DRAFT INTERNATIONAL STANDARD
ISO/DIS 16337

ISO/TC **69**/SC **8**

Secretariat: **JISC**

Voting begins on:
2019-11-08

Voting terminates on:
2020-01-31

Application of statistical and related methods to new technology and product development process — Robust Tolerance Design (RTD)

Application des méthodes statistiques et des méthodes liées aux nouvelles technologies et de développement de produit — Plans d'expériences robustes

ICS: 03.120.30

This document is circulated as received from the committee secretariat.

Reference number
ISO/DIS 16337:2019(E)

COPYRIGHT PROTECTED DOCUMENT

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

Published in Switzerland

Contents

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 69, Applications of statistical methods, Subcommittee SC 8, *Application of statistical and related methodology for new technology and product development*.

Introduction

A designer of a product decides the specification of the product, and hands it to manufacturing process for manufacturing. The specification includes the designed nominal values and tolerances of the parts or elements of the product. The optimum nominal values of design parameters are determined by Robust Parameter Design (RPD), and the optimum tolerances of them are determined by Robust Tolerance Design (RTD).

RPD described in ISO 16336 is applied to the objective product prior to RTD. In RPD, major noise factors are taken to evaluate robustness, that is, SN-ratio. SN-ratio represents the variability of the output of the product. SN-ratio is a measure of comparison of robustness between levels of control factors.

RTD described in this document is the method of selecting the degree of errors of the parts or elements of the product from the viewpoint of variability under the RPD-optimum condition, that is, the combination of optimum designed values of design parameters. If a manufactured product has some errors from the designed values of design parameters, the output of the product is deviated from the designed value. The error of design parameter should be smaller than the designed tolerance to keep the output of the product within the designed variability. This is the reason why the design parameter needs a tolerance.

The design of a product can be finalized by setting optimum tolerances of design parameters by RTD. The realistic variance of the product manufactured with errored parts or elements can be estimated in RTD. After RPD finds out a set of optimum values of design parameters, RTD is applied to check that actual variance is smaller than the target variance under the RPD-optimum condition.

RPD can set the optimum nominal values of design parameters without cost-up, but RTD is closely related to manufacturing cost. Smaller tolerances, that means higher-grade parts or elements, lead to cost-up, and larger tolerances, that means lower-grade parts or elements, lead to cost-down. To finalize the product design process, cost of manufacturing the product is considered. Loss function of Taguchi Methods is applied to transform the merits of improvement in quality to money scale as same as cost. The cost of improvement and the merits of improvement in quality are balanced in deciding the tolerances. Both of RPD and RTD give cost effective way of optimizing the design of product.

When RPD cannot realize the target variability of the product, smaller tolerances of the design parameters are applied to improve the variability, but smaller tolerances lead to cost-up.

On the other hand, when RPD can realize variability much smaller than the target variability, larger tolerances of design parameters are applied to save the manufacturing cost of the product, then larger tolerances lead to cost-down.

The product manufactured based on the combination of the optimum nominal values and tolerances of the design parameters is robust to noise conditions in users' stage of it. Robust product minimizes users' quality losses caused by defects, failures and quality problems.

Application of statistical and related methods to new technology and product development process — Robust Tolerance Design (RTD)

1 Scope

This document specifies guidelines for applying the Robust Tolerance Design (RTD) of Taguchi Methods to finalize the design process of products.

Robust Tolerance Design (RTD) is applied to the objective product to set the optimum tolerances of design parameters around the nominal values. RTD finds the effects of errors in design parameters on final product's output and estimates the total variance of the output when tolerances are changed. RTD achieves the target variance of the output from the viewpoints of robustness, performance and cost.

Tolerance expresses a maximum allowable error in the value of design parameter in manufacturing process. It is perfect that parts or elements of every product have the designed nominal values of the design parameters. However, actual manufacturing cannot give the exact designed values of the design parameters for all the products. The actual products have some errors in the values of parts or elements of the products. These errors are supposed to be within the designed tolerances in manufacturing.

This document is applicable to determine the optimum tolerances and finalize the design process of the product.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 16336 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1 tolerance

difference between a nominal value and its allowable limit.

3.2 robust tolerance design (RTD)

a method of setting optimum tolerances from the viewpoints of robustness, performance and cost.

4 Robust tolerance design

4.1 General

A product design section gives a specification of a product, that is, the nominal values and tolerances of design parameters, to manufacturing section. Manufacturing sections keeps the designed specification for every product. When a specification of a design parameter specifies the limits as $m \pm \Delta$, the design parameter's value x in manufacturing process satisfies the following restriction;

$$m - \Delta \leq x \leq m + \Delta ,$$

where m and Δ denote a nominal value and its tolerance respectively.

If absolute error of a design parameter is larger than the tolerance Δ, the variability of the product cannot keep the designed performance and specification.

Robust Tolerance Design (RTD) is applied in the design section to set the optimum tolerance for each design parameter to realize the designed performance, which is evaluated by the total variance of the output of product. Tolerances of design parameters mean maximum allowable errors around the nominal value in manufacturing process and they are closely related to the cost of manufacturing.

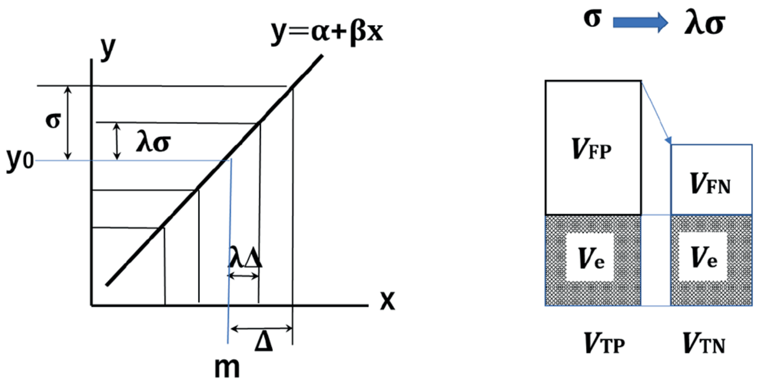
The nominal values of design parameters can be identified by Robust Parameter Design (RPD) through robustness. Selection of a robust designed system by setting the optimum values of design parameters in RPD is highly recommended prior to RTD. RPD can optimize the objective system by choosing the optimum combination of design parameters' nominal values from the point of view of the variability of the output without cost-up.

There is a case where RPD cannot achieve a target variability. RTD is applied, in this case, to find out possible tolerances for realizing the target variability even with cost-up. Smaller tolerance can achieve the smaller variability, but it means grade-up of parts or elements of the product and leads to cost-up of manufacturing. RTD investigates the balance of quality and cost of improvement.

Even when RPD achieves the target variance, RTD is applied, in some cases, to find out larger tolerance than that considered in RPD. Larger tolerance means larger variability. However, if the increased variability satisfies the target variability, the larger tolerance can be applicable, and it leads to cost-down of the designing product.

Purpose of RTD is to realize the target variability by setting optimum tolerance form the viewpoint of robustness, performance and cost. For this purpose, RTD forecasts the total variance of the output of the designing system when a tolerance of design parameter is changed. If a design parameter has a linear effect to the output of the system, total variance of the output can be estimated based on the result of analysis of variance (ANOVA).

Assume that a design parameter F has a linear effect on the output of the system y as shown in Figure 1 (a). When the present tolerance of x in F is $\Delta_P = \Delta$, the error distribution of the factor F has an influence on output y with the magnitude of $\sigma = \beta\Delta$. When the tolerance of F is reduced to new tolerance $\Delta_N = \lambda\Delta$ ($\lambda < 1$ in Figure 1 (a)) , the influence of F on the output is reduced to $\lambda\sigma = \beta\lambda\Delta$ and the variance of y due to the factor F is reduced from the present variance V_{FP} to new variance $V_{FN} = \lambda^2 V_{FP}$. As a result of this, the total variance of the output is reduced from V_{TP} to V_{TN} (Figure 1 (b)).



(a)Linear dependence of factor F **(b)Total variances by tolerance change**

Figure 1 — RTD mechanism for tolerance change of factor F

New total variance V_{TN} can be estimated as follows;

$$V_{\mathrm{TN}} = V_{\mathrm{FN}} + V_{\mathrm{e}} = \lambda^2 V_{\mathrm{FP}} + V_{\mathrm{e}}$$

where $\lambda = {\Delta_{\mathrm{N}}}/{\Delta_{\mathrm{P}}}$ is assumed.

When a tolerance of design parameter is reduced, that is, λ≤1, the magnitude of error of the design parameter becomes smaller and the total variance of output is reduced. Smaller tolerance means that up-graded part or element will be used, and production cost of a new design may be larger than the present design.

When a tolerance of design parameter is enlarged, that is, λ≥1, the magnitude of error of the design parameter becomes larger and the total variance of output is enlarged. Larger tolerance means that down-graded part or element can be used, and production cost of a new design may be smaller than the present design.

RTD has the following two steps;

1) RTD experiment: Data collection of the designing system and analysis of the data to find out the dependence of the output of the system on the design parameters.

2) Tolerance determination: Forecasting the total variance when tolerance is changed, and cost comparison for deciding the optimum tolerance.

RTD experiment studies actual variability of the designing system which has some errors in design parameters of the product. In RTD experiment, experimental design is applied to collect the data of output of the system under the situation where errors of design parameters exist. ANOVA shows the effects of errors in design parameters to the total variance of the output of the system. The output of the system has a target variance from the point of view of robustness and performance.

Controllable design parameters are taken as noise factors in RTD experiment. “Controllable” means that designer can set the nominal values and the tolerances of them. The linear effects of errors in controllable design parameters will be estimated. The level width *d* of the factors is taken proportional to tolerances. In RPD, controllable design parameters are taken as control factors because the values of design parameters can be fixed by designer as nominal values. However, in the actual manufacturing, the parts or elements of product have some errors and the errors of design parameters could not be fixed by designer. Designer can fix the limit of error as a tolerance. The errors of design parameters are causes of variability of output of the products. If an error of a factor has linear effect, the variance of output can be changed by resetting the tolerance of the design parameter. RTD experiment is applied to find out the contribution of the linear effects of errors to the total variance of product's output.

In tolerance determination step of RTD, the optimum tolerance can be chosen by considering the quality merit of tolerance change expressed by quality loss and the cost of tolerance change.

4.2 RTD experiment

4.2.1 Objective system

RTD experiment is applied to find the design parameters' linear effects for the present designed system. For this purpose, the relation between the output of the system and the error in design parameter is investigated. Multi-factor experimental design, orthogonal array, is applied to data collection.

There are three cases of objective system for data collection;

1) by a theoretical formula,

2) by an experiment with an actual system,

3) by a simulation experiment.

When theoretical formula of the objective system is known between the output and the design parameters, the data of the output can be directly calculated by the levels of design parameters. RTD offers orthogonal array as an experimental design for collecting the data under variation of noise factors as shown in the case study (1) in 6.1, and ANOVA for analysing the dependence of the output on noise factors. Mathematical analysis may be applied in this case. This mathematical analysis consists of using variance estimates for a system, for example, by propagating input variance through the system via Taylor series expansions of moment generating functions[4].

When actual systems can be constructed, an actual experiment on them can be applied, and the data of output of them can be collected. However, in many cases, it is difficult to set levels of experimental factor in an actual system, because the levels of noise factors are set within the error distribution of the design parameters. Simulation experiment can be applied in those cases. This is the reason why simulation experiments are often applied in RTD. Simulation program can give the data of the output of the objective system as shown in the case study (2) in 6.2.

4.2.2 Experimental design

RTD experiment is applied for collecting the data of output of the designed system under the situation where errors in design parameters exist. The purpose of RTD experiment is to know the linear effects of the errors in design parameters. Orthogonal array is applied for collecting the data. Orthogonal array with multi factor situation is effective for RTD experiment because output data under various situation can be collected in multifactor layout.

Orthogonal array L_{18} is applied for experimental layout for the factors A-H. Number of levels should be three for seven factors and two for one factor. If the proportional property is obvious for a factor, two-level setting is enough for this factor. Table 1 shows the factors assignment to orthogonal array L_{18} and the output data y_i calculated under the combinations of factors' levels which are indicated in low No. i of the orthogonal array L_{18}.

Table 1 — Factors assignment to orthogonal array L_{18} and the data of output

Factors	A	B	C	D	E	F	G	H	Data
No.	1	2	3	4	5	6	7	8	Output
1	1	1	1	1	1	1	1	1	y_1
2	1	1	2	2	2	2	2	2	y_2
3	1	1	3	3	3	3	3	3	y_3

Table 1 *(continued)*

Factors	A	B	C	D	E	F	G	H	Data
No.	1	2	3	4	5	6	7	8	Output
4	1	2	1	1	2	2	3	3	y_4
5	1	2	2	2	3	3	1	1	y_5
6	1	2	3	3	1	1	2	2	y_6
7	1	3	1	2	1	3	2	3	y_7
8	1	3	2	3	2	1	3	1	y_8
9	1	3	3	1	3	2	1	2	y_9
10	2	1	1	3	3	2	2	1	y_{10}
11	2	1	2	1	1	3	3	2	y_{11}
12	2	1	3	2	2	1	1	3	y_{12}
13	2	2	1	2	3	1	3	2	y_{13}
14	2	2	2	3	1	2	1	3	y_{14}
15	2	2	3	1	2	3	2	1	y_{15}
16	2	3	1	3	2	3	1	2	y_{16}
17	2	3	2	1	3	1	2	3	y_{17}
18	2	3	3	2	1	2	3	1	y_{18}

Table 2 shows an example of factors' levels of design parameters for the orthogonal array L_{18}. Upper and lower tolerances are assumed to be same for simplicity. Levels of experimental noise factors are set around the nominal value *m* with the level width *d*. Nominal value *m* is set as an optimum value by RPD from the point of view of robustness.

Table 2 — Example of level settings of factors

Factor	1	2	3
A	m_A-d_A	m_A+d_A	-
B	m_B-d_B	m_B	m_B+d_B
C	m_C-d_C	m_C	m_C+d_C
D	m_D-d_D	m_D	m_D+d_D
E	m_E-d_E	m_E	m_E+d_E
F	m_F-d_F	m_F	m_F+d_F
G	m_G-d_G	m_G	m_G+d_G
H	m_H-d_H	m_H	m_H+d_H

When actual standard deviation σ_x of the error in design parameter is not exactly known, assumptions $\sigma_x = \Delta/2$ or $\sigma_x = \Delta/3$ may be applied.

When actual standard deviation σ_x of the error in design parameter is known, the level width *d* and levels of the factors are set as follows;

For two-level factor, $d = \sigma_x$:

X1: First level $x_1 = m - \sigma_x$

X2: Second level $x_2 = m + \sigma_x$

For three-level factors, $d = \sqrt{\frac{3}{2}}\sigma_x$:

X1: First level $x_1 = m - d = m - \sqrt{\frac{3}{2}}\sigma_x$

X2: Second level $x_2 = m$

X3: Third level $x_3 = m + d = m + \sqrt{\frac{3}{2}}\sigma_x$

By setting the level of noise factors as mentioned above, the variance $\sigma_{y\ell}^2$ of the output *y* caused by the linear effect of the error in noise factor becomes $\beta^2\sigma_x^2$. where *β* represents a linear coefficient of the relation $y = \beta x$ between output *y* and input *x*.

Assume that data $y_{ij}\ (i = 1,\cdots,n,\ j = 1,\cdots,r)$ are taken as *r* repeated data on *i* level of x_i, linear coefficient *β* and sum of squares of a liner effect S_β are calculated as follows;

$$\beta = \frac{\sum_{i=1}^{n}\sum_{j=1}^{r}(x_i - \bar{x})(y_{ij} - \bar{y})}{r\sum_{i=1}^{n}(x_i - \bar{x})^2},$$

$$S_\beta = \frac{\left[\sum_{i=1}^{n}\sum_{j=1}^{r}(x_i - \bar{x})(y_{ij} - \bar{y})\right]^2}{r\sum_{i=1}^{n}(x_i - \bar{x})^2} = r\sum_{i=1}^{n}(x_i - \bar{x})^2 \cdot \beta^2$$

For two-level factor A with the levels of $x_1 = \bar{x} - d$ and $x_2 = \bar{x} + d$, the sum of squares of a liner effect S_β is calculated as $S_\beta = r \cdot 2d^2\beta^2$. If the linear effect of the factor A is significant, S_β approximately represents data number times of variance $\sigma_{y\ell}^2$ of each data, that is, $2r\sigma_{y\ell}^2$. If the level width *d* is set as σ_x, $S_\beta = 2rd^2\beta^2 = 2r\sigma_x^2\beta^2 \cong 2r\sigma_{y\ell}^2$. Then the variance $\sigma_{y\ell}^2$ of the output *y* caused by the linear effect of the error in noise factor becomes $\beta^2\sigma_x^2$.

For three-level factor B with the levels of $x_1 = \bar{x} - d, x_2 = \bar{x}$, and $x_3 = \bar{x} + d$, the sum of squares of a liner effect S_β is calculated as $S_\beta = r \cdot 2d^2\beta^2$. If the linear effect of the factor is significant, S_β approximately represents data number times of variance $\sigma_{y\ell}^2$ of each data, that is, $3r\sigma_{y\ell}^2$. If the level width *d* is set as $\sqrt{\frac{3}{2}}\sigma_x$, $S_\beta = 2rd^2\beta^2 = 2r \cdot \frac{3}{2}\sigma_x^2 \cdot \beta^2 = 3r\beta^2\sigma_x \cong 3r\sigma_{y\ell}^2$. Then the variance $\sigma_{y\ell}^2$ of the output *y* caused by the linear effect of the error in noise factor becomes $\beta^2\sigma_x^2$.

4.2.3 Analysis of variance of data of RTD experiment

Analysis of Variance (ANOVA) is applied to find out the linear effects of the factors and their contribution ratios to the total variance.