Lecture Notes on Multidisciplinary Industrial Engineering
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# Operations Management and Systems Engineering

## Select Proceedings of CPIE 2018

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# Lecture Notes on Multidisciplinary Industrial Engineering

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# Operations Management and Systems Engineering

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# About This Book

This volume contains extended research work of researchers who participated in the Fifth International Conference on Production and Industrial Engineering (CPIE) 2018. Manuscripts with analytical models, reliability and maintenance engineering, supply chain management, human factor engineering, decision-making case studies with simulation approaches in the area of operations management and systems engineering have been included.

The Conference on Production and Industrial Engineering (CPIE) series, from which this special issue has been derived, was started by the Department of Industrial and Production Engineering, Dr. B.R. Ambedkar National Institute of Technology Jalandhar, India, in March 2007. Subsequently, CPIE 2010, CPIE 2013 and CPIE 2016 were organized which attracted renowned academicians/researchers, noted industry representatives and delegates from countries like Canada, UK, France, Australia, Russia, Singapore, Iran, Egypt, Algeria, Bangladesh, Israel, Mauritius, Turkey and India. We would like to express our gratitude towards all the authors for contributing their valuable articles for our Conference. Finally, we would like to acknowledge the reviewers for their painstaking and time-consuming effort in reviewing manuscripts and providing their thorough evaluations for improving the quality of the articles.

We would also like to express our sincere gratitude towards the Springer team. Last but not least, we would also like to express our sincere gratitude towards our worthy Director (Professor) Lalit Kumar Awasthi for his wholehearted support for the smooth conduct of the conference.

# Contents

# About the Editors

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# Chapter 1
# Tolerance Analysis of Mechanical Assemblies Using Monte Carlo Simulation—A Case Study

**Pradeep K. Singh and Vaibhav Gulati**

**Abstract** Different parts of a mechanical assembly are usually manufactured at different units so as to be assembled later. The assembled parts must fit together without any interference or unnecessarily large clearance. This paper presents the study of the effect of variation in dimensions of individual parts on the assembly response using Monte Carlo simulation. This technique represents the process distribution of the dimensions of individual parts, which helps in determining the assembly response and yield estimation of successful assembly. A case study on a cylinder-piston assembly has been attempted. The simulation has been carried out using MATLAB 7.0 with different theoretical process distributions (uniform, normal, and beta) and yield has been estimated. The aim of this study is to establish a simple yet powerful technique (Monte Carlo simulation) for tolerance analysis and yield estimation of mechanical assemblies. This approach quantifies and handles both the normal and non-normal process distributions.

**Keywords** Tolerance analysis · Monte Carlo simulation · Assembly · Yield

## 1.1 Introduction

An engineering assembly is characterized by a critical parameter or critical dimension, commonly called assembly dimension or assembly response ($Y$). The relationship between the assembly dimension ($Y$) and the individual dimensions ($X_i$) is called assembly response function "$Y = f(X_i)$". Any variation in individual dimensions will directly affect the assembly dimension, and hence the performance of the assembly. In mass production, the individual dimensions have their own distributions. The random assembly of these dimensions gives rise to the distribution of the resultant assembly dimension. Tolerance analysis is the methodology to estimate the resultant

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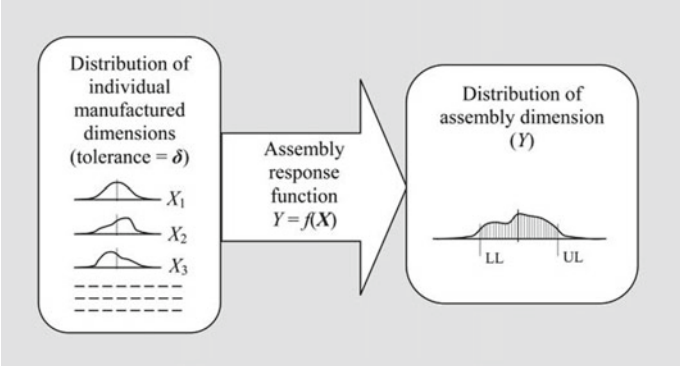



**Fig. 1.1** Tolerance analysis of mechanical assemblies [18] LL and UL: Lower and upper limits on assembly dimension

variation of the assembly dimension, given the tolerances associated with individual dimensions ($\delta_i$), and the assembly response function [1]. If the limits of variation of assembly dimension are set, the fraction of successful assemblies meeting the design requirements, called yield, can also be estimated (Fig. 1.1).

Tolerance analysis establishes a procedure to estimate (i) the resultant variation of the assembly dimension, (ii) distribution of the assembly dimension, and (iii) fraction of successful assembly (i.e., assembly yield), given the tolerances associated with individual dimensions, the assembly response function, and the specifications of the assembly dimension(s). Different approaches to tolerance analysis have been proposed over the decades. Traditional approaches to tolerance analysis, viz., the worst case, and the root sum square are based on a few unrealistic assumptions, and hence do not fulfill the requirements of the real-world assembly design. The importance of tolerance analysis in assembly design attracted the attention of a large number of researchers, with the result the topic has been addressed in depth. A brief account of these approaches has been presented by Singh et al. [18].

In this study, an effort has been made to demonstrate tolerance analysis of mechanical assemblies using Monte Carlo simulation with the help of a case study on a cylinder-piston assembly. The random sampling of the cylinder-bore and piston diameter has been carried out for three different theoretical process distributions (uniform, normal, and beta). The range of variation of assembly dimension (diametric clearance between the cylinder and the piston), mean, standard deviation, and yield of successful assembly have been estimated for all three cases. Effect of tightening of the tolerance (specified for the assembly dimension) on the yield of successful assembly has also been analyzed.

## 1.2 Literature Review

The tolerance design of mechanical assemblies has widely been explored in the research. With the increased interest in the tolerance design problem, various approaches to classical tolerance analysis and synthesis were evolved. A few survey articles on the topic have been reported by Gerth [6] and Ngoi and Ong [13]. Hong and Chang [9] present the most comprehensive discussion on tolerancing research covering various aspects. However, their focus on tolerance analysis and synthesis has been very limited. Singh et al. [18] seem to have presented a detailed and updated discussion fully dedicated to tolerance analysis.

A number of commercial and noncommercial software packages have been developed to make the tolerance design practice easier with a focus on tolerance analysis. With the help of software packages, tolerance synthesis can indirectly be carried out, by attempting tolerance analysis in an iterative manner. This is done by changing the input parameters (tolerances associated with individual dimensions) and estimating the accumulated tolerance and the yield, but without consideration of manufacturing cost.

Commercial software packages offer tolerance analysis capability either through add-ons to existing spreadsheet applications or integration with CAD packages [3]. Many of these are based on the application of Monte Carlo simulation. A brief review of the software packages has been presented by Singh [17].

According to the published literature, a large number of approaches to tolerance analysis have been proposed for tolerance analysis. The Monte Carlo simulation appears to be the most popular tolerance analysis approach because of its simplicity and versatility of application, and the unlimited achievable precision. The research applications of this approach include Gerth and Hancock [7], Bruye‘re et al. [2], Dantan and Qureshi [4], Gulati [8], Qureshi et al. [14], Yan et al. [20], etc. A detailed discussion on these researches shall not be useful. This approach is the basis of most of the tolerance analysis software, and has been applied in research as a reference (yardstick) for evaluating the performance of other approaches [5, 10, 15, 21].

## 1.3 Design of Simulation Methodology—Monte Carlo Simulation

The Monte Carlo simulation approach is based on stochastic sampling technique, and is useful to simulate the randomly occurring natural phenomena. Since the actual dimensions obtained in manufacturing are random in nature with a definite pattern, the approach can be applied to study an engineering assembly for statistical tolerance analysis. The approach appears to be simple to estimate the variation in the assembly response; and is applicable to both the linear and nonlinear assembly response functions, and, the normal and non-normal process distributions. This approach directly yields the distribution of assembly response, which makes it more useful [16]. The statistical tolerance analysis problem can be attempted through the simulation following a systematic procedure given below.

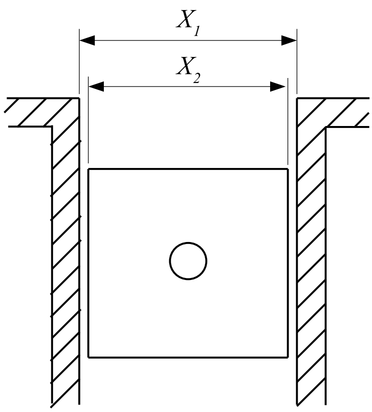
a. Identification of assembly dimension(s), individual dimensions, and dimension chain(s) in the assembly.
b. Formulation of the assembly response function(s) "$Y = f(X_i)$".
c. Specification of the probability density function (pdf) to individual dimensions.
d. Random sampling of individual dimensions and simulation of assembly, i.e., forming a virtual assembly to obtain assembly dimension(s).
e. Estimation of yield—the proportion of successful assembly, out of the total simulations.
f. Estimation of statistical parameter of distribution—spread (range), mean, standard deviation, etc. of the distribution of assembly dimension(s).

The accuracy of the results obtained with this approach is proportional to the square root of the sample size. This makes the approach highly computationally expensive for better results. In spite of this, a few authors explored the application of this approach in the tolerance design [5, 11, 12, 19]. With the availability of highly efficient modern computers at an economical rate, the application of the approach is no more a problem.

## 1.4 Case Study–Cylinder-Piston Assembly

The simulation-based computer-aided system for the tolerance analysis has been presented with the help of a numerical example of the cylinder-piston assembly (Fig. 1.2). The tolerance analysis has been carried out with the help of MATLAB 7.0.

**Fig. 1.2** Engine (cylinder-piston) assembly




Assembly response function: $Y = X_1 - X_2$

**Table 1.1** Dimensional details for cylinder-piston assembly (Courtesy: FMGI Ltd., Bahadurgarh)

| S. No. | Cylinder-bore diameter (mm) ($X_1 \pm \delta_1$) | Piston diameter (mm) ($X_2 \pm \delta_2$) | Specified assembly clearance (mm) ($Y$) |
|---|---|---|---|
| 1 | 95.042 ± 0.010 | 94.912 ± 0.010 | Worst-case assembly tolerance (0.130 ± 0.020) |
| 2 | 95.042 ± 0.010 | 94.912 ± 0.010 | Reduced assembly tolerance (0.130 ± 0.015) |
| 3 | 95.042 ± 0.010 | 94.912 ± 0.010 | Reduced assembly tolerance (0.130 ± 0.010) |

The need for tolerance analysis is especially prevalent in assemblies where some assembly features are more critical to the functioning of the product than others. An example of a critical design feature is the assembly clearance ($Y$) in the cylinder-piston assembly. In order to make the cylinder-piston assembly function properly, the assembly clearance must be larger than zero to prevent jamming, and smaller than a specified value to perform the axial motion between the cylinder and the piston satisfactorily.

This assembly clearance ($Y$) is not a manufactured feature, i.e., the actual size and shape of this gap is not directly controllable in manufacturing. Rather, it is an aggregate property of the assembly which results from the interaction between the mating features of the components when assembled. The size of the gap can be expressed in terms of component dimensions $X_1$ (cylinder diameter) and $X_2$ (piston diameter), (Eq. 1.1). The tolerance of $Y$ is the sum of the tolerances associated with the component dimensions $X_1$ and $X_2$, regardless of whether the component dimensions are added or subtracted (Eq. 1.2).

$$Y = X_1 - X_2 \tag{1.1}$$

$$Tol_Y = Tol_{X1} + Tol_{X2} \tag{1.2}$$

Based on either experience or adopted practices, the product designer assigns appropriate tolerance values to $X_1$ and $X_2$. The tolerance analysis can thus ensure the product functionality while allowing the widest allowable tolerances to be assigned to the component dimensions/features for economic production. The dimensional data of the cylinder-piston assembly for the proposed case study has been obtained from an automobile parts manufacturing company [Federal Mogul Goetze India Ltd. Bahadurgarh (Patiala)]. The same has been presented in Table 1.1.

### 1.4.1 Random Sampling of Dimensions

**(a) Cylinder-bore diameter ($X_1$)**

For the calculation of the sample size for cylinder-bores, a set of 2000 samples was generated in the specified tolerance range (95.042 ± 0.010) following a uniform distribution. After a set of 205 samples, the sample mean became almost constant within ±5% of the specified tolerance (i.e., 0.0005 mm) which is very close to the true mean (95.042 mm). Details have been presented in Fig. 1.3.

**(b) Piston diameter ($X_2$)**

For the calculation of the sample size for pistons, a set of 2000 samples was generated in the specified tolerance range (94.912 ± 0.010) following a uniform distribution. After a set of 100 samples, the sample mean became almost constant within ±5% of the specified tolerance (i.e., 0.0005 mm), which is very close to the true mean (94.912 mm). Details have been presented in Fig. 1.4.

In the same way, the practical approach has been used following normal and beta distribution. For the normal distribution, the approach estimates a sample size of 126 for cylinders and 25 for pistons. For beta distribution, the approach estimates a sample size of 56 for cylinders and 115 for pistons. For better accuracy of the results, $N_{simulation} \geq N$. Thus, tolerance analysis has been carried out for 500 assemblies by applying Monte Carlo simulation.

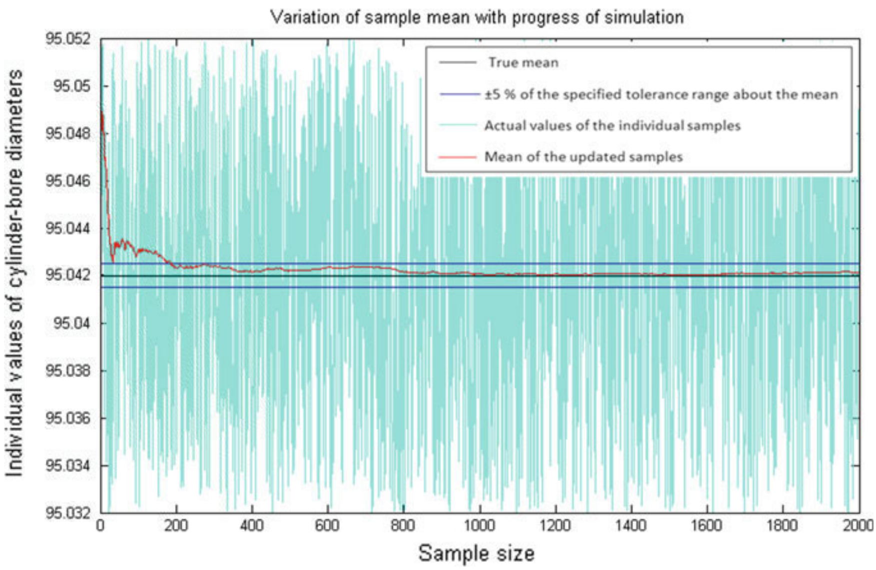



**Fig. 1.3** Variation of sample mean with progress of simulation ($X_1$)

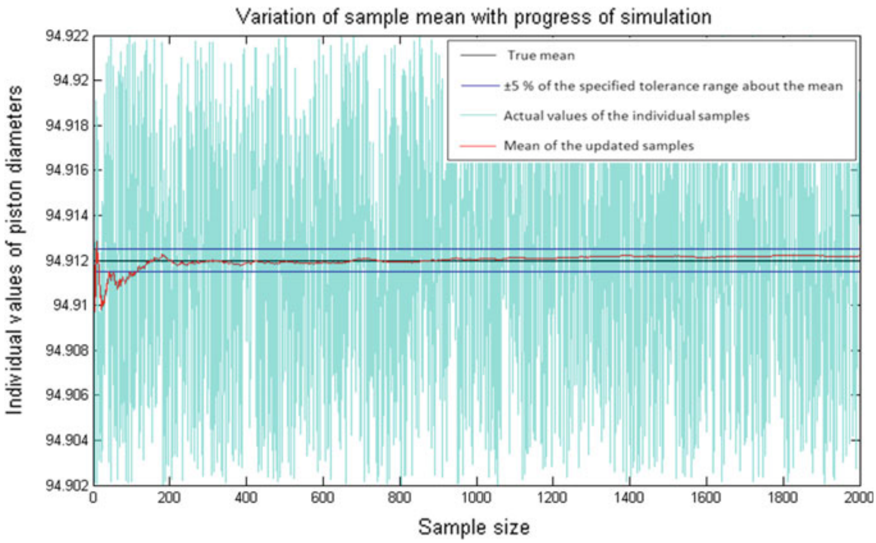



**Fig. 1.4** Variation of sample mean with progress of simulation ($X_2$)

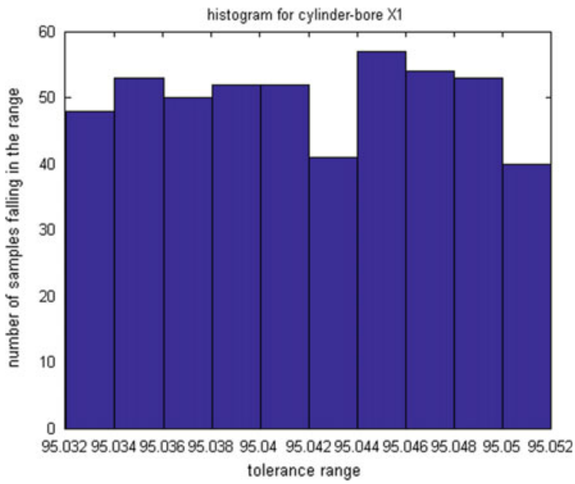



**Fig. 1.5** Histogram for distribution of cylinder-bore diameter ($X_1$) (uniform distribution)

## *1.4.2 Tolerance Analysis and Yield Estimation*

Tolerance analysis for assembly clearance has been carried out for 500 assemblies applying Monte Carlo simulation. Histograms showing distribution of the clearance between the cylinder-bore and piston have been drawn based on uniform (input) distribution. Similar histograms can be obtained for the normal and beta distributions as well.

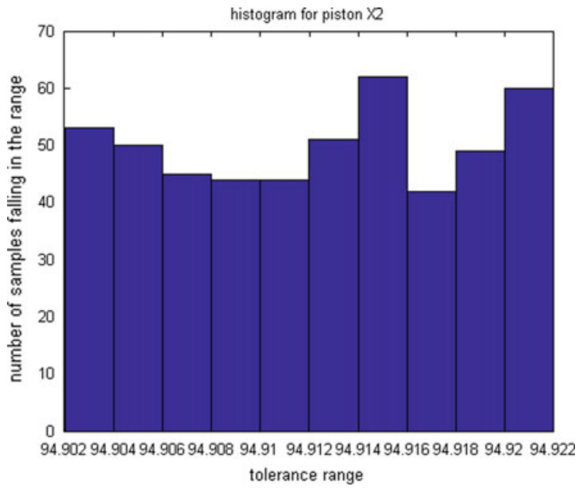



**Fig. 1.6** Histogram for distribution of piston diameter ($X_2$) (uniform distribution)

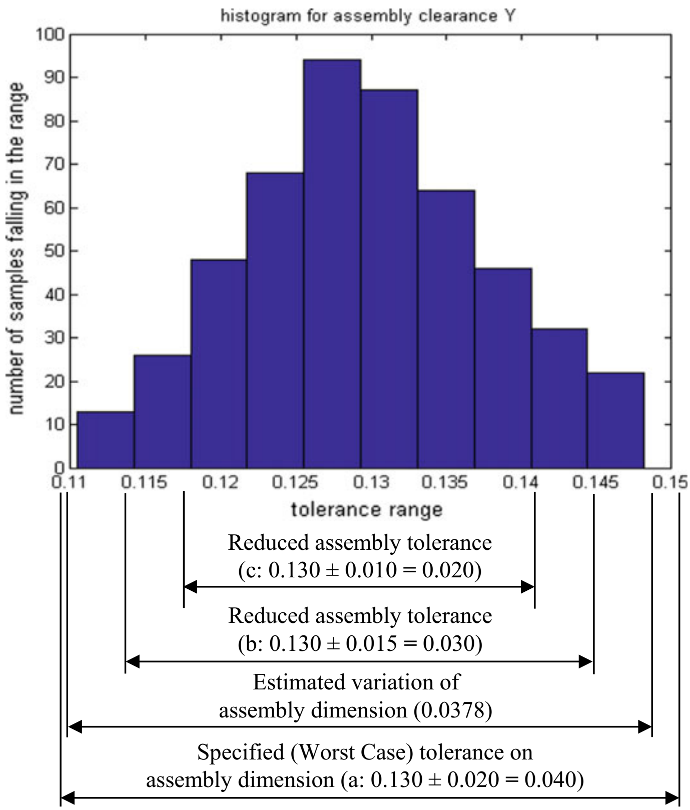



**Fig. 1.7** Histogram for distribution of assembly clearance ($Y$) (uniform distribution)

#### 1.4.2.1 Uniform Distribution

A set of 500 random samples for each of cylinder-bore ($X_1$) and piston ($X_2$) has been generated in the specified dimension range following uniform distribution and the assembly clearance ($Y$) has been obtained. The histograms for distribution of cylinder-bore diameter, piston diameter, and assembly clearance have been represented through the Figs. 1.5, 1.6 and 1.7. With the help of these histograms, it is easy to determine quickly that the current process is able to produce successful product assemblies with good yield percentage. The statistics of the tolerance analysis for the three cases, viz., worst-case tolerance on assembly clearance (0.130 ± 0.020), reduced tolerance on assembly clearance (0.130 ± 0.015) and (0.130 ± 0.010), has been presented in Table 1.2.

### *1.4.3 Normal Distribution*

A set of 500 random samples for each of cylinder-bore ($X_1$) and piston ($X_2$) has been generated in the specified dimension range following a normal distribution and the assembly clearance ($Y$) has been obtained. The histograms showing distribution of cylinder-bore diameter, piston diameter, and assembly clearance can also be presented as in case of uniform distribution. The statistics of the tolerance analysis for the three cases, viz., worst-case assembly clearance (0.130 ± 0.020), reduced tolerance on assembly clearance (0.130 ± 0.015), and (0.130 ± 0.010), has been presented in Table 1.3.

### *1.4.4 Beta Distribution*

A set of 500 random samples for each of cylinder-bore ($X_1$) [beta (2, 3)] and piston ($X_2$) [beta (3, 4)] has been generated in the specified dimension range following beta distribution and the assembly clearance has been obtained. The histograms for distribution of cylinder-bore diameter, piston diameter, and assembly clearance ($Y$) can also be presented as in the case of uniform distribution. The statistics of the tolerance analysis for the three cases, viz., worst-case assembly clearance (0.130 ± 0.020), reduced tolerance on assembly clearance (0.130 ± 0.015) and (0.130 ± 0.010), has been presented in Table 1.4.

## 1.5 Discussion

The results of the simulation study have been presented and analyzed in the previous Section (Figs. 1.5, 1.6 and 1.7 for uniformly distributed constituent dimensions,

**Table 1.2** Tolerance analysis of the assembly for uniform distribution of dimensions

| | | |
|---|---|---|
| Worst-case tolerance on assembly clearance $Y$ (0.130 ± 0.020) | Specified tolerance range = 0.150–0.110 | = 0.040 |
| | Estimated variation = 0.1482–0.1104 | = 0.0378 |
| | Mean | = 0.12967 |
| | Standard deviation | = 0.0081875 |
| | Number of simulated assemblies | = 500 |
| | Number of successful assemblies (within the specification limits) | = 500 |
| | Number of failed assemblies (beyond the specification limits) | = 0 |
| | Yield | = 100% |
| Reduced tolerance on assembly clearance $Y$ (0.130 ± 0.015) | Specified tolerance range = 0.145–0.115 | = 0.030 |
| | Estimated variation = 0.1482–0.1104 | = 0.0378 |
| | Mean | = 0.12967 |
| | Standard deviation | = 0.0081875 |
| | Number of simulated assemblies | = 500 |
| | Number of successful assemblies (within the specification limits) | = 463 |
| | Number of failed assemblies (beyond the specification limits) | = 37 |
| | Yield | = 92.6% |
| Reduced tolerance on assembly clearance $Y$ (0.130 ± 0.010) | Specified tolerance range = 0.140–0.120 | = 0.020 |
| | Estimated variation = 0.1482–0.1104 | = 0.0378 |
| | Mean | = 0.12967 |
| | Standard deviation | = 0.0081875 |
| | Number of simulated assemblies | = 500 |
| | Number of successful assemblies (within the specification limits) | = 381 |
| | Number of failed assemblies (beyond the specification limits) | = 119 |
| | Yield | = 76.2% |

**Table 1.3** Tolerance analysis of the assembly for normal distribution of dimensions

| | | |
|---|---|---|
| Worst case tolerance on assembly clearance $Y$ (0.130 ± 0.020) | Specified tolerance range = 0.150–0.110 | = 0.040 |
| | Estimated variation = 0.1445–0.1180 | = 0.0265 |
| | Mean | = 0.13033 |
| | Standard deviation | = 0.0044625 |
| | Number of simulated assemblies | = 500 |
| | Number of successful assemblies (within the specification limits) | = 500 |
| | Number of failed assemblies (beyond the specification limits) | = 0 |
| | Yield | = 100% |
| Reduced tolerance on assembly clearance $Y$ (0.130 ± 0.015) | Specified tolerance range = 0.145–0.115 | = 0.0300 |
| | Estimated variation = 0.1445–0.1180 | = 0.0265 |
| | Mean | = 0.13033 |
| | Standard deviation | = 0.0044625 |
| | Number of simulated assemblies | = 500 |
| | Number of successful assemblies (within the specification limits) | = 500 |
| | Number of failed assemblies (beyond the specification limits) | = 0 |
| | Yield | = 100% |
| Reduced tolerance on assembly clearance $Y$ (0.130 ± 0.010) | Specified tolerance range = 0.140–0.120 | = 0.0200 |
| | Estimated variation = 0.1445–0.1180 | = 0.0265 |
| | Mean | = 0.13033 |
| | Standard deviation | = 0.0044625 |
| | Number of simulated assemblies | = 500 |
| | Number of successful assemblies (within the specification limits) | = 486 |
| | Number of failed assemblies (beyond the specification limits) | = 14 |
| | Yield | = 97.2% |

**Table 1.4** Tolerance analysis of the assembly for beta distribution of dimensions

| | | |
|---|---|---|
| Worst case tolerance on assembly clearance $Y$ (0.130 ± 0.020) | Specified tolerance range = 0.150–0.110 | = 0.040 |
| | Estimated variation = 0.1449–0.1150 | = 0.0299 |
| | Mean | = 0.12925 |
| | Standard deviation | = 0.0053477 |
| | Number of simulated assemblies | = 500 |
| | Number of successful assemblies (within the specification limits) | = 500 |
| | Number of failed assemblies (beyond the specification limits) | = 0 |
| | Yield | = 100% |
| Reduced tolerance on assembly clearance $Y$ (0.130 ± 0.015) | Specified tolerance range = 0.1450–0.1150 | = 0.0300 |
| | Estimated variation = 0.1449–0.1150 | = 0.0299 |
| | Mean | = 0.12925 |
| | Standard deviation | = 0.0053477 |
| | Number of simulated assemblies | = 500 |
| | Number of successful assemblies (within the specification limits) | = 500 |
| | Number of failed assemblies (beyond the specification limits) | = 0 |
| | Yield | = 100% |
| Reduced tolerance on assembly clearance $Y$ (0.130 ± 0.010) | Specified tolerance range = 0.140–0.120 | = 0.0200 |
| | Estimated variation = 0.1449–0.1150 | = 0.0299 |
| | Mean | = 0.12925 |
| | Standard deviation | = 0.0053477 |
| | Number of simulated assemblies | = 500 |
| | Number of successful assemblies (within the specification limits) | = 467 |
| | Number of failed assemblies (beyond the specification limits) | = 33 |
| | Yield | = 93.4% |

**Table 1.5** Estimated yield (percentage) under different conditions

| | Distribution of independent dimensions (cylinder-bore and piston diameter) | | |
|---|---|---|---|
| Assembly dimension or clearance ($Y$) | Uniform | Normal | Beta |
| $0.130 \pm 0.020$ | 100 | 100 | 100 |
| $0.130 \pm 0.015$ | 92.6 | 100 | 100 |
| $0.130 \pm 0.010$ | 76.2 | 97.2 | 93.4 |

Tables 1.2, 1.3, and 1.4 for all three cases—uniform, normal, and beta distribution). The results have further been summarized in Table 1.5 for better clarity. The following points are observed.

1. When the independent dimensions (or variables) are normally distributed. The resultant dimension (or assembly response) also appears to be normally distributed.
2. In case, the independent dimensions are not normally distributed (for uniform distribution and beta distribution of the cylinder-bore and piston dimensions), the resultant dimension appears to be normally distributed. The observation is in accordance with the Central Limit Theorem. According to the theorem, a sampling distribution always results in significantly less variability, as measured by standard deviation, than the population it is drawn from. Thus, the distribution of assembly dimension will look more and more like normal distribution as the length of the simulation run is increased, even when the population itself is not normally distributed.
3. The specified tolerance on the assembly dimension based on the worst-case criteria results in 100% yield. As the specified tolerance on the assembly dimension is tightened, the yield varies accordingly because of reduction in fraction of accepted assemblies. Tightening the assembly tolerances, though results in better precision of the assembly characteristics, yet with the corresponding reduction in assembly yield.
4. In case of normally distributed dimensions, tightening of the tolerance on assembly dimension results in smaller variation in assembly yield, because of relatively less variability of the assembly dimension. In case of other distributions of independent dimensions, the assembly yield suffers more variation, because of the relatively larger variability of the assembly dimension. The maximum reduction in assembly yield occurs with the uniformly distributed individual constituent dimensions.

## 1.6 Conclusion

The objective of this study has been to estimate the distribution of the assembly response for a given set of dimensions of individual components, and the mathematical relationship among the dimensions of individual components and the assembly response. Monte Carlo simulation has been used for this purpose. A computer-aided system for tolerance analysis of mechanical assemblies has been presented in this work with the help of a numerical example of cylinder-piston assembly. The results have been presented as the histograms for uniformly distributed constituent dimensions, followed by tabulated data for the tolerance analysis for all three cases—uniform, normal, and beta distribution of dimensions of individual components. Salient features of the study have been presented in the previous section. The work can further be extended in the following directions.

- The assembly attempted in this study involves only two independent dimensions with simple dimension chains. More complex problems for assemblies with a large number of independent dimensions involving interrelated dimension chains, and two-dimensional cases can be attempted.
- In this study, only size tolerances have been considered. Tolerance analysis can also be carried out considering geometrical dimensioning and tolerancing (GD & T).
- This study makes use of only a particular probability density function, which has been considered for all the components of an assembly at a time. It is also possible to consider different probability density functions for different individual dimensions at a time.
- This study presents a mechanical assembly of rigid components. The work can be extended to include flexible and elastic components.

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# Chapter 2
# Operationalization and Measurement of Service Quality in Manufacturing Supply Chains: A Conceptual Framework

**Anish Sachdeva and Surjit Kumar Gandhi**

**Abstract** Service and service activities are perishable, complex, and multifunctional in nature, because of which the production and delivery of services are inseparable. Services in manufacturing, however need to be treated in a different manner. In a manufacturing organization, while early market leaders focus on innovation, the quality of services rendered along the supply chain would help in developing loyal customers, resulting in enhanced business performance. Research demonstrates that service quality (SQ) has strong linkages with business performance, cost reduction, feeling of delight, trust, and loyalty among partners and consequently leads to profitability. However, the service dominance perspective that establishes the importance of intangible aspects such as service and relationship is still to be widely embraced in the manufacturing sector. The scholarly attention accorded to service quality in manufacturing is still in its nascence. Against this preamble, this chapter aims to bring out a tailor-made framework to evaluate SQ at different interfaces of a manufacturing supply chain. This chapter conceptualizes SQ as a multidimensional construct, which operates at interfaces of supplier–manufacturer, manufacturer–employee, and manufacturer–distributor.

**Keywords** Service quality · Supply chain management · Small-medium manufacturing enterprises

## 2.1 Introduction

The fierce competition of today's marketplace is driving small-medium manufacturing enterprises to reshape their strategies in order to curtail overall cost and cut

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