Chapter

2

Dimensional Management

Robert H. Nickolaisen, P.E.
Dimensional Engineering Services
Joplin, Missouri

Robert H. Nickolaisen is president of Dimensional Engineering Services (Joplin, MO), which provides customized training and consulting in the field of Geometric Dimensioning and Tolerancing and related technologies. He also is a professor emeritus of mechanical engineering technology at Pittsburg State University (Pittsburg, Kansas). Professional memberships include senior membership in the Society of Manufacturing Engineers (SME) and the American Society of Mechanical Engineers (ASME). He is an ASME certified Senior Level Geometric Dimensioning and Tolerancing Professional (Senior GDTP), a certified manufacturing engineer (CMfgE), and a licensed professional engineer. Current standards activities include membership on the following national and international standards committees: US TAG ISO/TC 213 (Dimensional and Geometrical Product Specification and Verification), ASME Y14.5 (Dimensioning and Tolerancing), and ASME Y14.5.2 (Certification of GD&T Professionals).

2.1 Traditional Approaches to Dimensioning and Tolerancing

Engineering, as a science and a philosophy, has gone through a series of changes that explain and justify the need for a new system for managing dimensioning and tolerancing activities. The evolution of a system to control the dimensional variation of manufactured products closely follows the growth of the quality control movement.

Men like Sir Ronald Fisher, Frank Yates, and Walter Shewhart were introducing early forms of modern quality control in the 1920s and 1930s. This was also a period when engineering and manufacturing personnel were usually housed in adjacent facilities. This made it possible for the designer and fabricator to work together on a daily basis to solve problems relating to fit and function.

The importance of assigning and controlling tolerances that would consistently produce interchangeable parts and a quality product increased in importance during the 1940s and 1950s. Genichi Taguchi and W. Edwards Deming began to teach industries worldwide (beginning in Japan) that quality should be addressed before a product was released to production.

The space race and cold war of the 1960s had a profound impact on modern engineering education. During the 1960s and 1970s, the trend in engineering education in the United States shifted away from a design-oriented curriculum toward a more theoretical and mathematical approach. Concurrent with this change in educational philosophy was the practice of issuing contracts between customers and suppliers that increased the physical separation of engineering personnel from the manufacturing process. These two changes, education and contracts, encouraged the development of several different product design philosophies. The philosophies include engineering driven design, process driven design, and inspection driven design.

2.1.1 Engineering Driven Design

An engineering driven design is based on the premise that the engineering designer can specify any tolerance values deemed necessary to ensure the perceived functional requirements of a product. Traditionally, the design engineer assigns dimensional tolerances on component parts just before the drawings are released. These tolerance values are based on past experience, best guess, anticipated manufacturing capability, or build-test-fix methods during product development. When the tolerances are determined, there is usually little or no communication between the engineering and the manufacturing or inspection departments.

This method is sometimes called the “over-the-wall” approach to engineering design because once the drawings are released to production, the manufacturing and inspection personnel must live with whatever dimensional tolerance values are specified. The weakness of the approach is that problems are always discovered during or after part processing has begun, when manufacturing costs are highest. It also encourages disputes between engineering, manufacturing and quality personnel. These disputes in turn tend to increase manufacturing cycle times, engineering change orders, and overall costs.

2.1.2 Process Driven Design

A process driven design establishes the dimensional tolerances that are placed on a drawing based entirely on the capability of the manufacturing process, not on the requirements of the fit and function between mating parts. When the manufactured parts are inspected and meet the tolerance requirements of the drawings, they are accepted as good parts. However, they may or may not assemble properly. This condition occurs because the inspection process is only able to verify the tolerance specifications for the manufacturing process rather than the requirement for design fit and function for mating parts. This method is used in organizations where manufacturing “dictates” design requirements to engineering.

2.1.3 Inspection Driven Design

An inspection driven design derives dimensional tolerances from the expected measurement technique and equipment that will be used to inspect the manufactured parts. Inspection driven design does not use the functional limits as the assigned values for the tolerances that are placed on the drawing. The functional limits of a dimensional tolerance are the limits that a feature has to be within for the part to assemble and perform correctly.

One inspection driven design method assigns tolerances based on the measurement uncertainty of the measurement system that will be used to inspect finished parts. When this method is used, the tolerance values that are indicated on the drawing are derived by subtracting one-half of the measurement uncertainty from each end of the functional limits. This smaller tolerance value then becomes the basis for part acceptance or rejection.

Inspection driven design can be effective when the designer and metrologist work very closely together during the development stage of the product. However, the system breaks down when the designer has no knowledge of metrology, if the proposed measurement technique is not known, or if the measurements are not made as originally conceived.

2.2 A Need for Change

The need to change from the traditional approaches to dimensioning and tolerancing was not universally recognized in the United States until the 1980s. Prior to that time, tolerances were generally assigned as an afterthought of the build-test-fix product design process. The catalyst for change was that American industry began to learn and practice some of the techniques taught by Deming, Taguichi, Juran, and others (see Chapter 1).

The 1980s also saw the introduction of the Six Sigma Quality Method by a U.S. company (Motorola), adoption of the Malcolm Baldrige National Quality Award, and publication of the ISO 9000 Quality Systems Standards. The entire decade was filled with a renewed interest in a quality movement that emphasized statistical techniques, teams, and management commitment. These conditions provided the ideal setting for the birth of "dimensional management."

2.2.1 Dimensional Management

Dimensional management is a process by which the design, fabrication, and inspection of a product are systematically defined and monitored to meet predetermined dimensional quality goals. It is an engineering process that is combined with a set of tools that make it possible to understand and design for variation. Its purpose is to improve first-time quality, performance, service life, and associated costs. Dimensional management is sometimes called dimensional control, dimensional variation management or dimensional engineering.

2.2.2 Dimensional Management Systems

Inherent in the dimensional management process is the systematic implementation of dimensional management tools. A typical dimensional management system uses the following tools (see Fig. 2-1):

- Simultaneous engineering teams
- Written goals and objectives
- Design for manufacturability and design for assembly
- Geometric dimensioning and tolerancing

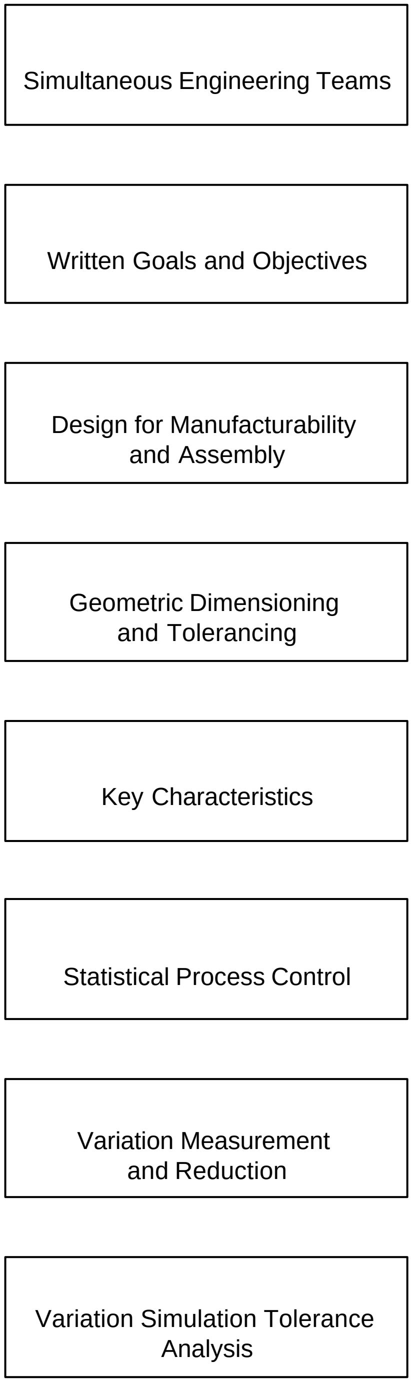

Figure 2-1 Dimensional management tools

- Key characteristics
- Statistical process control
- Variation measurement and reduction
- Variation simulation tolerance analysis

2.2.2.1 Simultaneous Engineering Teams

Simultaneous engineering teams are crucial to the success of any dimensional management system. They are organized early in the design process and are retained from design concept to project completion. Membership is typically composed of engineering design, manufacturing, quality personnel, and additional members with specialized knowledge or experience. Many teams also include customer representatives. Depending on the industry, they may be referred to as product development teams (PDT), integrated product teams (IPT), integrated process and product development (IPPD) teams, and design build teams (DBT).

The major purpose of a dimensional management team is to identify, document, and monitor the dimensional management process for a specific product. They are also responsible for establishing specific goals and objectives that define the amount of product dimensional variation that can be allowed for proper part fit, function, and assembly based on customer requirements and are empowered to ensure that these goals and objectives are accomplished. The overall role of any dimensional management team is to do the following:

- Participate in the identification, documentation, implementation, and monitoring of dimensional goals and objectives.
- Identify part candidates for design for manufacturability and assembly (DFMA).
- Establish key characteristics.
- Implement and monitor statistical process controls.
- Participate in variation simulation studies.
- Conduct variation measurement and reduction activities.
- Provide overall direction for dimensional management activities.

The most effective dimensional management teams are composed of individuals who have broad experience in all aspects of design, manufacturing, and quality assurance. A design engineer willing and able to understand and accept manufacturing and quality issues is a definite asset. A statistician with a firm foundation in process control and a dimensional engineer specializing in geometric dimensioning and tolerancing and variation simulation analysis add considerable strength to any dimensional management team. All members should be knowledgeable, experienced, and willing to adjust to the new dimensional management paradigm. Therefore, care should be taken in selecting members of a dimensional management team because the ultimate success or failure of any project depends directly on the support for the team and the individual team member's commitment and leadership.

2.2.2.2 Written Goals and Objectives

Using overall dimensional design criteria, a dimensional management team writes down the dimensional goals and objectives for a specific product. Those writing the goals and objectives also consider the capability of the manufacturing and measurement processes that will be used to produce and inspect the finished product. In all cases, the goals and objectives are based on the customer requirements for fit, function, and durability with quantifiable and measurable values.

In practice, dimensional management objectives are described in product data sheets. The purpose of these data sheets is to establish interface requirements early so that any future engineering changes related to the subject part are minimal. The data sheets typically include a drawing of the individual part or subassembly that identifies interface datums, dimensions, tolerance requirements, key characteristics, tooling locators, and the assembly sequence.

2.2.2.3 Design for Manufacturability (DFM) and Design for Assembly (DFA)

A design for manufacturability (DFM) program attempts to provide compatibility between the definition of the product and the proposed manufacturing process. The overall objective is for the manufacturing capabilities and process to achieve the design intent. This objective is not easy to accomplish and must be guided by an overall strategy. One such strategy that has been developed by Motorola Inc. involves six fundamental steps summarized below in the context of dimensional management team activities.

Step 1: Identify the key characteristics.

Step 2: Identify the product elements that influence the key characteristics defined in Step 1.

Step 3: Define the process elements that influence the key characteristics defined in Step 2.

Step 4: Establish maximum tolerances for each product and process element defined in Steps 2 and 3.

Step 5: Determine the actual capability of the elements presented in Steps 2 and 3.

Step 6: Assure $Cp \geq 2$; $Cpk \geq 1.5$. See Chapters 8, 10, and 11 for more discussion on Cp and Cpk.

Design for assembly (DFA) is a method that focuses on simplifying an assembly. A major objective of DFA is to reduce the number of individual parts in the assembly and to eliminate as many fasteners as possible. The results of applying DFA are that there are fewer parts to design, plan, fabricate, tool, inventory, and control. DFA will also lower cost and weight, and improve quality.

Some critical questions that are asked during a DFA study are as follows:

- Do the parts move relative to each other?
- Do the parts need to be made from different material?
- Do the parts need to be removable?

If the answer to all of these questions is no, then combining the parts should be considered. The general guidelines for conducting a DFA study should include a decision to:

- Minimize the overall number of parts.
- Eliminate adjustments and reorientation.
- Design parts that are easy to insert and align.
- Design the assembly process in a layered fashion.
- Reduce the number of fasteners.
- Attempt to use a common fastener and fastener system.
- Avoid expensive fastener operations.
- Improve part handling.
- Simplify service and packaging.

2.2.2.4 Geometric Dimensioning and Tolerancing (GD&T)

Geometric dimensioning and tolerancing is an international engineering drawing system that offers a practical method for specifying 3-D design dimensions and tolerances on an engineering drawing. Based on a universally accepted graphic language, as published in national and international standards, it improves communication, product design, and quality. Therefore, geometric dimensioning and tolerancing is accepted as the language of dimensional management and must be understood by all members of the dimensional management team. Some of the advantages of using GD&T on engineering drawings and product data sheets are that it:

- Removes ambiguity by applying universally accepted symbols and syntax.
- Uses datums and datum systems to define dimensional requirements with respect to part interfaces.
- Specifies dimensions and related tolerances based on functional relationships.
- Expresses dimensional tolerance requirements using methods that decrease tolerance accumulation.
- Provides information that can be used to control tooling and assembly interfaces.

See Chapters 3 and 5 for more discussion of the advantages of GD&T.

2.2.2.5 Key Characteristics

A key characteristic is a feature of an installation, assembly, or detail part with a dimensional variation having the greatest impact on fit, performance, or service life. The identification of key characteristics for a specific product is the responsibility of the dimensional management team working very closely with the customer.

Key characteristic identification is a tool for facilitating assembly that will reduce variability within the specification limits. This can be accomplished by using key characteristics to identify features where variation from nominal is critical to fit and function between mating parts or assemblies. Those features identified as key characteristics are indicated on the product drawing and product data sheets using a unique symbol and some method of codification. Features designated as “key” undergo variation reduction efforts. However, key characteristic identification does not diminish the importance of other nonkey features that still must comply with the quality requirements defined on the drawing.

The implementation of a key characteristic system has been shown to be most effective when the key characteristics are:

- Selected from interfacing control features and dimensions.
- Indicated on the drawings using a unique symbol.
- Established in a team environment.
- Few in number.
- Viewed as changeable over time.
- Measurable, preferably using variable data.
- Determined and documented using a standard method.

2.2.2.6 Statistical Process Control (SPC)

Statistical process control is a tool that uses statistical techniques and control charts to monitor a process output over time. Control charts are line graphs that are commonly used to identify sources of variation in a key characteristic or process. They can be used to reveal a problem, quantify the problem, help to solve the problem, and confirm that corrective action has eliminated the problem.

A standard deviation is a unit of measure used to describe the natural variation above an average or mean value. A normal distribution of a process output results in 68% of the measured data falling within ±1 standard deviation, 95% falling within ±2 standard deviations, and 99.7% falling within ±3 standard deviations.

The natural variation in a key characteristic or process defines its process capability. Capability refers to the total variation within the process compared to a six standard deviation spread. This capability is the amount of variation that is inherent in the process.

Process capability is expressed as a common ratio of "Cp" or "Cpk." Cp is the width of the engineering tolerance divided by the spread in the output of the process. The higher the Cp value, the less variance there is in the process for a given tolerance. A Cp ≥ 2.0 is usually a desired minimum value.

Cpk is a ratio that compares the average of the process to the tolerance in relation to the variation of the process. Cpk can be used to measure the performance of a process. It does not assume that the process is centered. The higher the Cpk value the less loss is associated with the variation. A Cpk ≥ 1.5 is usually a desired minimum value.

Cp and Cpk values are simply indicators of progress in the effort to refine a process and should be continuously improved. To reduce rework, the process spread should be centered between the specification limits and the width of the process spread should be reduced. See Chapters 8 and 10 for more discussion of Cp and Cpk.

2.2.2.7 Variation Measurement and Reduction

After key characteristics have been defined and process and tooling plans have been developed, parts must be measured to verify conformance with their dimensional specifications. This measurement data must be collected and presented in a format that is concise and direct in order to identify actual part variation. Therefore, measurement plans and procedures must be able to meet the following criteria:

- The measurement system must provide real-time feedback.
- The measurement process should be simple, direct, and correct.
- Measurements must be consistent from part to part; detail to assembly, etc.
- Data must be taken from fixed measurement points.
- Measurements must be repeatable and reproducible.
- Measurement data display and storage must be readable, meaningful, and retrievable.

A continuous program of gage and tooling verification and certification must also be integrated within the framework of the dimensional measurement plan. Gage repeatability and reproducibility (GR&R) studies and reports must be a standard practice. Assembly tooling must be designed so that their locators are coordinated with the datums established on the product drawings and product data sheets. This will ensure that the proper fit and function between mating parts has been obtained. The actual location of these tooling points must then be periodically checked and validated to ensure that they have not moved and are not introducing errors into the product. See Chapter 24 for more discussion of gage repeatability and reproducibility (GRER).

2.2.2.8 Variation Simulation Tolerance Analysis

Dimensional management tools have been successfully incorporated within commercial 3-D simulation software (see Chapter 15). The typical steps in performing a simulation study using simulation software are listed below (see Fig. 2-2):

Step 1: A conceptual design is created within an existing computer aided engineering (CAE) software program as a 3-D solid model.

Step 2: The functional features that are critical to fit and function for each component of an assembly are defined and relationships established using GD&T symbology and datum referencing.

Step 3: Dimensioning schemes are created in the CAE and are verified and analyzed by the simulation software for correctness to appropriate standards.

Step 4: Using information from the CAE database, a functional assembly model is mathematically defined and a definition of assembly sequence, methods, and measurements is created.

Step 5: Using the functional assembly model, a 3-D assembly tolerance analysis is statistically performed to identify, rank, and correct critical fit and functional relationships between the mating parts that make up the assembly.

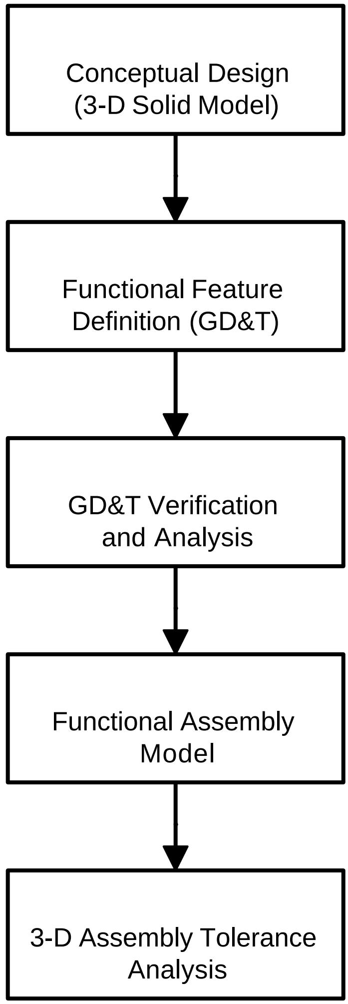

Figure 2-2 Variation simulation analysis

The advantages of using simulation software are that it can be integrated directly with existing CAE software to provide a seamless communication tool from conceptual design to final assembly simulation without the expense of building traditional prototypes. The results also represent reality because the simulations are based on statistical concepts taking into account the relationship between functional requirements as well as the expected process and measurement capabilities.

2.3 The Dimensional Management Process

The dimensional management process can be divided into four general stages: concept, design, prototype, and production. These stages integrated with the various dimensional management tools can be represented by a flow diagram (see Fig. 2-3).

The key factor in the success of a dimensional management program is the commitment and support provided by upper management. Implementing and sustaining the dimensional management process requires a major investment in time, personnel, and money at the early stages of a design. If top management is not willing to make and sustain its commitment to the program throughout its life cycle, the program will fail. Therefore, no dimensional management program should begin until program directives from upper management clearly declare that sufficient personnel, budget, and other resources will be guaranteed throughout the duration of the project.

It is imperative that the product dimensional requirements are clearly defined in written objectives by the dimensional management team at the beginning of the design cycle. These written objectives must be based on the customer's requirements for the design and the process and measurement capabilities of the manufacturing system. If the objectives cannot be agreed upon by a consensus of the dimensional management team, the program cannot proceed to defining the design concept.

The design concept is defined by developing a 3-D solid model using a modern computer-aided engineering system. The 3-D model provides a product definition and is the basis for all future work.

Key characteristics are identified on individual features based on the functional requirements of the mating parts that make up assemblies and sub-assemblies. Features that are chosen as key characteristics will facilitate assembly and assist in reducing variability during processing and assembly.

Geometric dimensioning and tolerancing schemes are developed on the basis of the key characteristics that are chosen. Other requirements for correct fit and function between mating parts are also considered. A major objective for this GD&T activity is to establish datums and datum reference frames that will

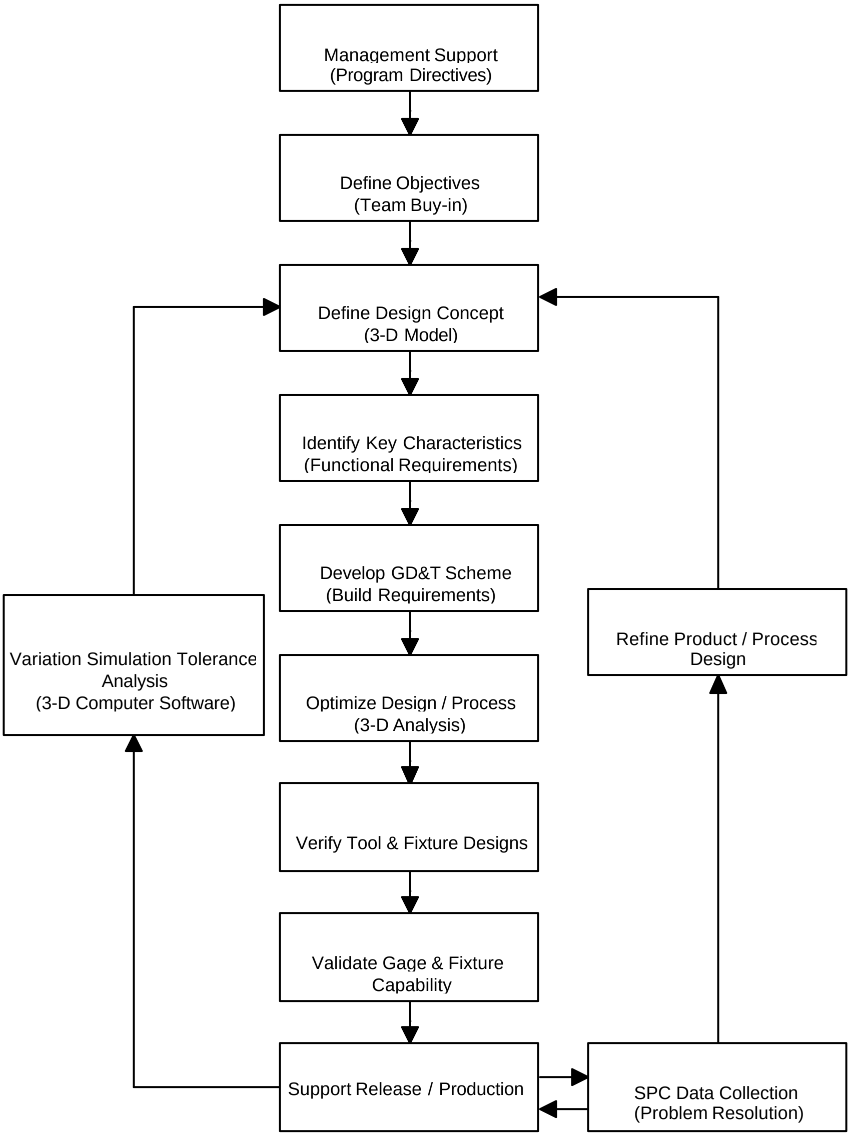

Figure 2-3 The dimensional management process

maintain correct interface between critical features during assembly. The datum system expressed by GD&T symbology also becomes the basis for determining build requirements that will influence processing, tooling, and inspection operations.

The product and process designs are optimized using variation simulation software that creates a functional assembly model. A mathematical definition of the assembly sequence, methods, and measurements that are based on the design concept, key characteristics, and GD&T scheme established in earlier stages of the program is created. This definition is used to statistically perform simulations based on known or assumed Cp and Cpk values, and to identify, rank, and correct critical fit and functional relationships between mating parts. These simulation tools are also used for the verification of the design of the tools and fixtures. This is done so that datums are correctly coordinated among part features, and the surfaces of tool and fixture locators are correctly positioned to reduce variation.

Measurement data is collected from gages and fixtures before production to verify their capability and compatibility with the product design. When the measurement data indicates that the tooling is not creating significant errors and meets the defined dimensional objectives, the product is released for production. If any problems are discovered that need a solution, further simulation and refinement is initiated.

During production statistical process control data is collected and analyzed to continually refine and improve the process. This in turn produces a product that has dimensional limits that will continue to approach their nominal values.

The dimensional management process can substantially improve dimensional quality for the following reasons:

- The product dimensional requirements are defined at the beginning of the design cycle.
- The design, manufacturing, and assembly processes all meet the product requirements.
- Product documentation is maintained and correct.
- A measurement plan is implemented that validates product requirements.
- Manufacturing capabilities achieve design intent.
- A feedback loop exists that ensures continuous improvement.

2.4 References

1. Craig, Mark. 1995. Using Dimensional Management. *Mechanical Engineering*, September, 986–988.
2. Creveling, C.M. 1997. *Tolerance Design*. Reading, MA: Addison-Wesley Longman Inc.
3. Harry, Mikel J. 1997. *The Nature of Six Sigma Quality*. Schaumburg, IL: Motorola University Press.
4. Larson, Curt, 1995. *Basics of Dimensional Management*. Troy, MI: Dimensional Control Systems Inc.
5. Liggett, John V. 1993. *Dimensional Variation Management Handbook*. Englewood Cliffs, NJ: Prentice-Hall Inc.
6. Nielsen, Henrik S. 1992. Uncertainty and Dimensional Tolerances. *Quality*, May, 25–28.

2.5 Glossary

Dimensional management - A process by which the design, fabrication, and inspection of a product is systematically defined and monitored to meet predetermined dimensional quality goals.

Dimensional management process - The integration of specific dimensional management tools into the concept, design, prototype, and production stages of a product life cycle.

Dimensional management system - A systematic implementation of dimensional management tools.

Key characteristics - A feature of an installation, assembly, or detail part with a dimensional variation having the greatest impact on fit, performance, or service life.

Variation measurement and reduction - Those activities relating to the measurement of fabricated parts to verify conformance with their dimensional specifications and give continuous dimensional improvement.

Variation simulation tolerance analysis - The use of 3-D simulation software in the early stages of a design to perform simulation studies in order to reduce dimensional variation before actual parts are fabricated.