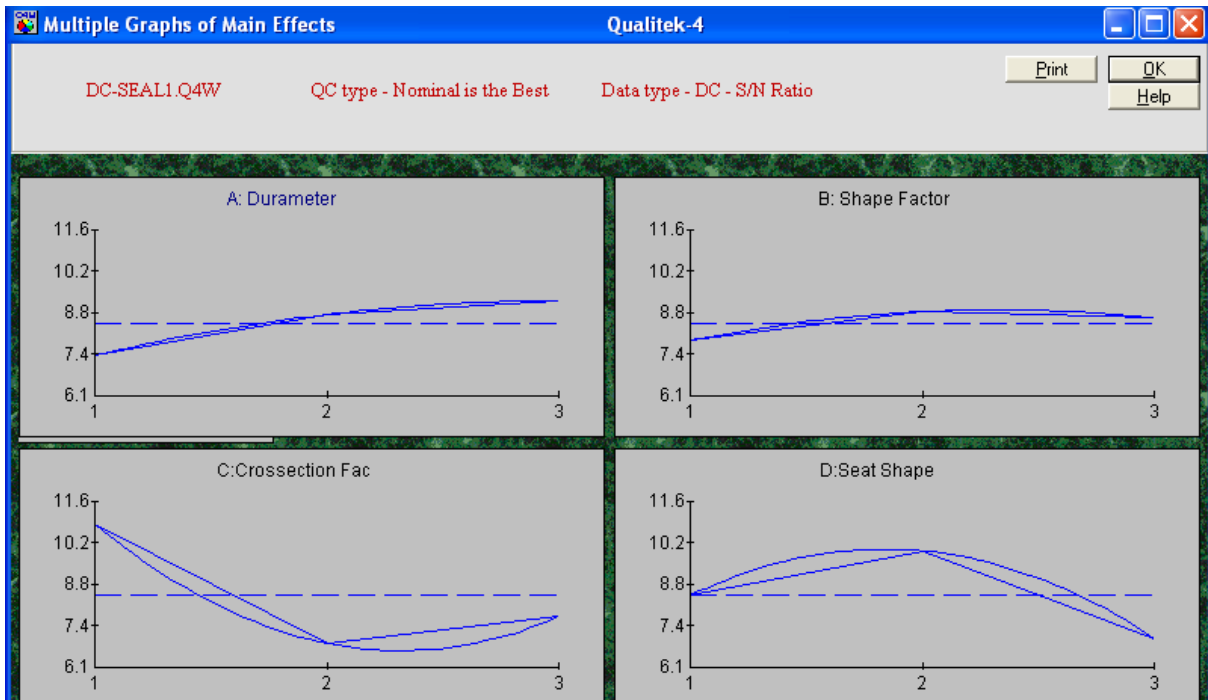




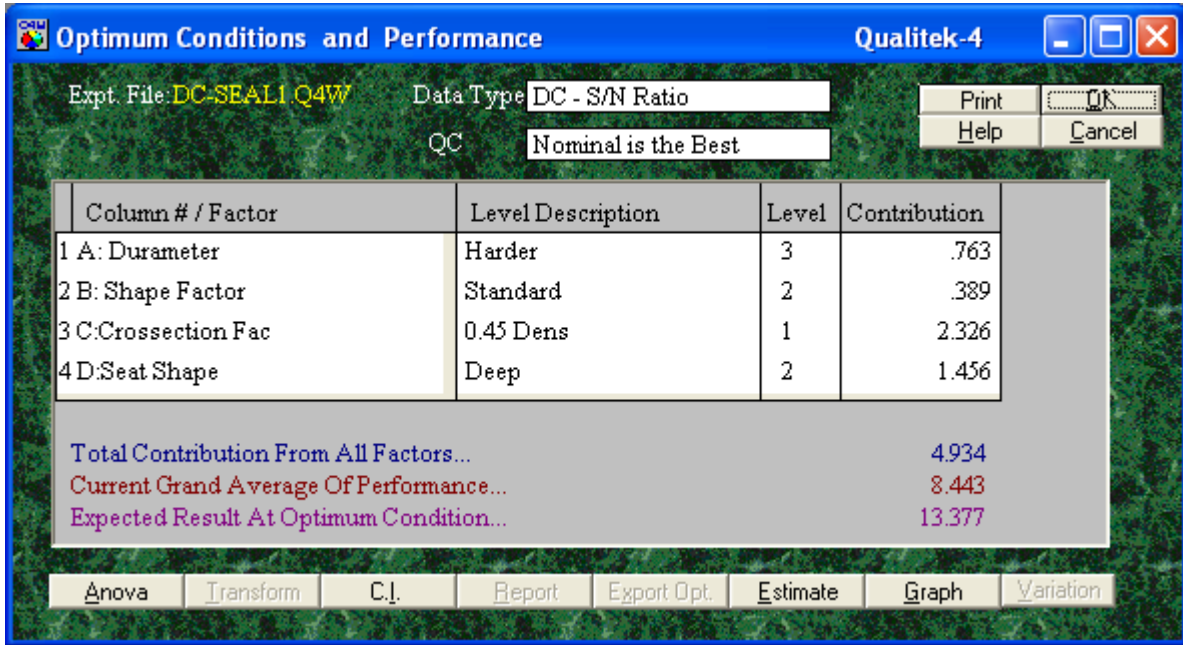
As you proceed with analysis, individual trial statistics (slope, variance, and S/N) are first calculated and displayed. Based on your selection of the Slope (Beta) or S/N, the factor main effects are calculated as shown below.



Screens below shows the trend of factor influence (Main Effects) and the relative influence of the factors to the variation of results.



The optimum design condition and the expected performance in terms of S/N ratio is shown in the screen below. Based on the calculation, the GAIN expected is about 5 decibels (S/N, in terms of Log of the ratio of slope to variance). Recall that an increase of 6 points in S/N reflects a 50% reduction of the standard deviation when the response characteristic is static.



Expected Gain: $13.377 - 8.443 = 4.934$ (dB or S/N)

Suggested Practice Exercise

Optimize the Paper Helicopter Design Shown

Construction: (Keep aspect ratio between 1 to 3)

- Split Wings by cutting along solid line
- Fold wings along the dashed lines
- Cut Lower Body to Upper Body joints
- Fold Lower Body sides along the dashed lines

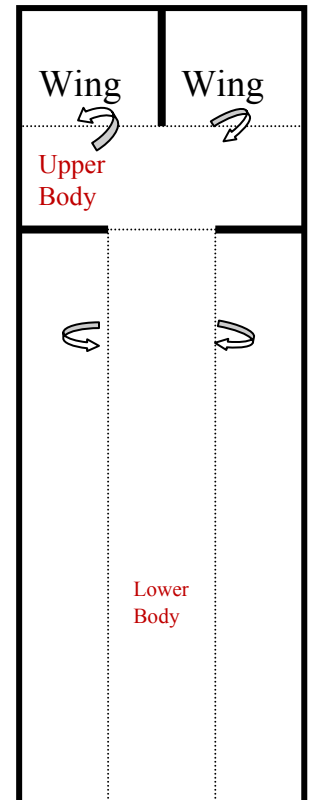
Objective: Make helicopter flight time the longest

Response: Flight time

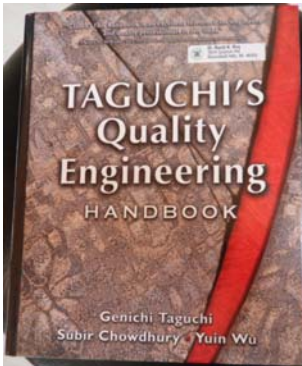
Suggested control Factors (4 or 5) and their levels:

Noise Factor: Drop Orientation (N), N1 = 0 degree, N2 = 15 degrees

Signal Factor (in case of Dynamic System): Drop height (72" - 96")



Additional Reference Case Studies



Taguchi's Quality Engineering Handbook - Genichi Taguchi, Subir Chowdhury, Yui Wu, John Wiley & Sons, ISBN: 978-0-471-41334-9, Hardcover, 1696 page.

CASE 4

Evaluation of Photographic Systems Using a Dynamic Operating Window

Abstract: The function of photographic image formation is represented by the characteristic curves of photosensitive materials. In color photography, variation in the characteristic curves of three colors [blue, green, and red (BGR)] affects color change. The purpose of this study was to use the chemical reaction function and compare it with the results from a traditional approach.

CASE 5

Application of Dynamic Optimization in Ultra Trace Analysis

Abstract: Ultra trace analysis with physical and chemical methods is of considerable importance in various fields, including medicine, the food industry, and solid-state physics and electronics. For manufacturing electronic devices, ultrapure water has to be monitored for metallic contamination. Extreme demands exist related to the reliability and reproducibility of quantitative results at the lowest possible concentration level. With such data, interpretation of the linear response with the least variability and the highest sensitivity can be achieved. For proof, the lowest detectable concentration is calculated and a robust detection limit below 1 ppt has been confirmed for some elements.

CASE 15

Robust Design for Frequency-Modulation Circuits

Abstract: In our research we verified highly repeatable experimentation (measurement characteristics) in regard to resonant circuits such as oscillator and modulation circuits, typical in the electrical engineering field.

1. Introduction

The majority of tasks requisite for electrical circuit design involve adjustment of quality characteristics to target values. More specifically, by implementing product confirmatory experiments called environmental or reliability tests, we have made a strong effort to match the quality characteristics to final specifications through the modification of part characteristics if the quality characteristics go beyond the standards. However, since this procedure is regarded only as "adjustment" and robustness cannot be built in, complaints in the marketplace regarding

oscillator (C_3), two resistors (R_1 and R_2), two capacitors (C_1 and C_2), and two variable capacitors (C_{v1} and C_{v2}), whose capacitance varies according to the voltage.

As illustrated in Figure 2, in actual modulation, when an alternating current such as a human voice is given on a direct bias voltage, the output voltage alternates between the lower and upper voltages around the bias voltage. This alternating signal makes the terminal capacitance, and consequently the frequency, change.

Therefore, the proportional relationship between voltages imposed on the variable capacitors

Practice Problem # 9A: [Reference Module 9, Robust designs with Dynamic Characteristics. Solve only if covered in the class.]

Concept – Experiment for Robust Design with Dynamic Characteristics

Engineers in a cold forming company planned an experiment to study one of the inherent problems with *cold heading process*: the breakdown/wear of tooling dimensions due to contact with the raw materials being formed. The study was initiated to find a suitable combination of the process parameters whereby certain raw material coatings can improve tool life.

Factors	Level I	Level II
A: Raw material type	Type 1	Type 2
B: Material strength	Lower	Higher
C: Application method	Method 1	Method 2
D: Lubricants	Low Viscosity	Higher Viscosity

Interactions: AxB, BxC, and CxA

Signal Factor: Material Size (3 levels: 0.25, 0.5, and 1.25)
Noise Factor: Cleaning Process (2 levels: Intermittent and Continuous)
Symptom: Excessive tool wear **Intent:** achieve longer tool life

Trial#	A	B	AxB	C	CxA	BxC	D	Results(QC= Zero Point Prop. DC)
1	1	1	1	1	1	1	1	Tool Life
2	1	1	1	2	2	2	2	24 results/trial condition 4 samples for each cell. (see below)
3	1	2	2	1	1	2	2	
4	1	2	2	2	2	1	1	
5	2	1	2	1	2	1	2	
6	2	1	2	2	1	2	1	
7	2	2	1	1	2	2	1	
8	2	2	1	2	1	1	2	

Trial#	Results:(8 Trial 24 results/trial)
1	20,80,13,25,66,73,23,81,52,30,46,23,21,90,20,88,12,95,87,19,65,87,87,55
2	44,63,69,86,18,2,59,44,92,74,40,75,48,59,89,58,62,34,86,69,12,76,10,88
3	69,61,85,27,18,95,48,64,85,53,62,8,38,99,94,24,41,1,10,76,60,22,74,33
4	46,73,16,74,95,20,35,23,11,21,23,78,96,81,82,43,55,3,16,22,90,88,28,16
5	23,85,60,93,97,98,85,62,96,70,31,36,11,93,85,5,30,56,42,59,45,50,89,90
6	63,95,19,41,77,2,93,92,44,54,34,54,91,82,69,55,47,13,28,23,40,75,36,86
7	52,47,87,2,93,94,11,76,3,26,60,44,96,58,51,20,88,7,98,20,96,85,20,58
8	99,94,90,54,23,55,79,43,66,86,15,80,82,43,51,19,26,76,40,11,50,40,36,10

Using Qualitek-4 software (Downloaded DEMO version from: <http://Nutek-us.com/wp-q4w.html> if needed), design the experiment and analyze the results to determine the optimum condition.

[Key answers: Optimum cond. – 1 1 1 1, Perf. S/N 1.79 + 3.342 = 5.132]

