ABSTRACT

DESIGN FOR QUALITY MANUFACTURABILITY ANALYSIS OF MISSING/MISPLACED PARTS AND PART INTERFERENCE

by
Altaf Yusuf Tamboo

Design for Quality Manufacturability (DFQM) is an approach that addresses the issue of quality manufacturability (QM) - the likelihood that defects will occur during manufacture of a product in a standard plant. The DFQM methodology is based on the premise that defects found in assembled products are often influenced by some features of the design and/or assembly process (influencing factors). These influencing factors cause defects in the presence of certain error catalysts.

One of the influencing factors is geometrical features such as shape and symmetry. A classification scheme for part shape and symmetry is developed. This scheme is summarized in a chart, in which each block bears a unique alpha-numeric code representing a class of parts. The chart is used to identify a given part with respect to its class. In DFQM analysis, the alpha-numeric code suggests potential problems which the part is likely to experience during its assembly.

Missing/Misplaced parts and Part Interference are two defect classes that are analyzed for QM. Error catalysts that promote the occurrence of these defects are identified and related to affecting factor variables using catalysis graphs. Each catalysis graph leads to a value between "0" and "1", based on the factor variables for the given design, implying the likelihood of occurrence of that specific defect. These values are normalized to obtain a QM score for the design. Higher the score, better the design from QM perspective.

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by
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DESIGN FOR QUALITY MANUFACTURABILITY ANALYSIS OF MISSING/MISPLACED PARTS AND PART INTERFERENCE

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This Thesis is dedicated to
my family, relatives and friends

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CHAPTER 1

INTRODUCTION

1.1 Modern Manufacturing

Manufacturing is undergoing rapid changes due to the introduction of new technologies and new methods. Manufacturing enterprises are being required to react to global competition, rapid changes in consumer preferences, proliferation of products, and a variety of competitor strategies to increase market share. In this active mode of competitiveness, manufacturing enterprises are engaged continuously in process and design improvements to build better products and increase consumer confidence and satisfaction.

Traditionally, the designing of products is the sole responsibility of the designer. The designer sends the final design with complete specifications and drawings to process planning. If conflict arises, the design is returned to the designer for modifications. The process is repeated until process planning is completed and the design is sent to the manufacturing department. Manufacturing ensures that the product can be made according to specifications. The design of a product and its production are thus traditionally performed sequentially, without concurrent consideration of the potential manufacturing procedures. This results in less satisfactory products being offered to the consumer. It is estimated that 80% of a product's cost is committed during the design stage. Moreover, consumers are becoming aware that quality, serviceability, and reliability are desirable features and are an important determinant of the price they are willing to pay. This has led to added complexity to manufacturing and product design. Therefore, these aspects should be considered early and designed in the product. Thus, a thorough integration of manufacturing activities such as marketing, product design, production process design, and assembly, is required to shorten the cycle time from marketing studies, through prototyping and full production. This has necessitated the evaluation of Simultaneous or Concurrent Engineering (CE) in which all relevant components of the manufacturing system including outside suppliers are made active participants in the design effort from the start. The team approach helps ensure that total product knowledge is as complete as possible at the time each design decision is made. One of the techniques in the field of Concurrent Engineering is called Design for Manufacturability (DFM).

1.2 Design for Manufacturability (DFM)

DFM may be defined as an approach for designing products so that, (i) the design is quickly transitioned into production, (ii) the product is manufactured at minimum cost, (iii) the product is manufactured with minimum effort in terms of processing and handling requirements and (iv) the manufactured product attains its designed level of quality. DFM represents a new awareness of the importance of design as the first manufacturing step. It recognizes that a company cannot meet quality and cost objectives with isolated design and manufacturing engineering operations. The essence of DFM approach is the integration of product design and process planning into one common activity. There are many techniques that deal with (i), (ii), and (iii) of the above listed objectives of DFM. The only technique that focuses explicitly on the manufactured quality of the product is known Design for Quality Manufacturability (DFQM).

1.3 Design for Quality Manufacturability (DFQM)

Quite frequently, a product can be found to be faulty not due to its basic design but due to the quality defects which were caused during its manufacture. Design for Quality Manufacturability is defined as a methodology involving the activities of product design, manufacturability analysis, process design and quality management for the efficient design of products which have a very low or almost no chance of producing defects. This also means that the products are so designed that they are most suited to manufacturing skills of the setup which thereby prevents the occurrence of defects.

The basic objective of DFQM is to enable the user to improve the design so as to reduce the likelihood of defective product being manufactured. It is an approach which would analyze a design for the likelihood of quality problems that might arise during its manufacture. It focuses on eliminating or improving features which can influence a quality defect during assembly. For example, excessive number of mating surfaces are likely to influence misalignment between two parts in an assembly. DFQM focuses explicitly on the "Quality Manufacturability (QM)" of a product and not on the design quality. The design itself can be technically very sound, but it can also be prone to manufacturing quality defects.

1.4 Research Objective

This thesis forms part of a three year research on DFQM which is currently underway. The research is partially funded by a grant from the National Science Foundation (NSF). Using the DFQM architecture, this project proceeds further by classifying parts with respect to their symmetry and geometry so that any given part is distinctly identified by the user for QM analysis. This thesis also provides an insight on the DFQM analysis of parts with respect to quality defects such as missing or misplaced parts and part interference.

1.5 Organization of the Thesis

This thesis consists of six chapters. The first chapter introduces concepts of DFM and DFQM and their importance in modern manufacturing. Chapter two gives a review of the literature pertaining to DFM, Design for Assembly (DFA), and current research in the area of DFQM. Classification of parts for QM analysis based on their symmetry and geometry is explained in chapter three. Chapter four deals with the QM analysis of missing and misplaced parts. QM analysis of part interference is shown in chapter five. Finally, chapter six contains conclusions and scope for further research in the area of DFQM.

CHAPTER 2

LITERATURE SURVEY

2.1 Product Quality

Continual product improvement and innovation are being widely practiced by successful manufacturers to stimulate consumption and to increase market share. The quality of a product undergoes a change at each value adding process in its manufacturing cycle. Quite frequently there is found on the market an inferior product or machine which owes its inferiority to the quality of the decisions made during the design. The attainment of high levels of product quality is a prerequisite for the success of a product.

Quality of any product can be broadly defined into two categories, namely: design quality and manufactured quality. Design quality is defined as the utility of a product as perceived by the customer. On the other hand, manufactured quality is defined as the extent to which a product deviates from its design specifications. Most of the available literature talks about either improving the design quality or the quality of the entire business process both inside and outside the manufacturing environment. Several approaches have stressed on building quality in the design, in the product, in the process, rather than develop it after the product has been produced.

2.2 DFM Techniques

Several DFM techniques have been proposed by various researchers, the primary objective of all is to identify product concepts that are inherently easy to manufacture, to focus on component design for ease of manufacture and assembly, and to integrate manufacturing process design and product design to ensure the best matching needs and requirements. A typical DFM process proposed by Stoll (1988) is shown in figure 2.1. The DFM process begins with a proposed product concept, a proposed process concept, and a set of design goals (both manufacturing and product goals). Each of the activities within the DFM process addresses a particular aspect of the design.

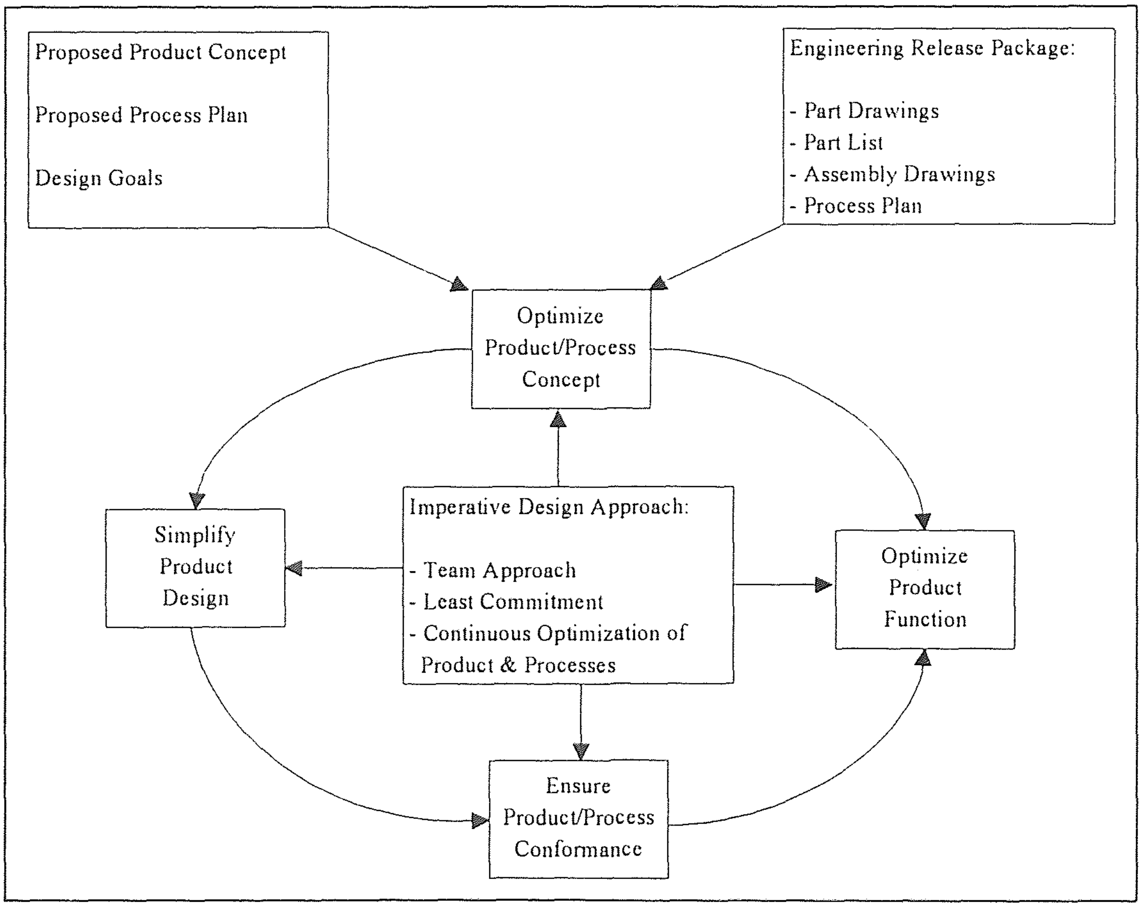

Figure 2.1 Typical DFM Process for Continuous Optimization of Product and Process

Numerous DFM methodologies are proposed by various authors. The most commonly used is the Design for Assembly (DFA) method developed by Boothroyd and Dewhurst (1983). Details of this methodology are presented in their handbook on DFA. The DFA method developed by Boothroyd and Dewhurst minimizes the cost of assembly by first reducing the number of parts and then ensuring that the remaining parts are easy to assemble. The Axiomatic Approach proposed by Suh, Bell and Gossard (1978) is based upon a hypothesis that there exists a small set of global principles, or axioms, which can be applied to decisions made throughout the synthesis of a manufacturing system including evaluation of a design decisions leading to a good design. Other DFM methodologies include DFM guidelines (Stoll 1988, 23), Designers Toolkit, Computer-Aided DFM, Group Technology, Failure Mode and Effects Analysis, Value Analysis, and Hitachi Assemblability Evaluation Method.

2.3 DFM and Quality

Most of the literature available on DFM talks about minimizing cost and integrating design and manufacturing. Taguchi Methods and concepts of Robust Design (Phadke 1989) provide a valuable insight into the role of design in determining the quality of a product or system i.e they address the issue of design quality. The term Taguchi Methods (Sullivan 1987, 76) refers to the parameter design, tolerance design, the quality loss function, on-line quality control, design of experiments using orthogonal arrays, and methodology applied to evaluate measuring systems. These methods were developed by Genichi Taguchi, a noted Japanese engineering specialist, to simultaneously reduce cost and improve quality. Taguchi's method of parameter design has changed the meaning of quality improvement from problem solving to reducing variability around target values, with the important point being how to measure quality improvement. Cause-Effect diagrams (Ishikawa 1980) and Total Quality Management (TQM) concepts promoted by Deming (1986) all consider prevention rather than problem solving. Daetz (1990) in his article on the effect of product design on product quality and cost has identified several factors of the design which contribute to defects. A set of guidelines for quality improvement are provided by Daetz (1990). Accordingly, from the quality standpoint, a design should be so simple that correct assembly and use of product are foolproof and should have as few options as possible.

The closest that has been done to tackle the QM issue is the "Variation Simulation Analysis" developed by Westinghouse Corporation (Prasad 1992, 14). It is a simulation technique used to analyze complex assemblies prior to prototype production. This enables measuring the variations and correcting them well before the actual model is developed. But this technique is limited to the dimensional measure of the design. Quality problems due to other factors such as material interrelationships, assembly process compatibility, fastening system, etc. cannot be analyzed by this technique.

The U.S. Department of Navy released a document describing two manufacturability evaluation tools (DoN 1991). The first computes the Producibility Assessment Worksheet Index (PAW-I). The second evaluation tool assesses the impact of product and process variation on the product quality. It identifies three causes of variation, namely: design margins, process control, and material instability. The likelihood of one of these causes resulting in a quality problem is computed via simple probability expressions. The drawback of this evaluation is that it restricts the causes of variations to a short list. Other research addressing manufactured quality issues include work on design representation by Wozny (1991) and identification of relationship between manufacturability and production lead times by Ulrich, Sartorius, Pearson, and Jakiela (1993). Ulrich et. al. (1993) have ignored product functionality and quality in their analysis and are unable to provide any clear insight on relationship among DFM, functionality and quality.

2.4 DFQM Methodology

The relationship between the design of a product and its manufactured quality is addressed by Das (1993) and Prasad (1992); introducing a methodology that focuses exclusively on evaluating a design from the "manufactured quality" perspective. A new method for evaluating designs based on their quality manufacturability is proposed. This methodology identifies a set of defects at the assembly stage of manufacture of the product. A set of factors responsible for the occurrence of these defects are investigated. The relationships to bring about an effective link between the defects and the factors is also proposed. The proposed methodology provides a means of relating the activities of quality improvement, product design, and manufacturability analysis. The objective of this methodology is to enable the user to improve the design so as to reduce the likelihood of defective product being manufactured.

General structure of DFQM methodology proposed by Das (1993) is shown in figure 2.2. This structure is a sort of reverse cause-effect analysis i.e. the effects are predicted after

after identifying the causes. The overall logic of this DFQM methodology is summarized as follows:

1. The manufactured quality of a product is an aggregate representation of several classes of defects that are commonly seen in assembled products. Any attempt to assess or improve the QM of a design must focus on these classes of defects. These defect classes can be further subdivided into specific defects.
2. The design of a product is characterized by several factors that influence the occurrence of these defects. Each of these influencing factors can be further broken down into factor variables.
3. There are certain error catalyst which promote the occurrence of a particular specific defect due to one or more factor variables inherent in the design.

2.5 Summary

Many available DFM techniques do not address the issue of manufactured quality. Several effective tools and methods have been developed in the quality area, but the majority of these are focused on process control and improvement. The proposed methodology for evaluation of a design to determine its quality manufacturability by Das (1993) focuses predominantly on the design-manufacturing interface. This methodology needs to be further developed to formulate a model that can evaluate QM of a design based on its factor variables. The research leading to the documentation of this thesis goes a step forward from the basic DFQM structure proposed by Das (1993). This work relates the class of defects influenced by the design parameters and catalyzed by the error catalysts. It

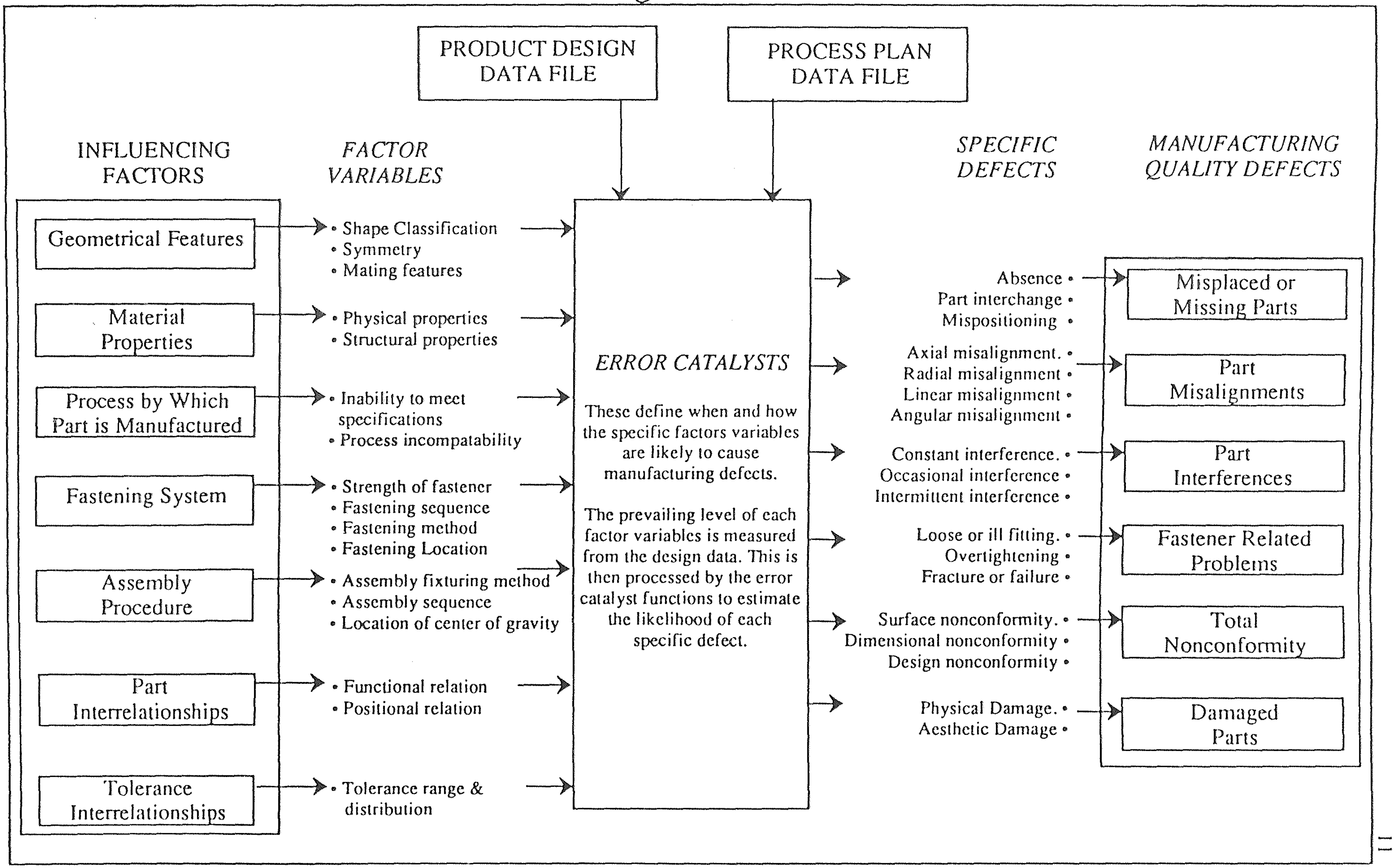
SCHEMATIC FOR ESTIMATING THE QUALITY MANUFACTURABILITY OF A DESIGN

Figure 2.2 Schematic for Estimating the Quality Manufacturability of a Design is an attempt to identify the error catalysts linking the various factor variables and specific defects and quantify the likelihood of occurrence of a certain defect by determining a QM score for the design.

CHAPTER 3

DFQM CLASSIFICATION OF PARTS BY SYMMETRY AND GEOMETRY

One of the most important influencing factors of any given product is the geometry of its components. This chapter deals with the influencing factor Geometrical Features. The two main factor variables of this influencing factor, namely: shape and symmetry, are discussed in detail. A classification scheme, based on shape and symmetry, is developed.

3.1 Geometrical Features

Geometrical features are those standard and nonstandard geometrical parameters, both internal and external, which are found in every part that goes into an assembly. Geometrical features such as edges, corners, surfaces etc., play a very important role in the assembly of parts. The position of mating surfaces, the factor of symmetry, the area of contact, the presence of constraining surfaces with respect to the dimensions and geometry of the body are very important concerns. The compatibility and finish of each feature influences the quality of assembly. This also includes the standard features like holes, grooves, slots and other nonstandard features like curves. The two factor variables of this influencing factor are shape classification and symmetry.

3.2 Classification of Parts by Symmetry and Geometry

Symmetry and basic shape are two parameters that play a very significant role in the processing and assembly of any part. The manufactured quality of a product is an aggregate representation of several classes of defects that are commonly seen in assembled products. The occurrence of these defects is influenced by several factors or characteristics that are inherent in the product's design. Shape and symmetry of components are two factor variables that have a strong influence on the quality manufacturability of a product.

It is possible that several times a particular shape selected by the designer for a certain component may have the potential of creating quality problems. This could manifest in any form, either directly or indirectly. For example, the effect of shape is also evident in missing and misplaced parts where shape similarities or size causes parts interchange during assembly. Symmetry of the part is also a very important feature of the assembly. The various kinds of symmetries, directly and indirectly, affect the specific defects especially in case of misalignments.

An individual can identify a given part with respect to its geometry and symmetry in numerous ways. This is because parts are being designed with increasing complexity. It is very essential that parts that would have similar effects on the quality manufacturability of the assembled product should be grouped together as a family. This necessitates classification of parts, based on symmetry and geometry, for the purpose of DFQM analysis. Classification with the objective of DFQM analysis cannot treat geometrical features and symmetry in isolation and thus needs to consider family of parts for both these factor variables simultaneously.

3.3 Classification Chart

The classification chart, shown in figure 3.1, identifies a part on the basis of its symmetry and shape. Shape by nature is a complex characteristic of a design in terms of measuring it as a dimension. The classification chart identifies any given part by a unique code depending on its geometrical features. It consists of six rows and twenty three columns. The rows classify a part based on its basic shape and the columns identify its symmetry and main features affecting symmetry. Rows are denoted using suitable letters (R, B, etc.) indicating the shape and the columns bear numbers from 1 through 23. Each block of the chart represents a family of parts with a unique alpha-numeric code. Thus any given part, classified first on the basis of its shape and then symmetry, shall have a unique alpha-numeric code for DFQM analysis. The figures shown on the chart represent a family of parts with similar features. Some notations or terms used on the chart are explained below:

A : Length of the rectangular envelope that would enclose the entire part.

Alpha-symmetric : An alpha-symmetric part is one that does not require orientation end-to-end.

Beta-symmetric : A beta-symmetric rotational part is one that does not require orientation about its principal axis.

Envelope : The smallest cylinder or rectangular prism that can enclose the part.

L : Length of the rectangular envelope enclosing the transverse element.

Silhouette : The smallest simple geometric outline that encloses the view of a part or its envelope.

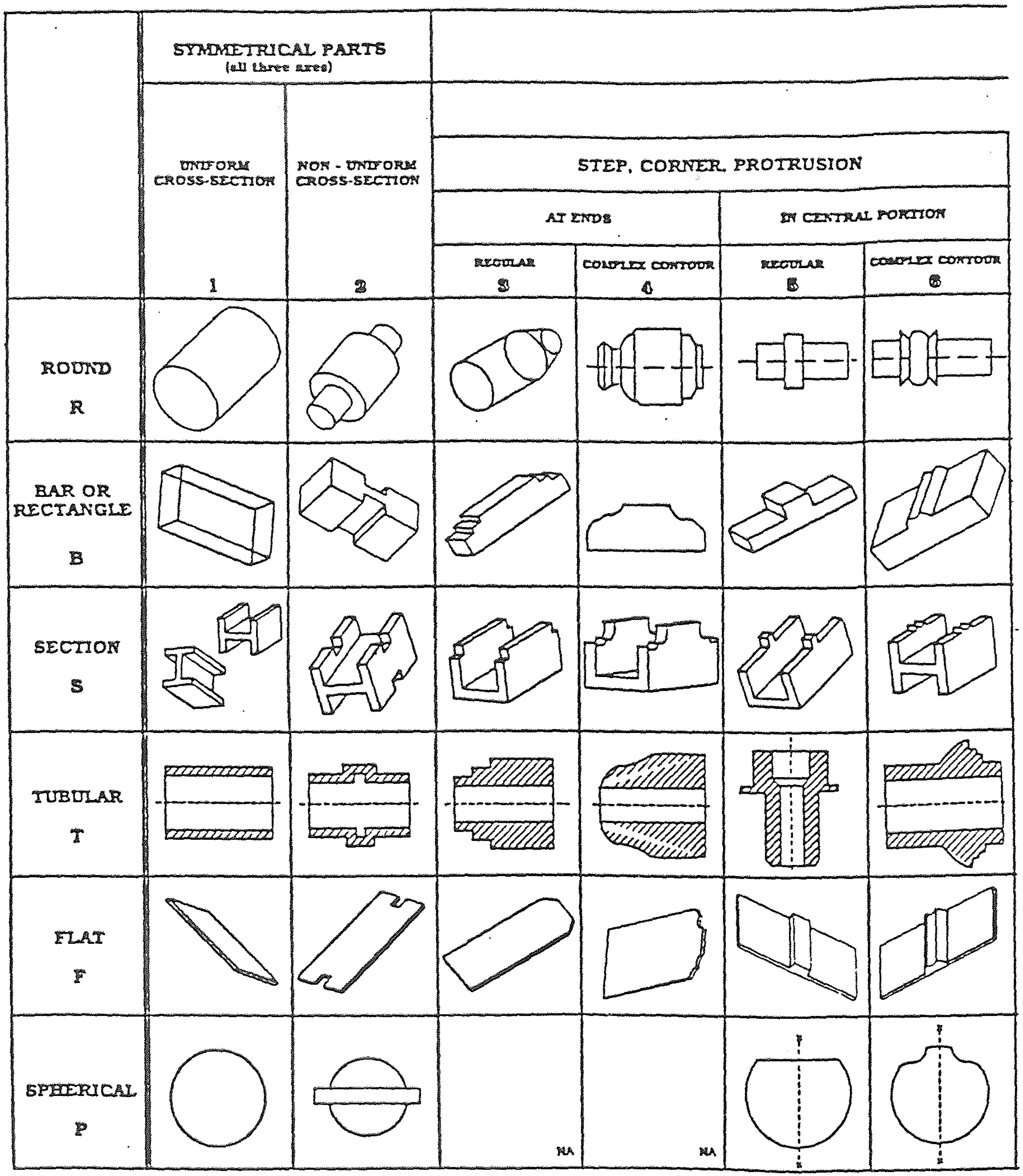

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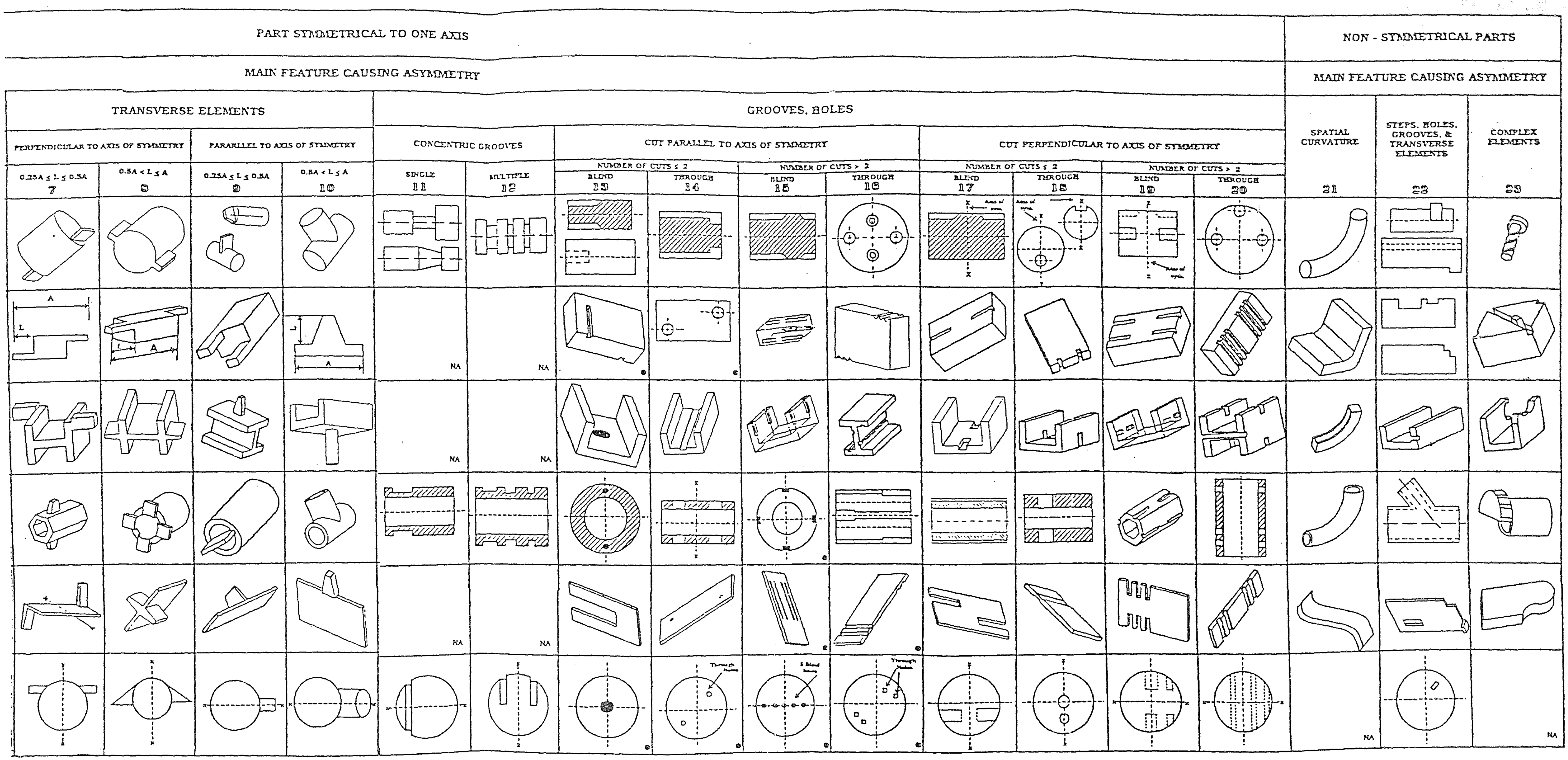
Figure 3.1 DFQM Classification of Parts by Symmetry & Geometry

DFQM CLASSIFICATION OF PARTS BY SYMMETRY & GEOMETRY



Parts symmetrical to only one axis of symmetry may contain more than one feature i.e. step, groove, transverse elements. In such cases, the following rules will be applied to uniquely identify the part:

1. The part will be identified with respect to the main feature that causes asymmetry; i.e., if this feature is to be removed, the part will become symmetrical.
2. If rule 1., stated above, does not give a unique identification, the part shall belong to the respective column classifications based on the following order of preference:
    - i. Grooves/Hole
    - ii. Transverse Elements
    - iii. Steps

NOTES :

A Length of the rectangular envelope that would enclose the entire part.

L Length of the rectangular envelope enclosing the transverse element.

⊗ Implies the axis of symmetry is perpendicular to the plane of the paper.

X Indicates the axis of symmetry wherever it is difficult to identify.

● Blind hole/groove

Flat - Shape with a very low thickness as compared to its length and width

Step - Geometric feature that results in a deviation of the silhouette of a part from the silhouette of its envelope.

Transverse Element - External projection other than beta symmetric step that can be seen in a silhouette with length of projection greater than 1/4 of A.

Groove - A cut that results in a deviation of a part from the silhouette of its envelope.

Blind Groove/Hole - Groove/hole which does not cut through the part lengthwise (length of the groove/hole).

Through Groove/Hole - Groove/hole which cuts through the part lengthwise (length of the groove/hole).

Direction of Groove Cutting - Means the direction in which the length of the groove runs(not the depth of the cut).

Silhouette - The smallest simple geometric outline that encloses the view of a part or its envelope.

Spatial Curvature - A non-symmetrical curved shape.

NA - Not Applicable

⊗ : Implies that the axis of symmetry is perpendicular to the plane of the paper.

X : Indicates the axis of symmetry wherever it is difficult to identify.

● : Indicates blind hole/groove.

3.3.1 Shape Classification

The DFQM classification chart broadly classifies the basic shape into six categories, namely: Round (R), Box (B), Section (S), Tubular (T), Flat (F), and Spherical (P). Any given part shall be identified with one of the six rows of the chart based on its basic shape - the shape which would cover the maximum volume when enclosed in a rectangular or cubical envelope.

1. Round (R): Circular cylindrical and conical parts belong to this category. Elliptical or oval cross-sections are also identified as a round shapes. Regular polygonal shapes (more than 8 sides) are also classified as rounds.
2. Bar or Rectangle (B): Any part with basic cross-section as a rectangle, square, rhombus, parallelogram, etc. is classified as a bar. Exceptions in this case are cross-sections with extremely low thickness as compared to its length and width. These are termed as flats (F).
3. Section (S): Parts with C-shaped, L-shaped, H-shaped and I-shaped cross-sections belong to this group broadly classified as sections.
4. Tubular (T): Circular as well as regular polygonal tubes belong to this category.

5. Flats (F): Flats are bars with extremely low thickness as compared to its length and width. They are identified separately compared to bars because these parts may require different treatment during DFQM analysis.
6. Spherical (P): All spherical shapes, including imperfect spheres, belong to this category.

3.3.2 Classification by Symmetry

The more symmetrical a part is, the more quickly it can be oriented during the handling phase of assembly. Thus achieving symmetry should be the first consideration during design. But this might have an adverse impact on another DFM consideration - reducing the number of parts; because reduction in the number of parts essentially leads to the complexity of remaining parts thus leading to asymmetry. An equally important consideration is to assure that if asymmetry must exist, then it should be clearly and easily recognized. Parts which must be avoided are those with only slight asymmetry i.e. parts with features which appear to be equi-spaced or symmetrically positioned but are not. If the functional features cannot be made asymmetrical, then a clearly visible non-functional feature should be added to define the orientation.

Symmetry of a part about an axis can be explained as: "if the part is rotated 180 degrees about that axis, the resulting orientation is exactly same as the original one." The basic shape of any component will always be symmetrical. It tends to loose its symmetry as more and more geometrical features like steps, grooves, holes, and transverse elements are added. Obviously, these features have a certain role to play in the assembly, at the same time these features individually or simultaneously can increase the possibility of quality defects. Thus, the classification of parts by symmetry takes into account the geometrical features that cause asymmetry. Parts are broadly classified on the basis of symmetry as : symmetrical parts, non-symmetrical parts, and parts symmetrical about only one axis.

3.3.2.1 Symmetrical Parts

Parts are said to be symmetrical if they are symmetrical about all three axes. Such parts are very easy to handle and pose very few problems during handling and assembly. They can be further sub-divided into uniform cross-section and non-uniform cross-section. Any further detailed sub-division of symmetrical parts is not necessary. This category occupies columns 1 and 2 on the classification chart

3.3.2.2 Non-symmetrical Parts

Parts that are not symmetrical about any axes are termed as non-symmetrical or asymmetrical. Although there might be numerous features causing asymmetry, the feature which if removed will make the part symmetrical about at least one axis; is considered as main feature causing asymmetry. This category is further sub-divided into three broad sub-classes depending on the main feature causing asymmetry. They are (i) spatial curvature, (ii) steps, holes, grooves, and transverse elements; and (iii) complex elements.

There is a possibility that the part would have more than one feature responsible for its asymmetry. In that case the part shall be identified with the feature which is most prominent and is likely to have considerable impact on assembling and handling i.e. such a feature which if removed will increase its assemblability. Asymmetry due to non geometrical features such as differences in surface coatings, lettering, differences in surface finish, etc. are ignored for the purpose of simplicity. This category occupies columns 21, 22, and 23 of the classification chart.

3.3.2.3 Parts Symmetrical About Only One Axis

It can be noticed that maximum area of the chart is covered by this category. This is due to the fact that if a part is symmetrical about only one axis, the main feature causing asymmetry is of interest from DFQM perspective. For example, parts with numerous mating surfaces are always prone to misalignments. Holes are likely to cause radial and axial misalignments, whereas grooves are more susceptible to linear misalignments. Degree of difficulty in orienting also depends on these geometrical features. This category occupies columns 3 through 20 of the classification chart. Parts symmetrical to only one axis are further classified on the basis of the main feature causing asymmetry, as follows:

A. Step, Corner, Protrusion (Columns 3 through 6) :

   Step or protrusion is a geometric feature that results in a deviation of the silhouette of a part from the silhouette of its envelope. For DFQM analysis any step with its largest dimension greater than 1/4 A is considered as a transverse element except for beta-symmetric steps in case of round or tubular shapes.

B. Transverse Elements (Columns 7 through 10) :

A transverse element is defined as an external projection other than a beta-symmetric step that can be seen in a silhouette with length of projection greater than 1/4 A. Transverse elements are further identified as perpendicular or parallel to the axis of symmetry because they behave differently from DFQM perspective. For example the orientation of a part would be less difficult if the axis of insertion is coincident to the axis of symmetry and parallel to the transverse element. Finally, transverse elements are further subdivided depending on their protruding lengths. This classification, although redundant in certain cases, may help in designing the anti-locators or assembly fixtures.

C. Grooves and Holes (Columns 11 through 20) :

A groove is a cut that results in deviation of a part from the silhouette of its envelope and the direction of groove cutting means the direction in which the length of the groove runs (not the depth of cut). Holes are also considered in the same class as grooves because both these features have relatively similar influence on quality manufacturability of a part in the presence of certain error catalysts. Thus, classifying them separately is not required. Multiple grooves/holes (more than two) are separated from grooves/holes less than two. This is done to account for the difficulty posed in assembly due to multiple mating surfaces. Grooves/holes are further divided into three sub-classes depending on the direction of cut with respect to the axis of symmetry, namely: concentric, cut parallel to the axis of symmetry, and cut perpendicular to the axis of symmetry. Concentric grooves are only related to round (R), tubular (T), and spherical (P) shapes. The three sub-categories are further subdivided depending on number and type of cuts i.e. blind or through.

Parts symmetrical to only one axis of symmetry may contain more than one feature, i.e. step, groove/hole, or transverse element. In such cases, the following rules are to be applied to uniquely identify the part:

i) The part shall be identified with respect to the main feature that causes asymmetry; i.e. the part will be symmetrical if this feature is removed

ii) If rule (i) stated above does not yield a unique identification, the part shall belong to the respective column based on the following order of preference:

    a. groove/hole
    b. transverse elements
    c. steps.

CHAPTER 4

DFQM ANALYSIS OF MISSING/MISPLACED PARTS

In assembled products 90% of the common defects can be classified into few categories known as Classes of Defects. Specific defects are more detailed descriptions of particular defects within each defect class. The DFQM structure (figure 2.2) identifies six classes of quality defects. They are:

1. Missing or Misplaced Parts
2. Part Misalignments
3. Part Interference
4. Fastener Related Problems
5. Total Nonconformity
6. Damaged Parts

The scope of this thesis is limited to DFQM analysis of the defect classes missing/misplaced parts and part interference. This chapter initially describes the methodology for QM analysis and subsequently applies it to the defect class missing/misplaced parts. DFQM analysis of part interference is covered in chapter five. Missing/misplaced parts is one of the most common defects occurring in assembly. Specific defects in this class are absence of parts, part interchange, and mispositioning of parts.

4.1 Relationship between Specific Defects, Error Catalysts, and Factor Variables

The general structure of the DFQM methodology suggests that the occurrence of any manufactured quality defect is influenced by several factors or characteristics that are inherent in the product's design. These defects must be related to the processes via which the product is assembled or manufactured. Typically, specific defects belonging to the same class will be similar in their overall effect on the quality of the product and their general nature. They will differ in terms of what causes them and their specific orientations.

The presence of any defect influenced by the factor variables of the design is catalyzed by the presence of certain error catalysts. Error catalysts define when and how the specific factor variables are likely to cause manufacturing defects. Presence of an error catalyst by itself will not induce quality defects unless certain characteristics of the design or process support it. Thus it is necessary to relate each specific defect to the affecting factor variables with due consideration to the error catalysts that catalyze the occurrence of the specific defect. This needs to be done for each individual specific defect. The factor variables are linked to the error catalysts using catalysis graphs. Each factor is weighed on the basis of perceived importance and relative likelihood of causing a particular defect.

4.2 Catalysis Graph

A Catalysis graph is a diagram similar to a decision tree used for systematic evaluation of factor variables to determine their relative effects on the occurrence of the specific defect under study. This helps in determining for a given design, what is the likelihood that the error catalyst will cause a particular specific defect. Based on the factor variables of a design, each catalysis graph leads to a score between '0" and "1". This score is indicative of the relative likelihood of the error catalyst influencing the specific defect under study.

As a part of this project, catalysis sheets are being prepared for each error catalyst under each specific defect. The purpose of preparing these sheets is to summarize the description of each error catalyst and simplify the catalysis process into decision graphs. Since this thesis is part of an ongoing research, the format used for catalysis sheets not only provides consistency, but also helps as an easy reference for other areas of the research. It will be of utmost important in the final stages of this project during the compilation phase. Identifying all error catalysts that can cause a specific defect and developing catalysis graphs for each error catalyst are the initial steps for QM analysis.

Chapter three describes the importance of unique identification of parts based on shape and symmetry for DFQM. Similarly other factor variables also need to be identified or quantified using metrics that shall be followed consistently for the entire DFQM analysis. Table 4.1 gives metrics that are used for other factor variables. These metrics are used in the catalysis graphs for measuring factor variables affecting the error catalysts. Figures 4.1 through 4.10 illustrate the catalysis graphs for the defect class missing/misplaced parts. Absence of parts, part interchange, and mispositioning of parts are the three specific defects under this class.

Table 4.1 Metrics Involved in Quantification of Factor variables

	FACTOR VARIABLES	MEASUREMENT or IDENTIFICATION SCHEME
1	Shape and Symmetry	DFQM Classification of Parts by Symmetry and Geometry (Figure 3.1)
2	Mating Features	Number of Mating Surfaces and Number of Mating Parts
3	Coefficient of Thermal Expansion	Ratio of Coefficients of Two mating Parts
4	Hardness	Hardness Number Ranges
5	Stress Properties	Ranges of Traditional Strength Measuring Units
6	Assembly Fixturing Method	Automatic, Manual, or Robotic Assembly
7	Assembly Sequence	Chronological
8	Functional and Motion Relationship	DFQM Classification of Functional Relationships (Appendix B)
9	Fitting Relationship	Press Fit, Loose Fit, and Running Fit
10	Positional Relationship	Positional Relationship Chart (Appendix A)
11	Fastening Sequence	Sequence
12	Fastening Type, Strength	Fastener Classification and Identification Chart

4.3 Quality Manufacturability Analysis

The purpose of quality manufacturability (QM) analysis is to obtain a matrix called the Quality Manufacturability Matrix (QMM) for the overall assembly and also to determine a final QM index for the design. This score will be indicative of the likelihood of the design leading to manufactured quality defects. Defect class to which the given design is more prone can also be deduced from this analysis. The QMM will serve as a strong tool in addressing the manufactured quality of a product and highlighting the parts that require attention from DFQM perspective.

The terms used in the equations for QM analysis are given below:

CD - Class of Defects

SD - Specific Defect

EC - Error Catalyst

k - 1,2,....6

m - number of specific defects under CD_k

n - Total number of error catalysts influencing SD_j

j - 1,2,......m

i - 1,2,.......n

p - number of parts in an assembly

L - 1,2,.......p

S_{ij} - Score for EC_i influencing SD_j

W_{ij} - Weightage on S_{ij} based on importance of EC_i for SD_j

Q_{jk} - QM score for each SD_j under CD_k

F_{jk} - Multiplication factor for Q_{jk} based on relative importance of SD_j belonging to CD_k

C_k - QM score for each CD_k

The following steps need to be taken for QM analysis.

STEP 1:

Identify all error catalysts (EC_i) and the affecting factor variables for each specific defect (SD_j). Refine these error catalysts to remove redundancy and to make them independent.

STEP 2:

Prepare catalysis graphs based on the factor variables affecting each of the n error catalysts. Thus, prepare n catalysis graphs for each SD_j ($j = 1,2,\ldots m$).

STEP 3:

Select any one component of the assembly at a time. Based on the characteristics of the design, use each catalysis graph to determine a score (S_{ij}) between '0" and "1". Obtain n values between "0" and "1" for each SD_j ($j = 1,2,\ldots m$).

STEP 4:

Assign weightages, based on relative importance of the error catalysts, to each of these S_{ij} values obtained in step 3. Determine QM score for each SD_j under CD_k using the following formula:

$$Q_{jk} = \frac{\sum_{i=1}^{n} S_{ij} * W_{ij}}{n}$$

STEP 5:

Multiply each of the m values of Q_{jk} obtained in step 4 by a factor F_{jk} depending on the relative importance of SD_j (j = 1,2,...m). Calculate QM score (C_k) for each CD_k as follows:

$$C_k = \frac{\sum_{j=1}^{m} Q_{jk} * F_{jk}}{m}$$

STEP 6:

Repeat steps 3 through 5 to obtain C_k (k = 1,2,...6) values for all components in the assembly. Constitute a matrix (QMM) with p rows and 6 columns.

STEP 7:

Normalize the QMM obtained in step 6 to obtain a final QM score for the design.

4.4 DFQM Analysis of Missing/Misplaced Parts

4.4.1 Absence of Parts

This defect is most commonly found when fasteners, parts, locking mechanisms, lining materials, gaskets, spacers, etc. are specified in the design. This defect is more common in case of manual assembly as compared to automated assembly. Primary influencing factors for this defect are geometrical features and assembly procedure. Number of small parts in any assembly plays a major role in the occurrence of this defect. Similarity of parts also enhances the possibility of this defect. Figures 4.1 through 4.4 show the catalysis graphs for the four error catalysts that influence this defect.

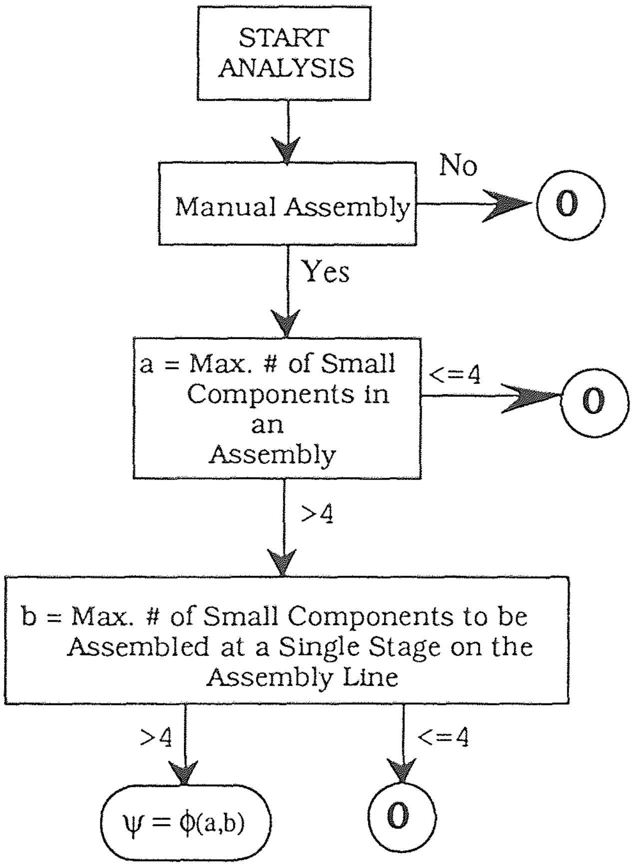
ERROR CATALYSIS SHEET

DEFECT CLASS Missing/Misplaced Parts	*SPECIFIC DEFECT* Absence of Parts	*SHEET NO:* EC111
ERROR CATALYST Manual Assembly of Too Many Similar Components		

DESCRIPTION

In cases of assemblies which require many similar components, there is a likelihood that the assembler misses some parts. This is likely to happen when the assembly process is monotonous leading to negligence on the part of the assembler in placing parts at various locations on the main component. Parts like washers and lock nuts are most likely to be missed. Similar, but not identical parts may get interchanged due to this.

CATALYSIS GRAPH



$$\phi(a, b) = \frac{b}{a} - 0.2 \qquad \text{for } \frac{b}{a} > 0.2$$

$$= 0 \qquad \text{for } \frac{b}{a} </= 0.2$$

Figure 4.1 Catalysis Graph for Manual Assembly of Too Many Similar Components

ERROR CATALYSIS SHEET

DEFECT CLASS
Missing/Misplaced Parts

SPECIFIC DEFECT
Absence of Parts

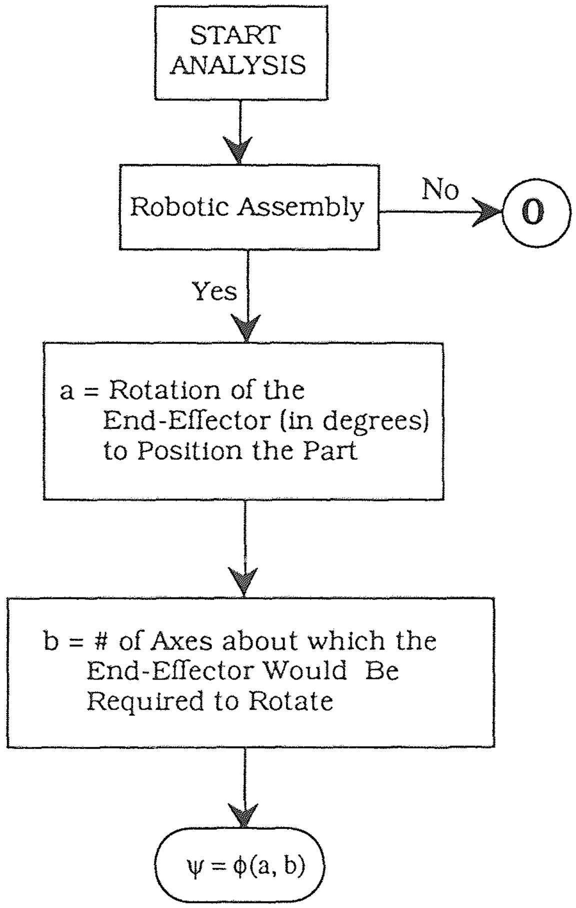
SHEET NO:
EC211

ERROR CATALYST
Robotic Assembly at Difficult Locations

DESCRIPTION

In case of robotic assembly with parts to be fitted in a main component at very odd locations, some of the parts may drop before actual assembly. This may happen due to slight error in location of the main component which will consequently lead to the robot end-effector releasing the part without proper fitting. This may also happen due to error in end-effector tracking.

CATALYSIS GRAPH



$$\psi = \phi(a, b) = \frac{a}{360 * b}$$

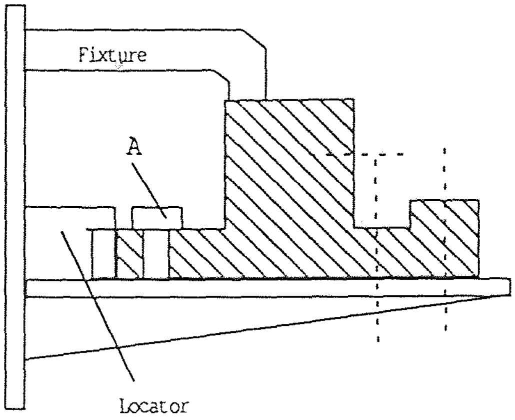
Figure 4.2 Catalysis Graph for Robotic Assembly at Difficult Locations

ERROR CATALYSIS SHEET

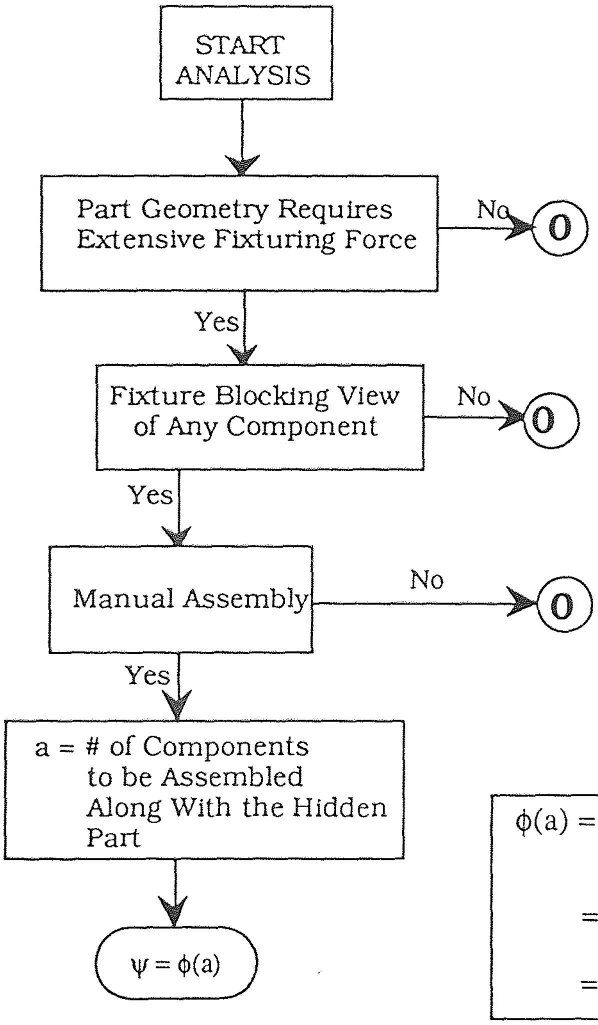
DEFECT CLASS Missing/Misplaced Parts	*SPECIFIC DEFECT* Absence of Parts	*SHEET NO:* EC311
ERROR CATALYST Fixture Hiding Part Location		

DESCRIPTION

The Figure shows a main block held by a fixture. Part A is located in such a spot that it is hidden under the fixture. In case of manual assembly, if the worker is assembling many other components at the same workstation, Part A is likely to be missed.



CATALYSIS GRAPH



$\phi(a) = \frac{a}{10} - 0.1$ for 4 </= a </= 10

$= 0$ for 1 </= a </= 3

$= 1$ for a > 10

Figure 4.3 Catalysis Graph for Fixture Hiding Part Location

ERROR CATALYSIS SHEET

DEFECT CLASS
Missing/Misplaced Parts

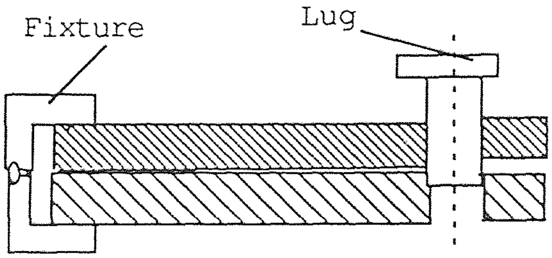
SPECIFIC DEFECT
Absence of Parts

SHEET NO:
EC411

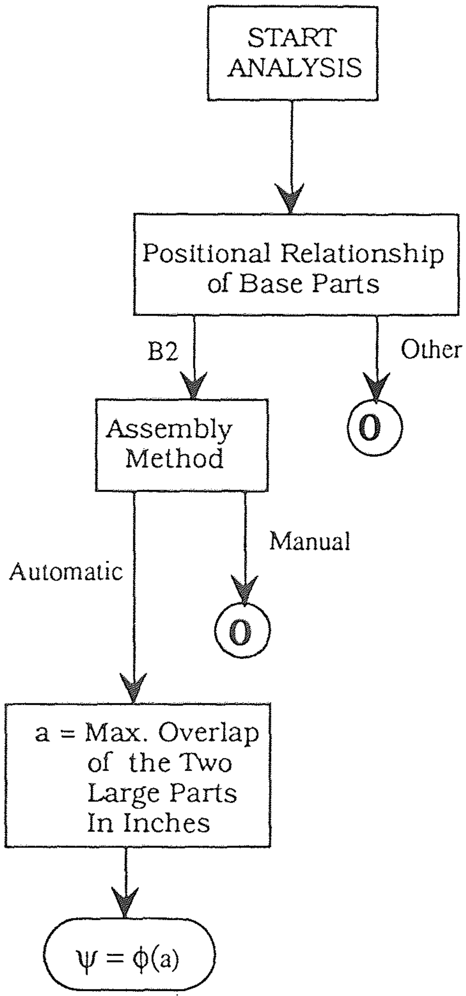
ERROR CATALYST
Unbalanced Fixturing Force

DESCRIPTION

In case of automatic insertion, the part may not fit properly due to unbalanced fixturing. For example, the figure shows a lug to be placed in the hole to position the two sheets. If the fixturing force is unbalanced, the sheets will be misaligned while the lug is being inserted automatically. Consequently, the lug may not fit in and fall off during subsequent handling.



CATALYSIS GRAPH



$$\phi(a) = \frac{1}{a} - 0.2 \qquad \text{for } a > 1$$

$$= 0.9 \qquad \text{for } a </= 1$$

Figure 4.4 Catalysis Graph for Unbalanced Fixturing Force

Four independent error catalysts are identified as the ones which influence absence of parts. They are :

1 Too many similar components - EC_{111}

2 Robotic assembly at difficult locations - EC_{211}

3 Fixture hiding part location - EC_{311}

4 Unbalanced fixturing force - EC_{411}

Analytically analyzing these error catalysts with respect to their relative influence, it is inferred that too many similar components is the one which mostly influences absence of parts. Thus it would get the highest ranking. Unbalanced fixturing force and part hidden by fixture can be considered to be relatively at the same level and are given the second highest weightage. Missing parts due to incapability of the process during robotic assembly is given the lowest weightage as compared to the other three error catalysts because its likelihood is relatively less.

Relative weightages for the four error catalysts causing the specific defect absence of parts are given as follows :

$W_{11} = 1; \quad W_{21} = 0.7; \quad W_{31} = 0.4; \quad W_{41} = 0.7$

Therefore, the QM score for the specific defect absence of parts (SD_{11}) is given as:

$$Q_{11} = \frac{S_{11} + (0.7 * S_{21}) + (0.4 * S_{31}) + (0.7 * S_{41})}{4}$$

4.4.2 Part Interchange

Part interchange may occur in most assemblies due to great similarity between two parts. Lack of evident distinguishing features, human inconsistency, absence of anti-locating elements are the primary reasons for the occurrence of this defect. Figures 4.5 and 4.6 illustrates the catalysis graphs for this defect. Part interchange has two error catalysts as follows:

1 Absence of positioning elements - EC_{121}

2 Congruent mating features in automatic fixturing - EC_{221}

Referring to the error catalyst descriptions on figures 4.5 and 4.6, it is noted that absence of positioning elements is more prominent as compared to congruent mating features. From the nature of the second error catalyst itself it appears less probable as compared to the first one.

Based on relative importance, their weightages are as follows:

$W_{12} = 1; \qquad W_{22} = 0.5$

Therefore, the QM score for the specific defect part interchange (SD_{21}) is given as:

$$Q_{21} = \frac{S_{12} + (0.5 * S_{22})}{2}$$

4.4.3 Mispositioning

Mispositioning can be defined as placing a part with a different orientation or placing it at a location other than the desired one. This should not be mistaken for misalignments. Part geometry, positional relationship, fitting relationship, assembly method, fastening method

ERROR CATALYSIS SHEET

DEFECT CLASS
Missing/Misplaced Parts

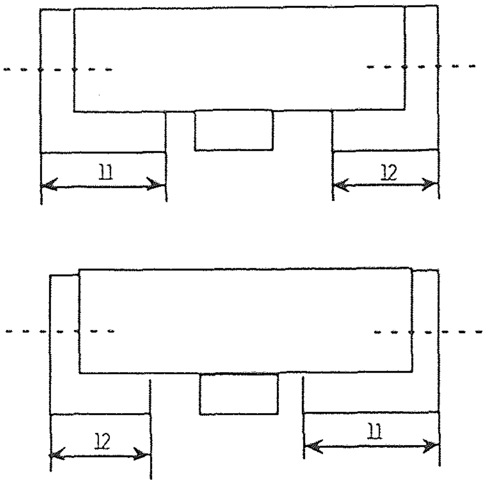
SPECIFIC DEFECT
Part Interchange

SHEET NO:
EC121

ERROR CATALYST
Absence of Positioning Elements

DESCRIPTION

Parts that have very similar shapes but slightly different dimensions, such that the difference is not easily noticeable, are likely to get interchanged in case of manual assembly. The figure shows one such example where the absence of anti-locating elements leads to interchange of parts. This type of defect may lead to mispositioning of subsequent components. This defect can also be avoided using assembly fixtures that check against such interchange.



CATALYSIS GRAPH

$$\begin{aligned}\phi(a) &= a && \text{for } 0.81 </= a</=1\\ &= a - 0.2 && \text{for } 0.6 </= a</=0.8\\ &= 0 && \text{for } a < 0.6\end{aligned}$$

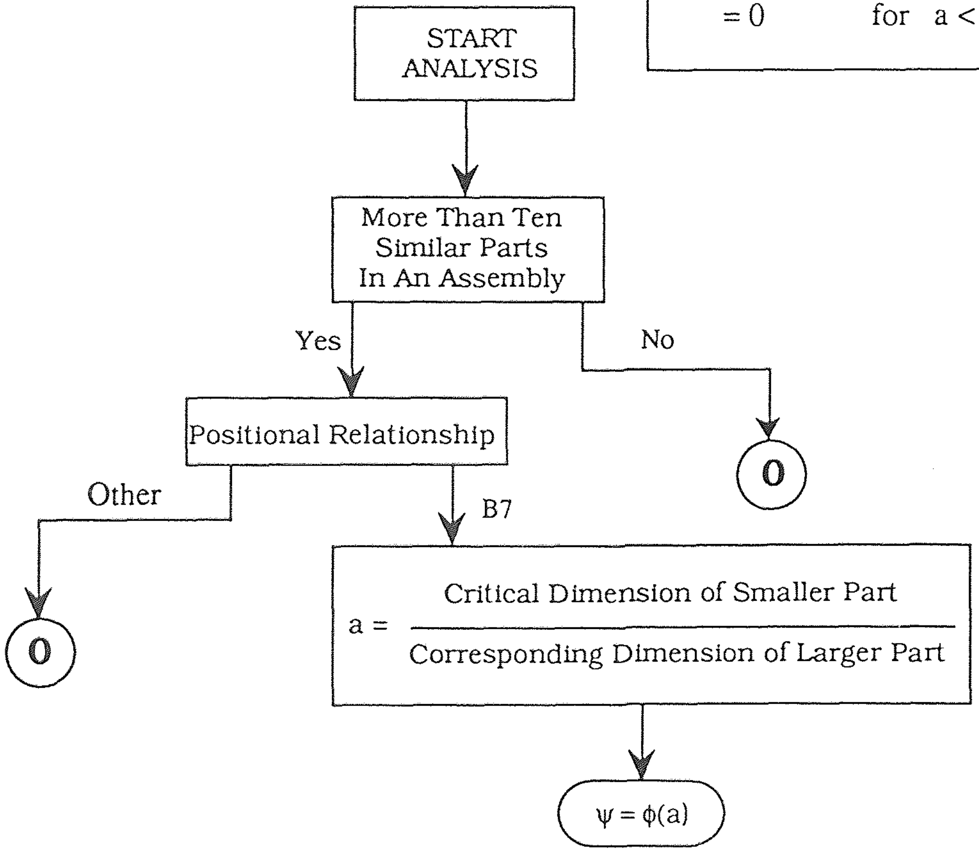


Figure 4.5 Catalysis Graph for Absence of Positioning Elements

ERROR CATALYSIS SHEET

DEFECT CLASS

Missing / Misplaced Parts

SPECIFIC DEFECT

Part Interchange

SHEET NO:

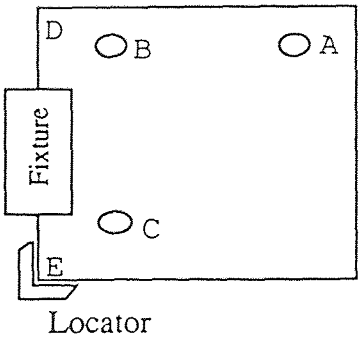
EC221

ERROR CATALYST

Congruent Mating Features in Automatic Fixturing

DESCRIPTION

Part interchange can occur due to congruent mating features. This is more likely if the parts are small. For example, the assembly procedure may be such that the fixture holds the main component against Corner E, Part B and Part C are fitted in first, and Part A is fitted subsequently at locations A, B, and C respectively. If all three parts have congruent mating features with the main component and if the main component is located on Corner D instead of E as desired, Part B will fit in at location A and Part C in place of B. Furthermore, in case of automatic assembly, if the same orientation continues, Part C is likely to be absent. Part A is likely to be fitted in place of C in case of manual assembly.



CATALYSIS GRAPH

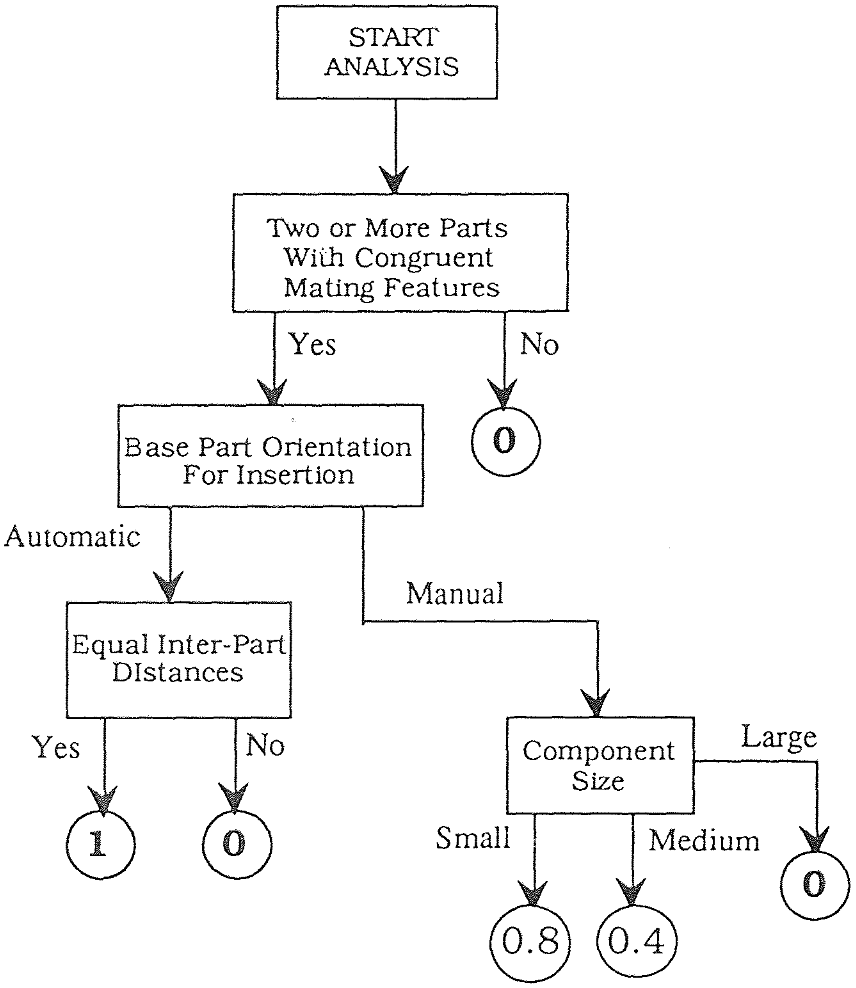


Figure 4.6 Catalysis Graph for Congruent Mating Features in Automatic Fixturing

are some factor variables that greatly influence this defect. Figures 4.6 through 4.9 describe the error catalysts for this defect. Error catalysts influencing this defect are:

1 Congruent mating features - EC_{131}

2 Weak part forced in undesirable positions - EC_{231}

3 Absence of alignment checking features - EC_{331}

4 Unfinished surfaces - EC_{431}

Mispositioning of small parts with similar configuration and congruent features is the most common cause of mispositioning errors. Absence of alignment checking features is likely to go unnoticed in most cases, but yet it is not as effective as the first error catalyst. Unfinished surfaces can be considered at the third relative level. Weak parts forced in undesirable positions is likely to happen, but at the same time more likely to be noticed. Thus the relative weightage of the four error catalysts can be given as follows:

$W_{13} = 1;$ $W_{23} = 0.4;$ $W_{33} = 0.8;$ $W_{43} = 0.6$

Therefore, the QM score for the specific defect mispositioning of parts (SD_{31}) is given as:

$$Q_{31} = \frac{S_{13} + (0.4 * S_{23}) + (0.4 * S_{33}) + (0.6 * S_{43})}{4}$$

4.5 QM Score for Defect Class Missing/Misplaced Parts (CD_1)

The QM score for any defect class is obtained using formula given in Step 5 of QM analysis (section 4.3). Each of the three specific defects under the defect class missing/misplaced parts need to be analyzed on the basis of their relative importance depending on the functional requirements and nature of the product. These ratings are to

ERROR CATALYSIS SHEET

DEFECT CLASS
Missing/Misplaced Parts

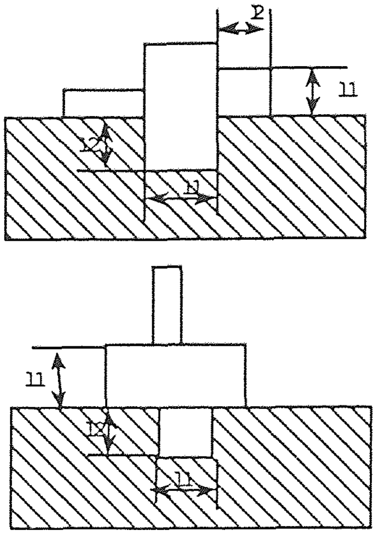
SPECIFIC DEFECT
Mispositioning

SHEET NO:
EC131

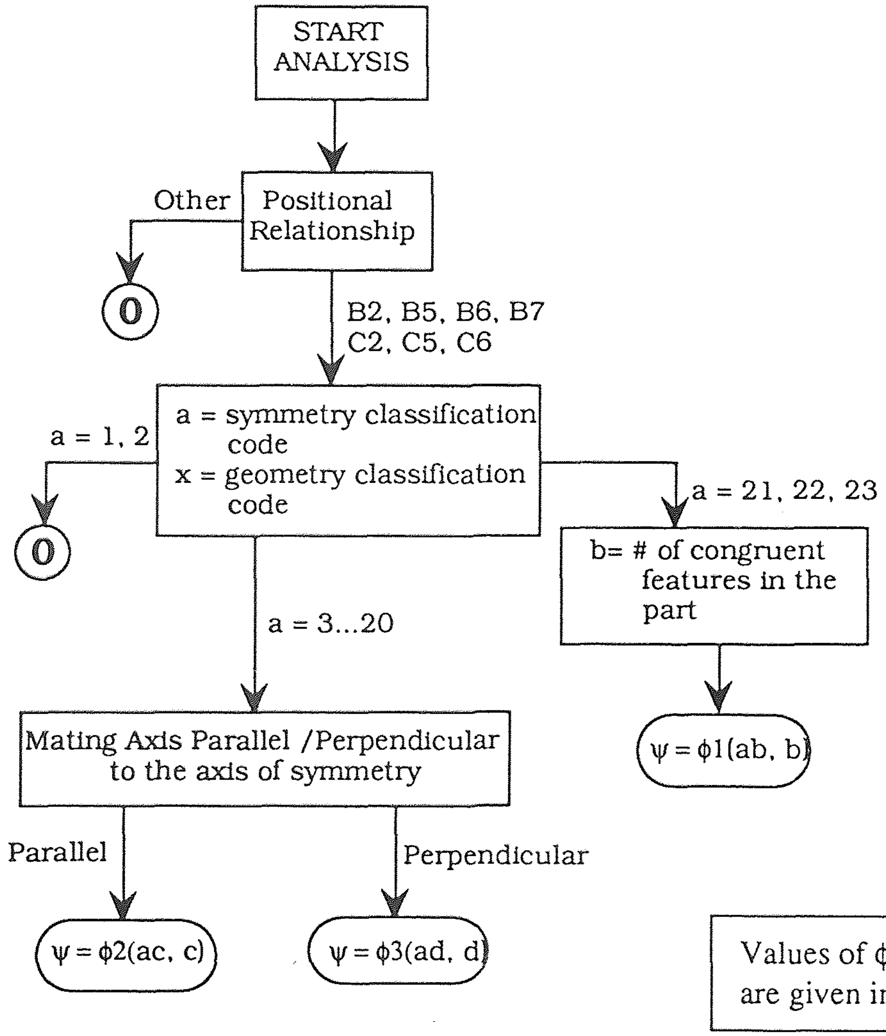
ERROR CATALYST
Congruent Mating Features

DESCRIPTION

Absence of positioning elements can influence mispositioning of a part with more than one congruent mating feature. This is more likely in case of manual assembly. For example, the part shown in the figure can fit the slot in two different ways. This mispositioning is likely to go unnoticed if parts have similar features. Orientation of the part shown is also difficult in case of automatic feeder.



CATALYSIS GRAPH



Values of ϕ1, ϕ2, and ϕ3 are given in Table 4.2

Figure 4.7 Catalysis Graph for Congruent Mating Features

Table 4.2 Error Catalysis Scores for Congruent Mating Features (EC_{13})

c/d	b	a_b	a_c	a_d	$\phi_1(a_b,b)$	$\phi_2(a_c,c)$; $\phi_3(a_d,d)$
R, T, B, F, S, P	0	21...23	-	-	0	-
	2	21...23	-	-	0.5	-
	3	22	-	-	0.6	-
	> 3	22	-	-	0.7	-
	3	23	-	-	0.7	-
	> 3	23	-	-	0.9	
R, T	-	-	3,4	3, 4, 9, 10	-	0
	-	-	9, 10	12	-	0.2
	-	-	6...8, 12	5...8, 11	-	0.4
	-	-	5, 11, 14, 17...20	17...20	-	0.6
	-	-	13	13...16	-	0.8
	-	-	15, 16	-	-	0.9
B, F	-	-	-	9, 10	-	0
	-	-	3, 4, 7...10	4	-	0.2
	-	-	13, 14, 16...20	7, 8, 17, 18, 19, 20	-	0.4
	-	-	5, 6, 15	3, 5, 6, 13, 14, 16	-	0.6
	-	-	-	15	-	0.8
S	-	-	4, 6...10	3, 4, 9, 10	-	0
	-	-	3, 5	5....8, 17...20	-	0.2
	-	-	13...16	-	-	0.4
	-	-	17...20	13...16	-	0.6
P	-	-	5, 6, 9, 10	5...13; 15	-	0
	-	-	7, 8, 11, 12, 15	-	-	0.2
	-	-	17, 19, 20	14, 16, 17, 18, 20	-	0.4
	-	-	13, 18	-	-	0.6
	-	-	14, 16	-	-	0.8

c/d : This column indicates the basic shape of the component (refer to classification chart figure 3.1)

a_b; a_c; a_d : These columns indicate the symmetry of components (refer to classification chart figure 3.1)

ERROR CATALYSIS SHEET

DEFECT CLASS
Missing / Misplaced Parts

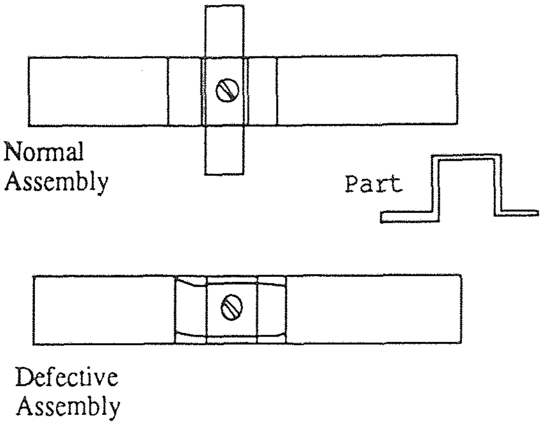
SPECIFIC DEFECT
Mispositioning

SHEET NO:
EC231

ERROR CATALYST
Weak parts forced into undesirable positions

DESCRIPTION

Flat parts made of soft metal or plastic can fit in undesirable positions due to the use of power fastening devices. Geometry of the mating part plays a important role in this type of defect. The Figure shown demonstrates this defect. Under normal assembly, two lips on the part cannot fit the slots in the main component. If such a part is made of a soft material , there is a possibility that the part changes its orientation due to vibrations of a power driven fastening device and is further forced as shown. Manual fastening is not likely to cause this defect.



CATALYSIS GRAPH

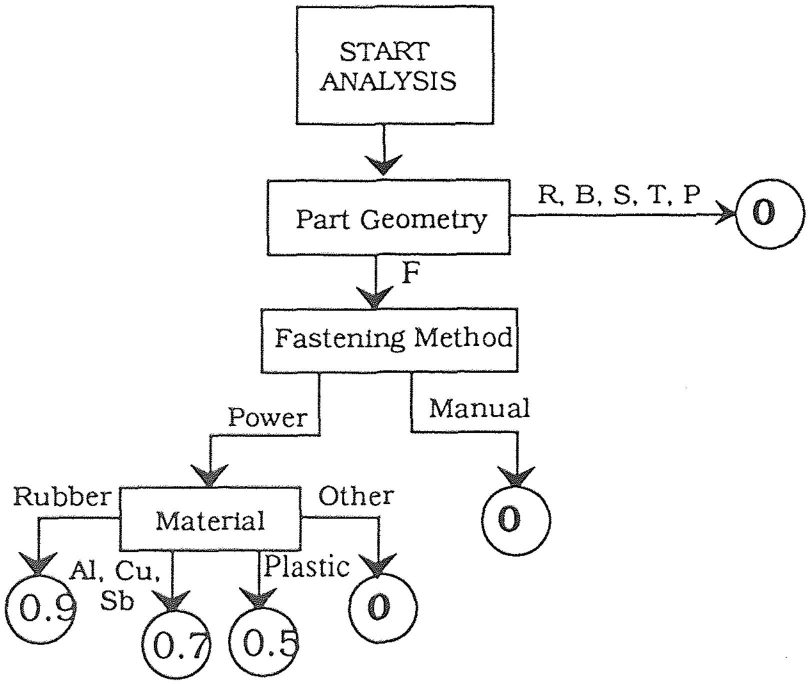


Figure 4.8 Catalysis Graph for Weak Parts Forced in Undesirable Positions

ERROR CATALYSIS SHEET

DEFECT CLASS
Missing/Misplaced Parts

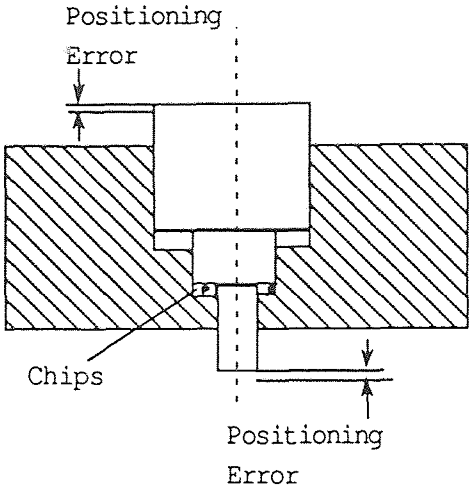
SPECIFIC DEFECT
Mispositioning

SHEET NO:
EC331

ERROR CATALYST
Absence of Alignment Checking Features

DESCRIPTION

Mispositioning is likely to occur if the alignment of two mating parts cannot be clearly defined. For example, the figure shows a component passing through a block. Due to the dimensions of the component and the type of mating, it cannot be easily determined if the component has fit the block as desired. If the assembly is press fitted, the length of the component required to protrude out of the block may not be met. Or, even if it is a loose or running fit, the presence of chips, burrs, or other foreign elements is likely to influence mispositioning of this type.



CATALYSIS GRAPH

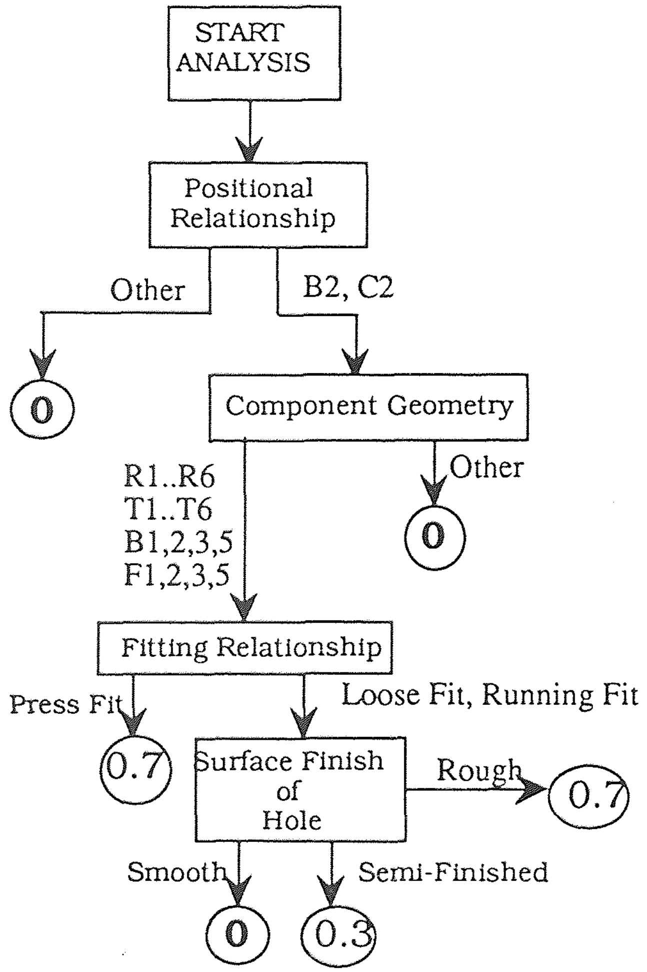


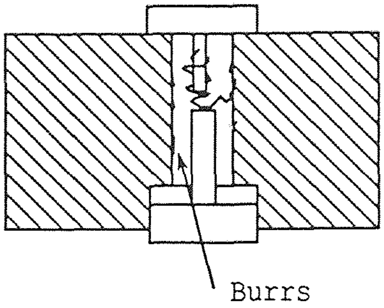
Figure 4.9 Catalysis Graph for Absence of Alignment Checking Features

ERROR CATALYSIS SHEET

DEFECT CLASS Missing/Misplaced Parts	*SPECIFIC DEFECT* Mispositioning	*SHEET NO:* EC431
ERROR CATALYST Unfinished Surfaces		

DESCRIPTION

In certain assemblies, the surface finish of holes is not required to be smooth because it is not critical from the design perspective. The figure shows a block which has an unfinished hole. Since the hole surface has no planned contact with any mating part, the designer would not desire a finished one. This is likely to cause quality problems. For example, as shown in the figure, the spring may get mispositioned due to burrs present on hole surfaces. Distortion of the spring may lead to misalignment of the pins, or the spring may also get undesirably compressed in its initial position, disabling its function. The same reasoning also applies to rubber bushing.



CATALYSIS GRAPH

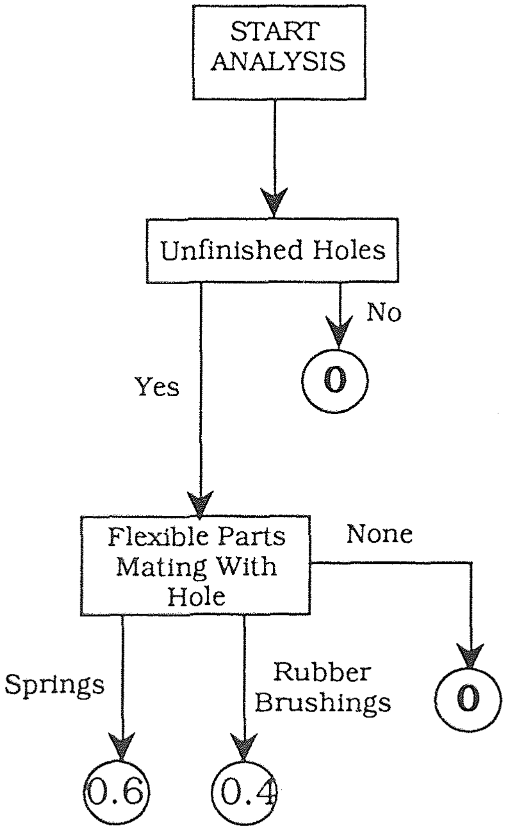


Figure 4.10 Catalysis Graph for Unfinished Surfaces

be judged by the user. In general, mispositioning of parts (SD_{31}) can be considered as most troublesome, but depending on the significance of the missing part, SD_{11} can turn out to be the most important. In another case, part interchange may have serious effect on the quality of the product.

If F_{11}, F_{21}, and F_{31} are the multiplication factors assigned to SD_{11}, SD_{21}, and SD_{31}, respectively, based on their relative importance; the QM score for the defect class missing/misplaced parts is given by:

$$C_1 = \frac{(Q_{11} * F_{11}) + (Q_{21} * F_{21}) + (Q_{31} * F_{31})}{3}$$

CHAPTER 5

DFQM ANALYSIS OF PART INTERFERENCE

Interference is caused whenever there is undesired physical contact between two moving parts. Interference has a significant impact on the functionality of a product as well as its perceived quality. It can occur due to several factors at different stages of the product's manufacturing cycle. In some cases interference may be absorbed by parts due to the nature of the material, but in other cases, part interference may have a cascading effect thus resulting in several other defects. This chapter deals with the DFQM analysis of the defect class Part Interference.

5.1 DFQM Analysis of Part Interference

DFQM analysis of part interference is performed using the same methodology as described in section 4.3. It is not repeated in this chapter to avoid redundancy. Part interference is listed as third defect class in the DFQM methodology. Thus for the sake of consistency, $k = 3$ is used as a subscript for this defect class. The same concept of catalysis graph (refer to section 4.2), used to obtain a score for each error catalyst, is used to analyze every specific defect under this class. Based on the frequency of their occurrence, three specific defects are identified under this defect class. They are (i) constant interference, (ii) occasional interference, and (iii) intermittent interference. Figures 5.1 through 5.5 illustrate all catalysis graphs for the three specific defects under this class.

5.1.1 Constant Interference

This is the type of interference which is observed constantly during the entire motion cycle of the moving part. A rotating pulley constantly touching a surface of the nearest part is an example of constant interference. The occurrence of this defect is mainly attributed to designing of the product where the moving members are in close proximity to the stationary parts. This defect is also influenced by assembly related factors such as divergence from assembly procedures. In the insertion process, geometrical features, assembly procedure, and material properties, are the influencing factors related to this defect. Fastening system and assembly procedure are the influencing factors pertaining to constant interference in welded assemblies. Constant interference in fastened assemblies are due to deficiencies in the fastening system and assembly procedure. Deformation of parts during handling or assembly may lead to constant interference.

Three independent error catalysts influencing constant interference are identified. They are:

1 Proximity of rotating members to stationary part - EC_{113}
2 Method of fastening rotating member - EC_{213}
3 Bending of shafts - EC_{313}

Catalysis graphs for the above mentioned error catalysts are shown in figures 5.1 through 5.3. Scores obtained from the catalysis graphs are S_{11}, S_{21}, and S_{31}. Analyzing these error catalysts, it is inferred that rotating members being too close to the stationary parts is the most prominent one; such that it would require an extremely high degree of accuracy during assembly. The error catalyst of method of fastening the rotating member

ERROR CATALYSIS SHEET

DEFECT CLASS
Interference

SPECIFIC DEFECT
Constant Interference

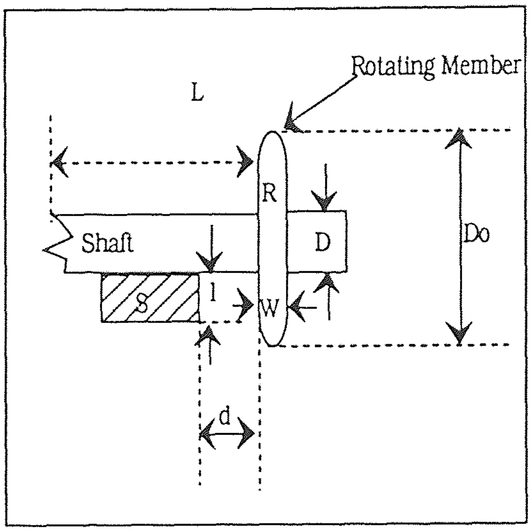
SHEET NO:
EC113

ERROR CATALYST
Proximity of Rotating Members to Stationary Parts

DESCRIPTION

If the assembly design is such that the rotating member is too close to stationary part(s), the probability of contact increases significantly due to the incapability of the process to assemble the parts correctly. The factors that would be of importance in the DFQM analysis of this deficit include:

i) Dimension of the rotating part and the shaft
ii) Minimum distance between the surfaces most likely to have constant interference
iii) Method of mounting on and fastening to shaft



Do - Maximum dimension of the rotating part in a direction perpendicular to the axis of the shaft.
l - length of the surface that the rotating member can possibly interfere with.
d - minimum distance between the rotating surface(R) and a stationary surface(S) closest to it.
D - Maximum dimension of the shaft cross-section
L - Length of shaft from the support(nearest to the R) to R
W - Width of the rotating member overlapping the shaft

The Catalysis Graph for this error catalyst is shown on the following page.

Figure 5.1 Catalysis Graph for Proximity of Rotating Members to Stationary Parts

ERROR CATALYSIS SHEET

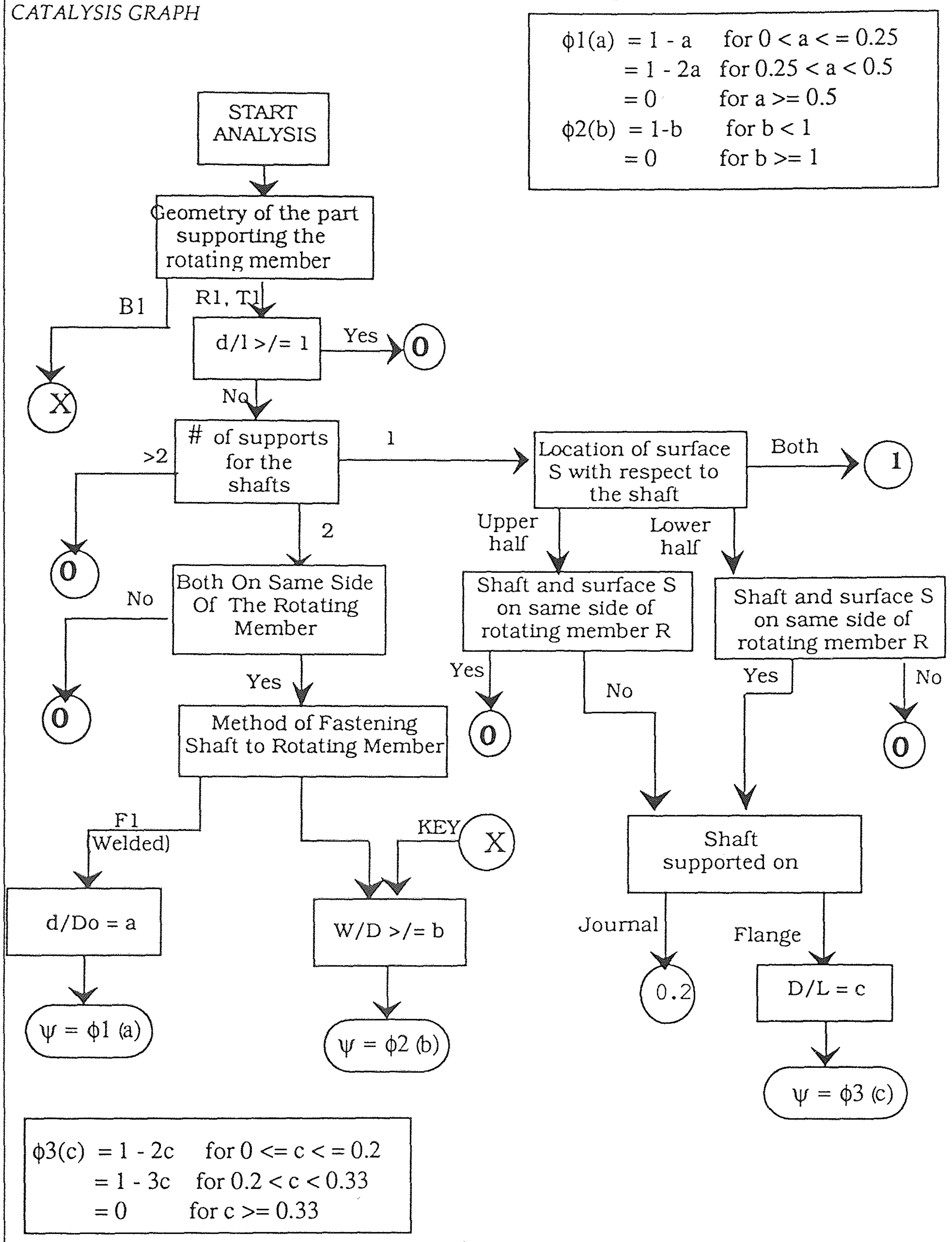
DEFECT CLASS
Interference

SPECIFIC DEFECT
Constant Interference

SHEET NO:
EC113
(Continued)

ERROR CATALYST
Proximity of Rotating Members to Stationary Parts

CATALYSIS GRAPH



$\phi 1(a) = 1 - a$ for $0 < a <= 0.25$
$= 1 - 2a$ for $0.25 < a < 0.5$
$= 0$ for $a >= 0.5$
$\phi 2(b) = 1 - b$ for $b < 1$
$= 0$ for $b >= 1$

$\phi 3(c) = 1 - 2c$ for $0 <= c < = 0.2$
$= 1 - 3c$ for $0.2 < c < 0.33$
$= 0$ for $c >= 0.33$

Figure 5.1 (Continued) Catalysis Graph for Proximity of Rotating Members to Stationary Parts

ERROR CATALYSIS SHEET

DEFECT CLASS
Interference

SPECIFIC DEFECT
Constant Interference

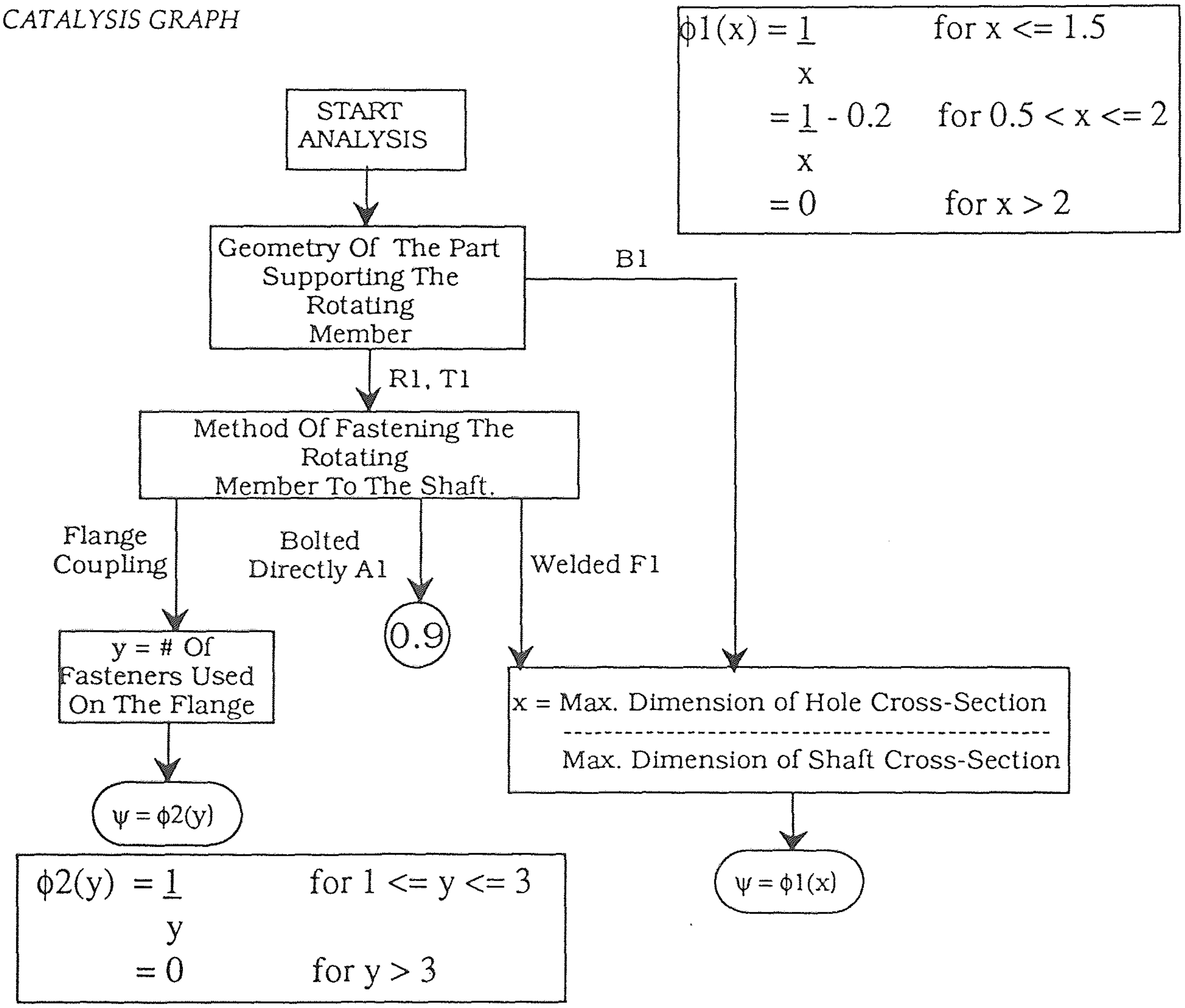
SHEET NO:
EC213

ERROR CATALYST
Method of Fastening the Rotating Member

DESCRIPTION

The method of fastening rotating members to a shaft is important for DFQM analysis. If the rotating member is mounted on a shaft using a flange coupling, correct fastening sequence must be followed so that the rotating member is not misaligned and does not cause constant interference with a neighboring surface. In assemblies with very low clearance between the rotating member and the neighboring surface or between shaft and hole, if the rotating member is welded to the shaft, the weld metal deposits may constantly interfere with the shaft housing.

CATALYSIS GRAPH



$$\phi1(x) = \frac{1}{x} \quad \text{for } x <= 1.5$$
$$= \frac{1}{x} - 0.2 \quad \text{for } 0.5 < x <= 2$$
$$= 0 \quad \text{for } x > 2$$

$$\phi2(y) = \frac{1}{y} \quad \text{for } 1 <= y <= 3$$
$$= 0 \quad \text{for } y > 3$$

Figure 5.2 Catalysis Graph for Method Of Fastening the Rotating Member

ERROR CATALYSIS SHEET

DEFECT CLASS
Interference

SPECIFIC DEFECT
Constant Interference

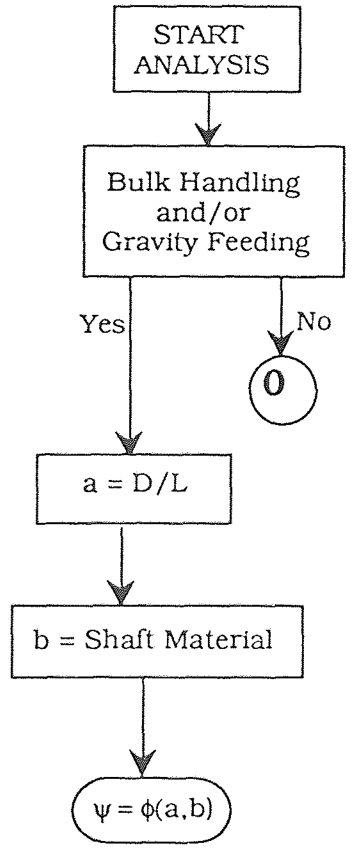
SHEET NO:
EC313

ERROR CATALYST
Bending of shafts during handling or assembly

DESCRIPTION

Shafts that support the rotating members are likely to be subjected to undesirable bending during material handling or assembly processes. Bending is likely to happen if the shaft material is not very strong and the shaft has a high length to diameter (diagonal for rectangular cross-section) ratio. Constant interference will occur if the clearance between the rotating member and a neighboring surface is very small.

CATALYSIS GRAPH



Al and Cu : $b = 0.9$
Plastic : $b = 0.6$
Hard material : $b = 0$

$\phi(a,b) = (1 - a)b$

Figure 5.3 Catalysis Graph for Bending of Shafts During Handling is ranked second followed by bending of shafts. Relative weightages for the three error catalysts leading to the specific defect constant interference are given as follows:

$W_{11} = 1; \qquad W_{21} = 0.75; \qquad W_{31} = 0.5$

Therefore the QM score for the specific defect constant interference is given as:

$$Q_{13} = \frac{S_{11} + (0.75 * S_{21}) + (0.5 * S_{31})}{3}$$

5.1.2 Occasional Interference

Occasional Interference is encountered randomly once in a while. This interference is observed at varied points in time and does not follow any particular cyclical pattern. It can also be termed as random interference. Flexible part in the vicinity of moving parts influence this defect. This is due to the fact that it is difficult to completely define the positional relationship between the flexible part and other parts in an assembly.

This type of defect predominantly occurs when flexible parts like hoses, ducts, wires, etc. are close to moving parts. It is unlikely that the assemblyman ensures proper positioning and fastening of these parts envisaging the probability of them interfering with moving parts when the product is used. Even if extra care is taken, parts being flexible may revert to undesirable positions; thus interfering with moving members in an assembly. There is only one significant error catalyst identified for this defect, namely : flexible parts in the vicinity of moving parts (EC_{123}). Analysis of this error catalyst is illustrated in figure 5.4.

he QM score for this specific defect is equal to the score (S_{12}) obtained from the catalysis graph (figure 5.4) for the single error catalyst. QM score for occasional interference is given as:

$$Q_{23} = S_{12}$$

5.1.3 Intermittent Interference

Intermittent interference is the type of interference which is encountered at fixed intervals in the motion cycle. It is also termed as periodic or cyclic interference because it is observed in the assembled product at specific intervals of time, each observation related to the previous by the duration of occurrence.

The QM score for intermittent interference is equal to the score obtained from the catalysis graph (S_{13}) for the single error catalyst described in figure 5.5. Therefore, QM score for this specific defect is given as:

$$Q_{33} = S_{13}$$

5.2 QM Score for the Defect Class Part Interference

The three specific defects under this class are analyzed with respect to their relative importance. It is evident that constant interference is the most important one and needs to be eliminated completely. Any product with its moving parts constantly interfering with the neighboring fixed surfaces is definitely not acceptable from quality and functionality perspective. Intermittent interference also affects the quality and functionality of the product, but it can be considered relatively less troublesome as compared to constant

ERROR CATALYSIS SHEET

DEFECT CLASS
Interference

SPECIFIC DEFECT
Occasional Interference

SHEET NO:
EC123

ERROR CATALYST
Flexible parts in the vicinity of moving parts

DESCRIPTION

When flexible parts like hoses, ducts, wires, etc., are in the vicinity of moving parts; they are likely to cause occasional interference. It is difficult to completely define the positional relationship between the flexible parts and other parts. Assembly processes may not precisely position the slackness in the flexible so that it does not interfere with the motion of the moving parts. This defect is likely to go unnoticed until the product is operated.

CATALYSIS GRAPH

L = Length of the flexible part

d = Distance between the two ends of the flexible parts to be connected

s = Shortest possible distance between the moving part and a straight line connecting the two ends of the flexible part

$$\begin{aligned} \phi 1(y) &= 1 && \text{for } y >= 1 \\ &= 0 && \text{for } y < 1 \\ \phi 2(x) &= 1 && \text{for } x >= 1 \\ &= 0 && \text{for } x < 1 \end{aligned}$$

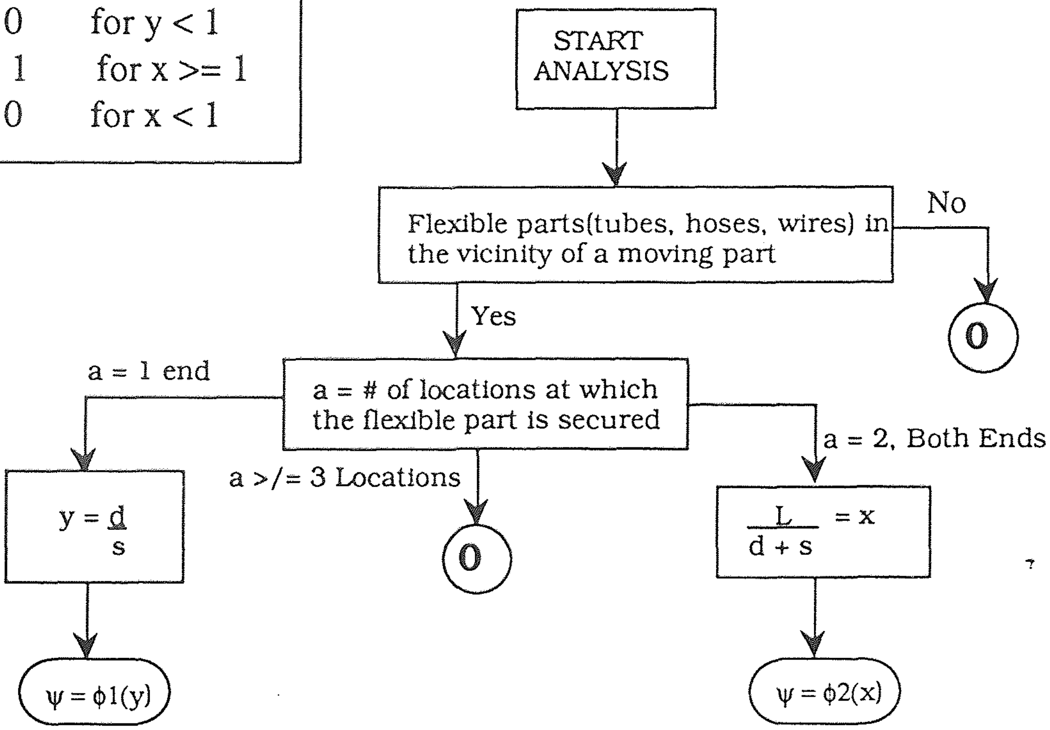


Figure 5.4 Catalysis Graph for Flexible Parts in the Vicinity of Moving Parts

ERROR CATALYSIS SHEET

DEFECT CLASS
Interference

SPECIFIC DEFECT
Intermittent Interference

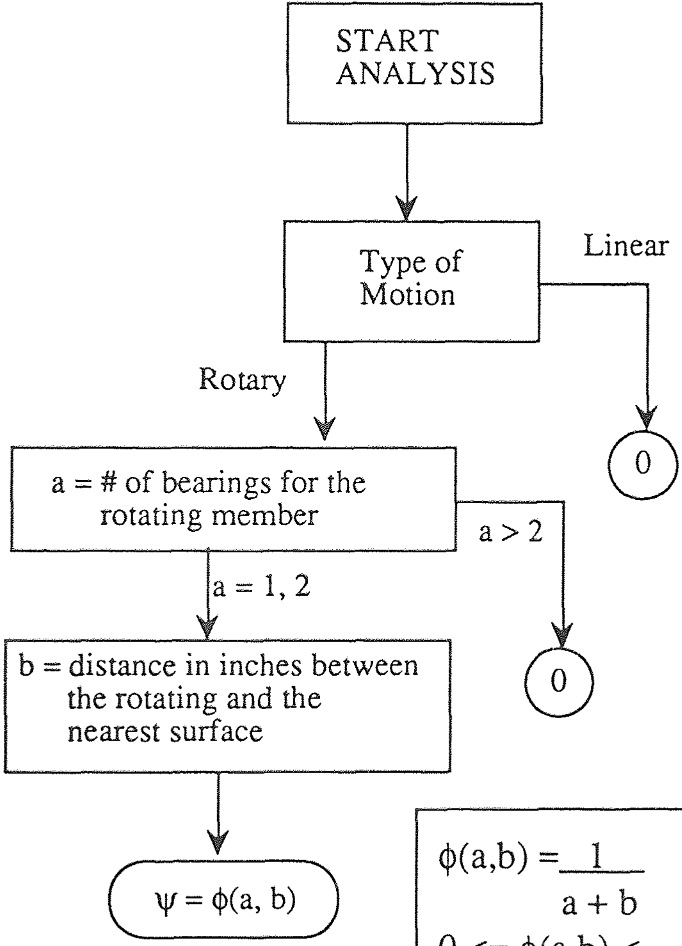
SHEET NO:
EC133

ERROR CATALYST
Improper Installation of Bearings

DESCRIPTION

Improper installation of bearings may encounter intermittent interference. This may cause the rotating member to vibrate in an unprecendented direction and come into intermittent contact with peripheral surfaces in the close proximity thus causing intermittent interference. These vibrations are more likely if the assembly is subjected to vibrations from external source.

CATALYSIS GRAPH



$$\phi(a,b) = \frac{1}{a+b} \qquad \text{for } b <= 1 \text{ inch}$$

$$0 <= \phi(a,b) < \frac{1}{a+b} - 0.3 \qquad \text{for } b > 1 \text{ inch}$$

Figure 5.5 Catalysis Graph for Improper Installation of Bearings interference. Occasional interference is also not desirable from the quality perspective, but it has comparatively much lesser impact on the functionality of the product.

Overall, it is inferred that constant interference must get the maximum rating followed by intermittent interference and finally occasional. Comparing on a scale of 0 to 1, the following multiplication factors are assigned to the three specific defects, namely: constant interference (SD_{13}), occasional interference (SD_{23}), intermittent interference (SD_{33}), respectively.

$F_{13} = 1$; $F_{23} = 0.7$; $F_{33} = 0.4$

Therefore, the QM score for the defect class Part interference is given by :

$$C_3 = \frac{Q_{13} + (0.7 * Q_{23}) + (0.4 * Q_{33})}{3}$$

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH

6.1 Conclusions

The DFQM methodology helps in bridging the gap between product design and its manufactured quality. The feature by feature analysis of the design and assembly process exposes the strengths and weaknesses of the design. In this thesis, parts are classified on the basis of their symmetry and geometry. This enables unique identification of parts for DFQM analysis of all the specific defects belonging to the six defect classes. This research presents a methodology for evaluating the quality manufacturability (QM) of a design. Specific defects under the defect classes missing/misplaced parts and part interference are analyzed in detail. Error catalysts influencing these specific defects are identified. The error catalysts are further quantified based on their relative likelihood of influencing the specific defect being analyzed. The methodology to determine QM score for each defect class is presented this thesis. QM analysis of the defect classes missing/misplaced parts (CD_1) and part interference (CD_3) are discussed in detail. QM scores for these two defect classes can be obtained for any given part using the proposed methodology.

Another research in the area of DFQM is being presented by Mr. Suriyanarayanan Ramachandra. This work is process-driven whereby various assembly processes are analyzed in detail to identify the factors influencing the occurrence of quality defects. The analysis focuses on justification of the DFQM structure (figure 2.2) by determining the error catalysts relevant to the various assembly processes. The research presented in this thesis moves in the direction of quantifying the DFQM structure after synthesizing the error catalysts into a functionally independent set. It is defect-driven approach where each error catalyst is related to the defects and evaluated based on the factor variables of a design.

6.2 Quality Manufacturability Matrix (QMM)

The Quality Manufacturability Matrix (QMM) is obtained as a result of the QM analysis of the defect classes discussed earlier. This is final outcome of using the DFQM methodology. It contains the QM scores (C_k) for each defect class for all p parts in an assembly. Thus, the QMM has k = 6 columns and p rows. Table 6.1 shows an example of a QMM.

Table 6.1 Quality Manufacturability Matrix (QMM)

	CD_1	CD_2	CD_3	CD_4	CD_5	CD_6
P_1	0.5	0.9	0.8	0.3	0	1
P_2	1	0.2	0.5	0	0.5	0
P_3	0	0.8	0.3	0	0.7	0
.	.	.	.	.	.	.
	.	.	.	.	.	.
P_L	C_{1L}	C_{2L}	C_{3L}	C_{4L}	C_{5L}	C_{6L}

This matrix contains QM scores for all parts with respect to each of the six defect classes. The values shown in Table 6.1 are for the sake of illustration. These scores will assist the designer in focusing attention on parts which are more susceptible to certain defects. At the same time, if a certain defect is not perceived as significant considering the function of the respective part, the defect can be ignored. This will help the designer to concentrate only on parts which are most prone to defects that are intolerable from the quality and functionality perspective. For example, consider parts P_2 and P_3 from the matrix.

P_3 has QM score $C_2 = 0.8$ (for CD_2 i.e. misalignment)

P_2 has a QM score $C_3 = 0.5$ (for CD_3 i.e. interference)

Now, the designer has to analyze parts P_2 and P_3 with respect to their functions. It is possible that although part P_3 is more prone to misalignments, it may not be a matter of concern for that part. At the same time, part P_2 having relatively less score for interference may still be unacceptable. Thus the QMM is a strong tool which would aid the designer in modifying the design based on the needs and priority of the problem associated with certain parts. Values from the QMM can be normalized to obtain a singular QM index for the whole assembly. This index would be on a 0 to 100 scale. Higher the index, better the design from quality manufacturability perspective.

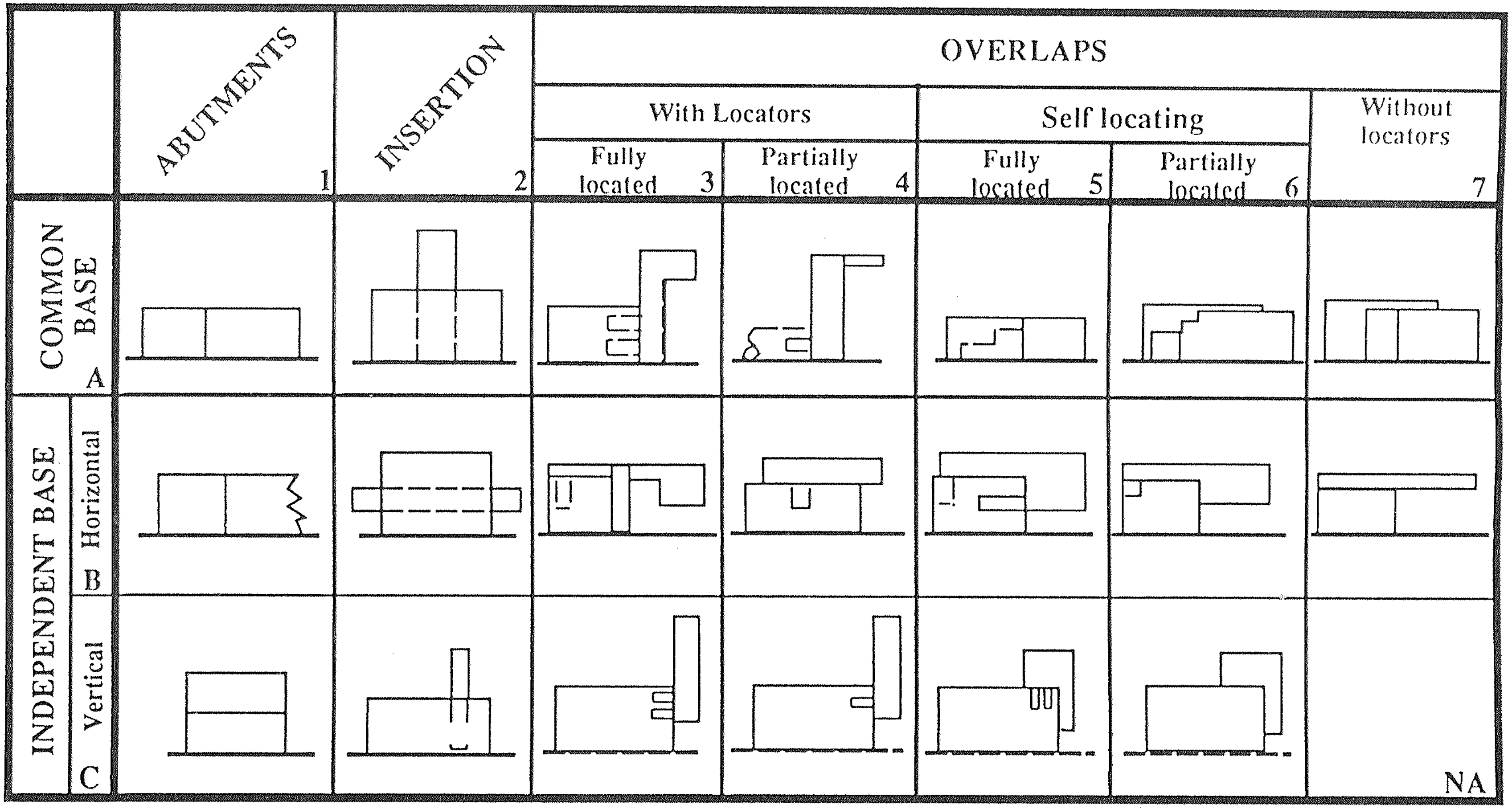
The Boothroyd-Dewhurst method computes the design efficiency of an assembly. The design efficiency signifies the difficulty associated with handling and assembling various components of a product. It does not take into consideration the quality defects that might arise during its manufacture. DFQM methodology proposed in this thesis focuses on the issue of quality manufacturability. The QMM and QM index obtained as a result of the quality manufacturability analysis serve as effective tools that can be used to improve the manufactured quality of a product.

6.3 Future Work

The scope of this thesis is limited to two defect classes out of six classes identified in the DFQM structure. Immediate future research is required to be done on the other four defect classes, namely: Part Misalignments, Fastener Related Problems, Total Nonconformity, and Damaged Parts. Similar analysis as described in chapters four and five of this thesis is required for these four defect classes. It is evident from the methodology that the user would have to go through a lot of queries and lengthy calculations to reach the final QMM. Thus this methodology is planned to be computerized. The software to be developed for DFQM analysis would require the user to answer certain questions indicative of the factor variables of the design and based on this input the program would run a routine and come up with the QMM and QM index. In addition it will also generate a set of inferences for the user. The step of computerization is subsequent to the DFQM analysis of all the remaining defect classes. Further advancement in this area would be integrating the DFQM software with CAD package like ProEngineer. In this case, the CAD drawings itself would be analyzed from DFQM perspective.

APPENDIX A

DFQM CLASSIFICATION OF POSITIONAL RELATIONSHIPS.



Note: The `base' means the supporting structure. If the parts have different supports then they are independent base parts and if they share the same support then they are common base. Eg a pulley and it's shaft are independent base because the shaft is supported by bearings and the pulley is supported by the shaft.

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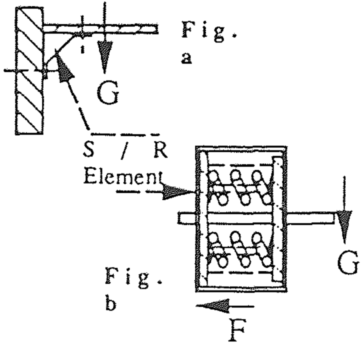
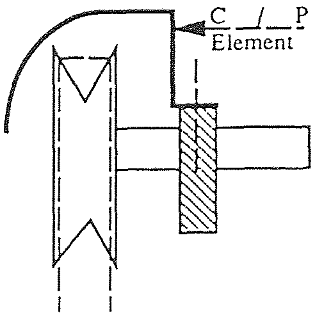
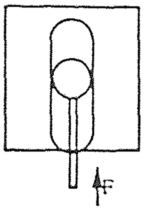
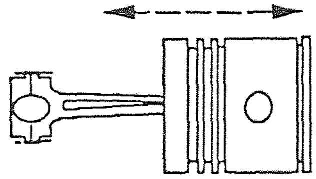
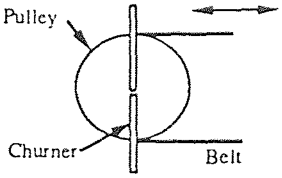
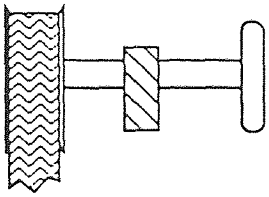
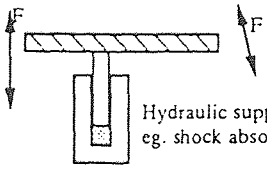
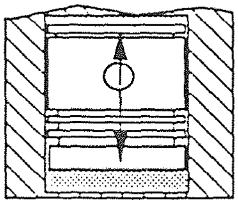
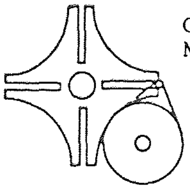
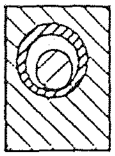
APPENDIX B

DFQM CLASSIFICATION OF FUNCTIONAL RELATIONSHIPS

	SUPPORT/RETENTIVE 1	COSMETIC/PROTECTIVE 2
NO MOTION A		

APPENDIX B - (Continued)

DFQM CLASSIFICATION OF FUNCTIONAL RELATIONSHIPS

		NON CONTINUOUS N1	CONTINUOUS N2
CONGRUENT MOTION	LINEAR B		
	ROTARY C		
RELATIVE MOTION	LINEAR D	 Hydraulic support eg. shock absorbers	
	ROTARY E	 Geneva Mechanism	 Front view Bearing & shaft.

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