DESIGN FOR QUALITY MANUFACTURE: FORMULATION OF THE MACRO ARCHITECTURE FOR A DFQM METHODOLOGY

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ABSTRACT

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The focus of the available techniques in concurrent engineering for the development and improvement of the design of a product, has been in the areas of product assemblability and manufacturability. These techniques are concerned with the reduction of the cost associated with the manufacture and handling of the product.

The Design For Quality Manufacturability focuses on the quality manufacturability issue of the product design. A macro architecture is developed for the introduction of a new methodology to evaluate designs based on the quality manufacturability of these designs. A set of defects occurring at the assembly stage of the manufacture of the product are identified. These defects are investigated using reverse cause-effect techniques to identify a set of factors responsible for the occurrence of these defects. Relationships are developed to bring about an effective link between the defects and the factors. Macro and micro level loops are developed to further analyze the dependence of the factors and defects.

A methodology is developed as a means for quantifying the quality of a design. This technique is applied to an example model to evaluate a set of probability functions. These probability functions enable feature by feature analysis of a design and serve as an indicator for the defects that can be expected due to the design features. This would also enable the user to assess the feature by feature superiority of one design over the other as relates to the quality of the product. This macro architecture can be used to evaluate the probability functions for all the defect classes, thereby aiding in the development of a methodology for DFQM analysis.

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This Thesis is dedicated to
the "new" member of the family,

with love.....

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CHAPTER ONE

INTRODUCTION

1.1. INTRODUCTION

Product quality may be defined as "fitness for use" or "the ability to function as intended". Juran (1985) and Deming (1986) among others, have expanded the definition of quality to describe it in terms of the following:

a. *Functionality*- - Performs a needed function
b. *Usability*- - Executes the function simply and quickly
c. *Reliability*- - Conformance to specifications, and time to failure
d. *Performance*- - Level at which the function is executed
e. *Serviceability*- - Restoration of the product once it has failed
f. *Availability*- - Continuity of product and support
g. *Price*- - Cost of function to customer.

The attainment of high levels of product quality is a prerequisite for the success of a product. Presently, manufacturers are experimenting with a variety of methods designed to improve quality. In general the quality of a manufactured product may be divided into the following two segments:

Design Quality - This is the design quality of the product as perceived by the customer. The quality is either high or low depending on the inherent features of the design. A product may be of excellent quality if it has many innovative quality features incorporated in it. This reflects the "built in quality" of the product, without the influence of the manufacturing setup.

Manufactured Quality - The transformation from a basic design to a manufactured product brings about the manufactured quality of the product. This is the extent to which a product deviates from its design specifications. It is possible that a product of good design might not be acceptable due to low manufactured quality.

In this thesis our focus is only on the improvement of the manufactured quality of a product. The transformation of any raw material into a finished product involves manufacturing processes, machinery, labor, designs, and tools to name a few. The quality of the product resulting from the transformation depends on all or some of these inputs. Any variation in one or more of these factors will effect the output quality. Further the quality and capability of each of the inputs must be appropriate to our manufacturing requirements. The premise of this thesis is that during the design stage, the state of these inputs may be considered by the designer, so that a design less likely to be manufactured with defects is developed. We shall call this process as design for quality manufacturability or DFQM.

1.2. DEFINING DESIGN FOR QUALITY MANUFACTURABILITY

In any repetitive production facility, no matter how perfect the operations, defective products will intermittently appear in the output. Even if a plant targets a 100% quality yield, then in all probability it will achieve this target only if an extensive effort is expended in monitoring and inspecting the processes. Defective and/or low quality products occur due to a variety of reasons. These reasons can be classified into the following five categories: bad design, design perturbation, design to manufacturing interface, manufacturing perturbation, and bad manufacturing. Bad design refers to problems in which the design is fundamentally inappropriate (e.g, GM's 4+6 cylinder engine). Design perturbation refers to problems in which the design is inherently sound but certain key parameters need to be further adjusted to improve quality (e.g, the elasticity of the rubber molding on a car door). Design to manufacturing interface refers to problems in which the design is sound, but from a manufacturing point of view the potential for defects arising exists (e.g, using a liquid adhesive to affix body side moldings on a car). Manufacturing perturbation refers to problems in which some of the production processes, including inspection and monitoring, need modifications so as to further improve the yield (e.g, controlling the pressure in an injection molding machine). Bad manufacturing refers to problems that stem from a lack of skill, training, discipline, or inadequacy in terms of processing capabilities (e.g; a sheet metal press is operated improperly by inattentive worker). The first two classes of reasons determine the design quality of a product, while the remaining three classes govern the manufactured quality. This project focuses on the design to manufacturing interface class of reasons, and how it effects manufactured quality.

To illustrate how manufactured quality is adversely effected by the design to manufacturing interface, consider the example shown in figure 1A. The design of a car door assembly, consisting of five parts, is depicted. All the parts except B, are welded to the main frame of the car body, while part B is affixed to the frame via two hinge fasteners. Though several defects could occur in the production of this assembly, let us consider only misalignments between parts. It can be induced that the likelihood of misalignment defects is:

$$\text{Prob}\begin{bmatrix}\text{Misalignment}\\ \text{Defects}\end{bmatrix} = \text{fn}\begin{bmatrix}\text{Number of mating surfaces; Sequence in which}\\ \text{A1,A2,A3,B, \& C are assembled; Fastening Method}\end{bmatrix}$$

The above probability is indicative of the quality manufacturability (QM) of a design. In order to improve the QM, the design team must focus on the functional variables identified above. Figure 1B illustrates an alternative design, proposed after QM analysis. In the new design A2 and A3 are no longer visible and instead are lapped below B. Further B is extended upwards so that the gap between A1 and B is on the roof, and hence away from the direct vision of the user. Finally, the hinged fasteners are redesigned so that B is automatically aligned to C. Clearly, the QM-Index of the second design will be greater than the first.

Thus Design for Quality Manufacturability can be 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

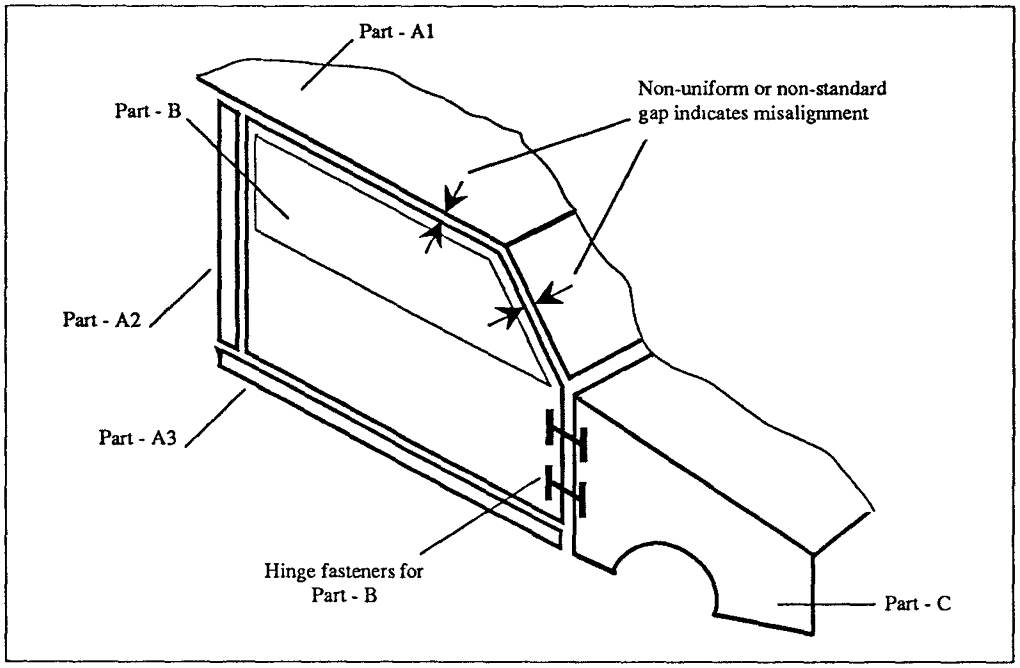

Figure 1A. Initial Design of a Car Door Assembly

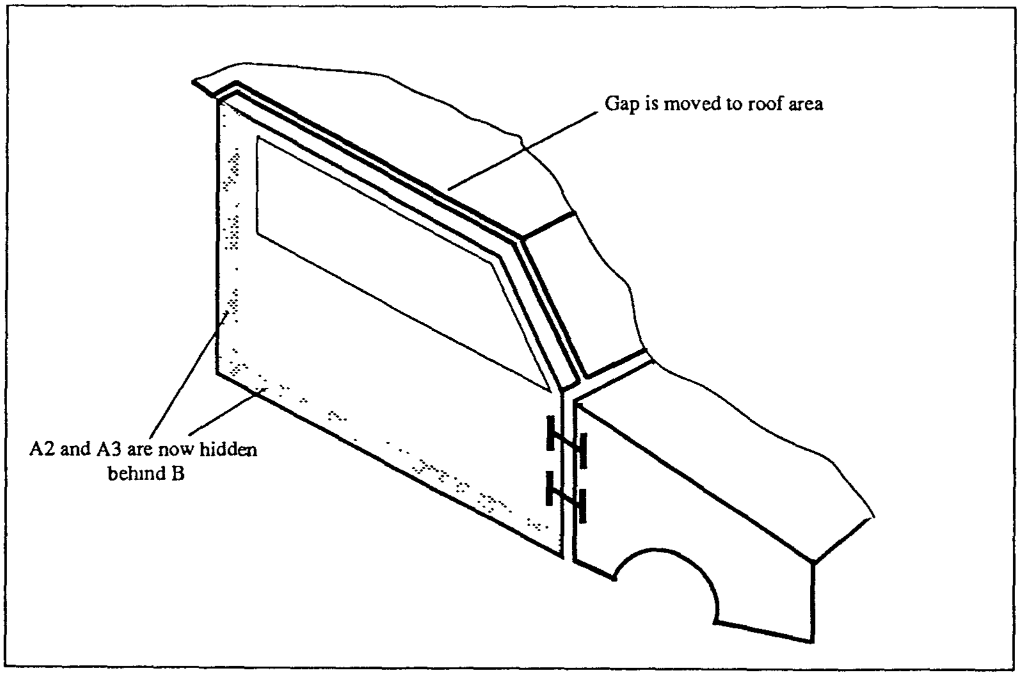

Figure 1B. Modified Design of a Car Door Assembly With Improved QM the manufacturing skills of the setup which thereby prevents the occurrence of defects.

1.3. PROBLEM STATEMENT

The ability to develop and design new products in short cycle times, and the ability to ascertain the manufacturability of these designs a priori, are essential requirements of today's competitive manufacturer. Realization of these abilities requires a set of methodologies that permit several aspects of a design to be concurrently evaluated and improved in the early stages. Design for manufacturability (DFM) is one specific methodology in this. 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 a minimum effort in terms of processing and handling requirements, and (iv) the manufactured product attains its designed level of quality.

Several techniques for DFM have been developed and implemented in industry. Typically, a technique will focus on one or more of the above listed objectives. The more well known among the reported DFM techniques include the Boothroyd-Dewhurst approach, the Hitachi Assembly Evaluation method, the Westinghouse DFM calculator, the producibility index of Priest, the axiomatic design methodology. Also a variety of other concurrent engineering methods, and proprietary in-house methods are known to exist in industry. In almost all cases the objective of the currently available methods is to either compress the product transition time, or to minimize the effort and cost associated with the assembly handling process.

A subset of DFM is the methodology of DFQM. But a review of the literature indicates that none of the available techniques explicitly focus on the quality objective. There is therefore a need to develop a new methodology which will close this gap.

1.4. RESEARCH OBJECTIVE

This project addresses the issue of Quality Manufacturability. The focus is on the defects occurring at the assembly stage of manufacturing. The goal of this project is to develop a Macro-Architecture for the identification and analysis of these defects. This Macro-Architecture would enable the user to develop the DFQM-Index for a particular product. The architecture would also inform the user of the drawbacks, both potential and existing, of the product design and the manufacturing process, thereby aiding in choosing the right corrective action to be taken.

1.5. ORGANIZATION OF THE THESIS

The thesis consists of six chapters. The introduction to the problem of Quality manufacture, the problem area to be worked upon and the objective of the research is summarized in chapter one. Chapter two gives a review of some of the articles pertaining to Total Quality Management, Design Integrated Manufacturing techniques like Design for Manufacture and Design for Assembly which were researched in order to understand the present state of knowledge in this field. Chapter three gives an introduction to the general methodology for the development of the macro-architecture, the identification of the factors and the related assembly defects and the QM-Index relationship function. Chapter four deals with the development of the analysis loops both macro and micro and provides the rationale behind the analysis of the functional relationships for the defect groups. Chapter five is an application of chapter four to an example model. The misalignment defects are analyzed the full extent and the probability functions are developed. The last chapter, chapter six contains a brief gist of the entire research and the results and conclusions. It also mentions the scope of DFQM in the future.

CHAPTER TWO

LITERATURE REVIEW

The quality of a product undergoes a change at each value adding process in its manufacturing cycle. The quality may increase or decrease depending on the outcome of the process. Traditional approaches to improving the quality of the product have always been focussed on either monitoring the process itself or inspecting the output of the process. Deming (1988) complains that manufacturers are too dependent on "inspection" as the road to quality, rather than problem solving methods which prevent low quality from occurring in the first place. In response to a call for quality prevention approaches several new methods have been reported in the literature.

Several studies have introduced the new concept of "Quality by Design" (Clausing and Simpson 1990, Deming 1988, Phadke, 1990). In this concept the emphasis is on "prevention"' rather than problem solving. Others have developed Cause and Effect diagrams and Quality Flowcharts as an approach for identifying where the quality problems originate (Ishikawa 1943, Burr 1990). It is evident that quality should be built into the product and 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 (Huthwaite 1988, Yost, 1987). The challenge of incorporating quality into the design has been clearly addressed by Iverson (1990). He outlines the different methods used to define, determine and measure quality. Clearly quality is no longer simply a problem of inspection or process control, and in fact extends to all functions and activities of the organization. Recognition of this has resulted in a new management technique called "Total Quality Management" which has been successfully used and implemented in many big corporations in Japan and the U S.

2.1. TOTAL QUALITY MANAGEMENT

Total Quality Management is a technique which encompasses all boundaries both inside and outside the manufacturing environment. This technique is a prevention-based quality system that is organized and multidisciplined. It involves the interaction of the various departments inside the company. The objective is to deliver quality at every step of the process. This technique brings about an awareness to quality, right down to the grass root level. Every member of the organization has a very important role to play in the successful implementation of this technique. A total commitment to quality is essential. Yost (1990) says "there seems to be a barrier between manufacturing and quality a barrier which rests on a very sound foundation . This barrier has information at its base. If we are ever going to achieve our quest for quality and overcome this barrier, it will be through better management of information, not just through better machines, processes and control." Figure 2 illustrates the barriers as perceived by Yost. Yost says TQM systems must be prevention-based and that quality cannot come out of the shop floor alone and that vendor management is also an important factor in the development of quality, low cost products.

A large number of U.S. companies, including Allen Bradley, General Motors, and Ford have successfully implemented TQM techniques. The importance of TQM as a systems approach tool has given birth to several such approaches in the field of manufacturing. One such all encompassing technique is Design Integrated Manufacturing. This is also called Simultaneous Engineering or Concurrent Engineering.

2.2. DESIGN INTEGRATED MANUFACTURING

In the late 70s and the early 80s, extensive development was made in the area of Manufacture and Assembly. There was a need to develop new techniques in order to remain competitive and profitable. Manufacturers started a systems approach towards product design. This new approach was often called Concurrent Engineering or Simultaneous Engineering. This approach

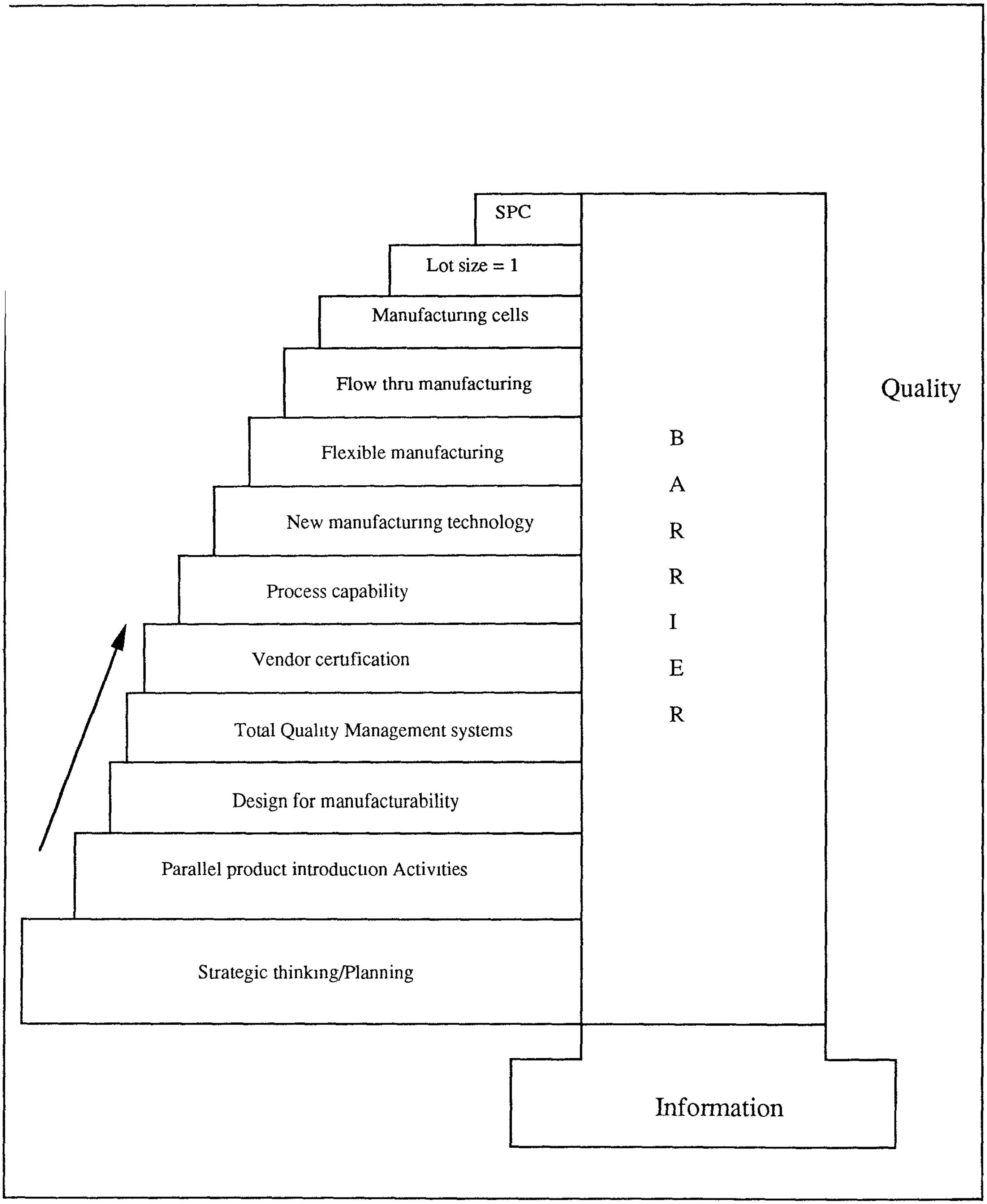

Figure 2. Barrier to Achieving Quality

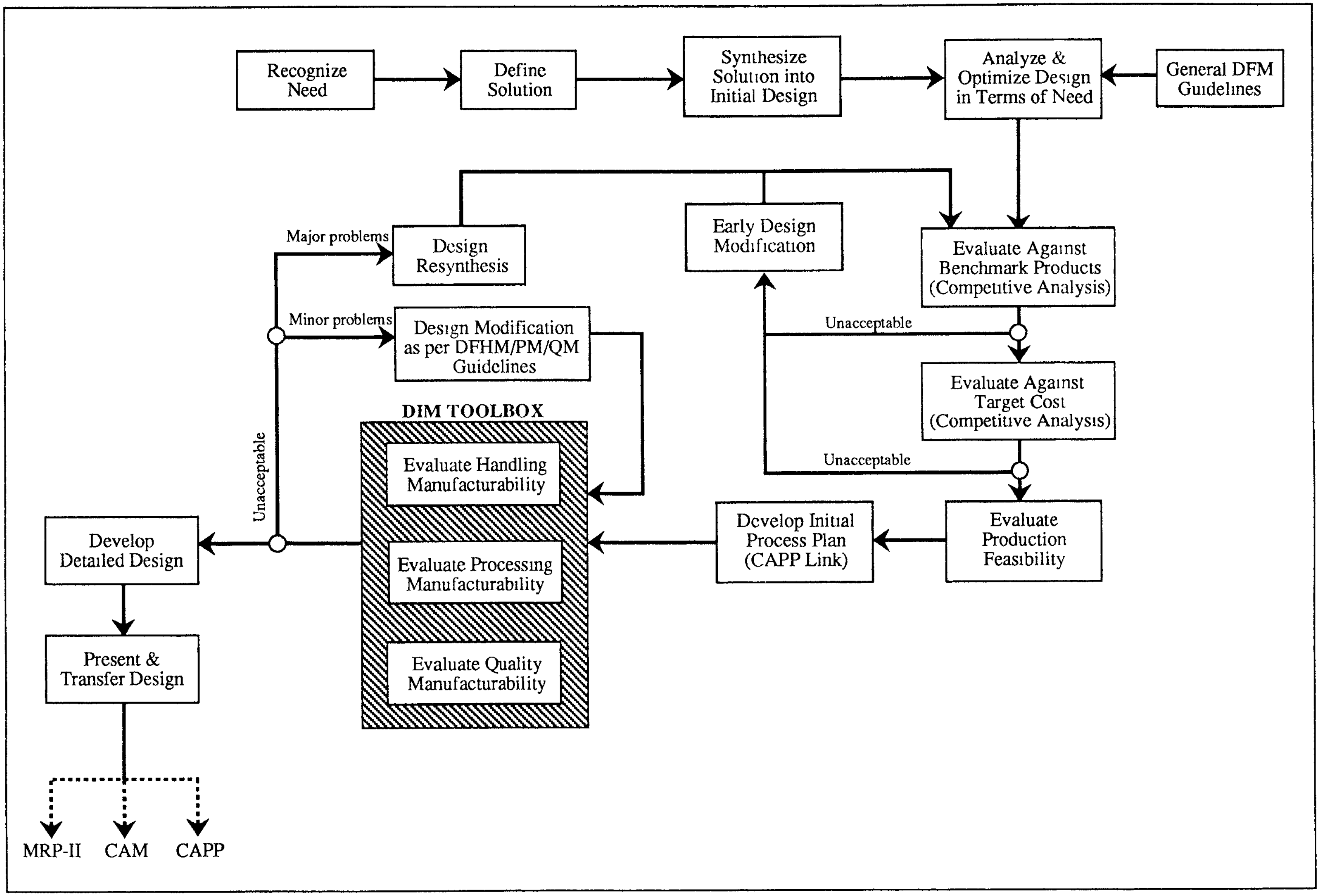

Figure 3. A Concurrent Engineering Approach to Product Design

suggested that all activities which were undertaken in the design of a product be executed in a cooperative fashion, by multi-functional teams. An integration of both product and process information was incorporated into the design process. This approach is shown schematically in figure 3. Among the different techniques of concurrent engineering adapted to product design Design for Manufacturability and Assembly has proved very successful.

2.3. DESIGN FOR MANUFACTURABILITY AND ASSEMBLY (DFMA)

In the early 80's Boothroyd and Dewhurst (1983) developed a methodology for designing products for easier manufacture and assembly. The approach was to reduce the anomalies of the product in the design stage so that there would be no more problems during manufacture and assembly.The Boothroyd and Dewhurst approach analyzes each part in the assembly from the standpoints of:

a. Necessity of existence as a separate part.
b. Ease of handling , feeding and orienting.
c. Ease of assembly.

The results of these analyses included an estimate of the assembly time and a rating for design efficiency.

A variety of companies including NCR corporation, IBM, Motorola, Ford Motor Company, Texas Instruments, have adopted DFMA principles with remarkable results and benefits. The focus of DFMA is basically on the "handling time and cost" and "assembly time and cost" of the parts of the product. DFMA activities may be summarized as follows:

a. Minimizing the number of parts
b. Minimizing the assembly surfaces
c. Designing for top down assembly
d. Improving assembly access
e. Maximizing part compliance

f. Maximizing part symmetry
g. Optimizing part handling
h. Avoiding separate fasteners
i. Providing parts with integral self locking features
j. Driving towards modular design.

These DFMA techniques though useful in many ways can affect the time involved in the introduction and subsequent manufacture of the products. It has been determined by Ulrich (1991) that the physical integration of smaller parts into bigger parts (which is the basis for DFMA) has a very pronounced effect on the costs associated with the complex tooling, product development and lead time. A trade off between lower unit costs and longer product development time must therefore be made when implementing DFMA techniques.

In addition to the DFMA method of Boothroyd and Dewhurst several in house proprietary methods have also been developed. The more prominent among these are briefly discussed below.

2.3.1. Hitachi's Assemblability Evaluation Method

In 1983 Hitachi's Production Engineering Research Lab (PERL) developed a systematic and quantitative methodology for evaluation of a design for assembly. This approach is very similar to DFMA but is considered proprietary by Hitachi. Later on a license for the methodology was obtained by General Electric . GE then further improved it and converted it into the English language, and then marketed under the trade name DFA-GE. This method has been used by several companies including Hewlett Packard. The DFA-GE approach also emphasizes "assembly simplicity" and "reducing the number of parts" in the assembly.

The primary focus of this approach is on the "cost" involved in the handling and assembly of the parts. Hitachi conducted extensive research in the area of "product assembly" and identified the following different sub-areas to focus on:

a. Availability of the required parts
b. Assemblability of the parts
c. Conformance of the parts
d. Orientation and presentation of the parts
e. Handling of the parts
f. Assembling of the parts
g. Fastening of the parts.

The problems which occur at the assembly stage are not always noticed. Some of the problems might be very obvious and may affect the assemblability of the product and others may affect the quality of the product, but may manifest later on. Product Design has a lot to contribute to these problems which occur at the assembly stage of the product manufacturing cycle. Daetz (1990) in his article on the effect of the product design on product quality and product cost has identified several factors of the design which contribute to defects, these include:

a. Designs with numerous parts may cause part mix-ups, missing parts and more test failures.

b. If some parts are very similar but not identical, the chances of an assembler using the wrong part in a given location are increased.

c. Parts without details to prevent insertion in the wrong orientation may be assembled improperly.

d. Complicated assembly steps and/or tricky joining processes may lead to incorrect, incomplete, unreliable or otherwise faulty assemblies.

e. Designs that require adjustments during or after assembly increase the chance of errors.

f. The designer's failure to consider the condition that parts will be exposed to in the assembly process, ex: temperature, humidity, vibration, static electricity, finger oils and dust, may lead to subtle weaknesses in some units or unit failures during testing.

A set of guidelines provided by Daetz for quality improvement is shown in figure 4.

All of the above problems occurring at the final assembly stage can lead to many different types of quality defects. The technique of DFA-GE cannot solve the problems of assembly completely. But its application will certainly have an effect on the product quality. A much more accurate evaluation must be done to determine the changes in the "quality component" during these phases of production and the application of various technologies.

2.3.2. Variation Simulation Analysis

A new kind of methodology has been developed in-house at the Technology/Quality Division of the Westinghouse Corporation at Pittsburgh. This approach is called the "Variation Simulation Analysis", and it is a simulation technique used to analyze complex assemblies prior to their prototype production. This enables the designer to vary dimensions, tolerances, static and geometric model, fit and function etc., to get the best yield, thereby reducing the odds of quality defects occurring at the assembly stage. This approach has developed a quantifying methodology for the critical dimensions and their effects on the assembly. The simulation thereby helps the designer to measure the variations and correct them well before the actual model can be developed. This analysis is also able to generate data on the capability of the production processes to achieve this desired level of conformance and quality.It also informs the user on the dimensions that are very critical and thereby helps in easing tolerances on not so critical dimensions. This technique however is limited to the dimensional measure of the design.

Design guideline		Result
Minimize number of parts		
- Fewer part & assembly drawings - Less complicated assemblies - Fewer parts to hold to required quality characteristics - Fewer parts to fail	→	Less volume of drawings and instructions to control Lower assembly error rate Higher consistency of part quality Higher reliability
Minimize number of part numbers		
- Fewer variations of like parts	→	Lower assembly error rate
Design for robustness (Taguchi method)		
- Low sensitivity to component variability	→	Higher first-pass yield Less degradation of performance with time
Eliminate adjustments		
- No assembly adjustment errors - Eliminates adjustable components with high failure rates	→	Higher first-pass yield Lower failure rate
Make assembly easy and foolproof		
- Parts cannot be assembled wrong - Obvious when parts are missing - Assembly tooling designed into part - Parts are self securing - No force fitting of parts	→	Lower assembly error rate Lower assembly error rate Lower assembly error rate Lower assembly error rate Less damage to parts, better serviceability
Use repeatable, well understood processes		
- Part quality easy to control - Assembly quality easy to control	→	Higher part yield Higher assembly yield
Choose parts that can survive process operations		
- Less damage to parts - Less degradation of parts	→	Higher yield Higher reliability
Design for efficient and adequate testing		
- Less mistaking good for bad product and vice versa	→	Truer assessment of quality less unnecessary rework
Lay out parts for reliable process completion		
- Less damage to parts during handling and assembly	→	Higher yield higher reliability
Eliminate engineering changes on released products		
- Fewer errors due to changeovers and multiple revisions/versions	→	Lower assembly error rate

Figure 4. Design Guidelines for Quality Improvement

2.4. SUMMARY

A review of the literature related to Design Integrated Manufacturing gives many insights. Total Quality Management has a lot of potential and can benefit the entire manufacturing community if properly implemented and realized. It is a very positive note that an awareness exists in the manufacturing environment to build quality into a product rather than monitor and prevent defects in production. It can also be noticed that a lot of progress has been done in the areas of DFM and DFA. Though each of the techniques are very useful in their own right, they however do not address the issue of "product quality". From the schematic in figure 3 it is obvious that the Quality Manufacturability of the DFM toolbox, a very important issue needs to be developed further.

The closest that has been done to tackle quality manufacturability is the variation simulation analysis developed by Westinghouse Corporation. This also addresses part of the problem. All the quality problems which are due to factors like material defect, process defect etc.,other than dimensional inaccuracies cannot be analyzed by this technique. This brings to light the need for developing a Quality Manufacturability technique that can act integratively with the product and process design within the boundaries of TQM and facilitate the manufacture of quality products at competitive prices.

CHAPTER THREE

DEVELOPMENT OF THE DFQM MACRO-ARCHITECTURE

3. 1. THE GENERAL METHODOLOGY

The DFQM methodology involves, first an analysis of common assembly problems, second the identification of common defects known to occur at the assembly stage, and finally investigating backwards to the beginning of the product manufacturing cycle to investigate the presence of some cause factors responsible for the occurrence of these defects. The cause factors are identified at each and every stage of the product manufacturing cycle. Extensive investigation is done in order to establish the validity of the defects and the associated cause factors. The contribution of each cause factor towards the occurrence of the defects is justified. The separate existence of both the defects and the cause factors is studied. Studies are conducted to group the defects and factors on the basis of some commonality.

A functional relationship is established between the cause and defect in order to provide a basis for understanding the nature and occurrence of these defects. A set of loops both macro and micro are developed for each of the defect classes. The loops are investigated further to justify their existence. A study is made to evaluate the role of the causes in the occurrence of these defects. The dependence of the various defects on the causes is established and graphically represented to understand the probability of occurrence of these defects with respect to the cause factors. These are used in the main task of developing the QM-Index functions and for the quantification of quality.

3. 2. QUALITY AS A PARAMETER

In order to develop the QM-Index quality must be expressed as a measurable parameter. Quality can be expressed as a parameter by understanding the meaning and differences in quality. The simplest way to define quality for this exercise, would be to develop a measure for the defects. Then the quality can be expressed as a measure of the defects. A product with less number of defects can be said to be of better quality than a product with more number of defects. The problem however is not restricted to the number of defects. The nature of defects, the place of occurrence, the frequency of occurrence, the potential effects of the defects etc., must also be considered in order to evaluate a measure of defects. The defects are to be identified and grouped in order to develop defect classes which would make it easier to measure the defects. One way to do this are cause-effect diagrams.

3.2.1. Ishikawa or Cause-effect Diagrams

Ishikawa sums up his philosophy on quality management with the simple statement - "quality begins with education and ends with education". To improve production processes, one must continuously strive to obtain more information about those processes and their output. A very valuable tool for accomplishing this is the cause effect diagram. This was first developed in 1943 by Kaoru Ishikawa at the University of Tokyo. They have also been called Fishbone and cause-effect diagrams.

The diagram consists of a main spine with the "effect" on one side of the spine. This "effect" would be the quality characteristic to be improved or under consideration. Branches are drawn to the main spine which are the "causes" which bring about the "effect". The "causes" will have sub-branches of "sub causes"' which contribute to the generation of the "cause". These diagrams aid in understanding the actual factors both active and dormant which come into play during the cycle of operations. They help in identifying and establishing the factors to be developed or improved upon in order to achieve the desired objective. These diagrams have been used for analyzing process dispersion, brainstorming, problem solving , etc., for many years. Figure 5 is a pictorial representation of an Ishikawa diagram.

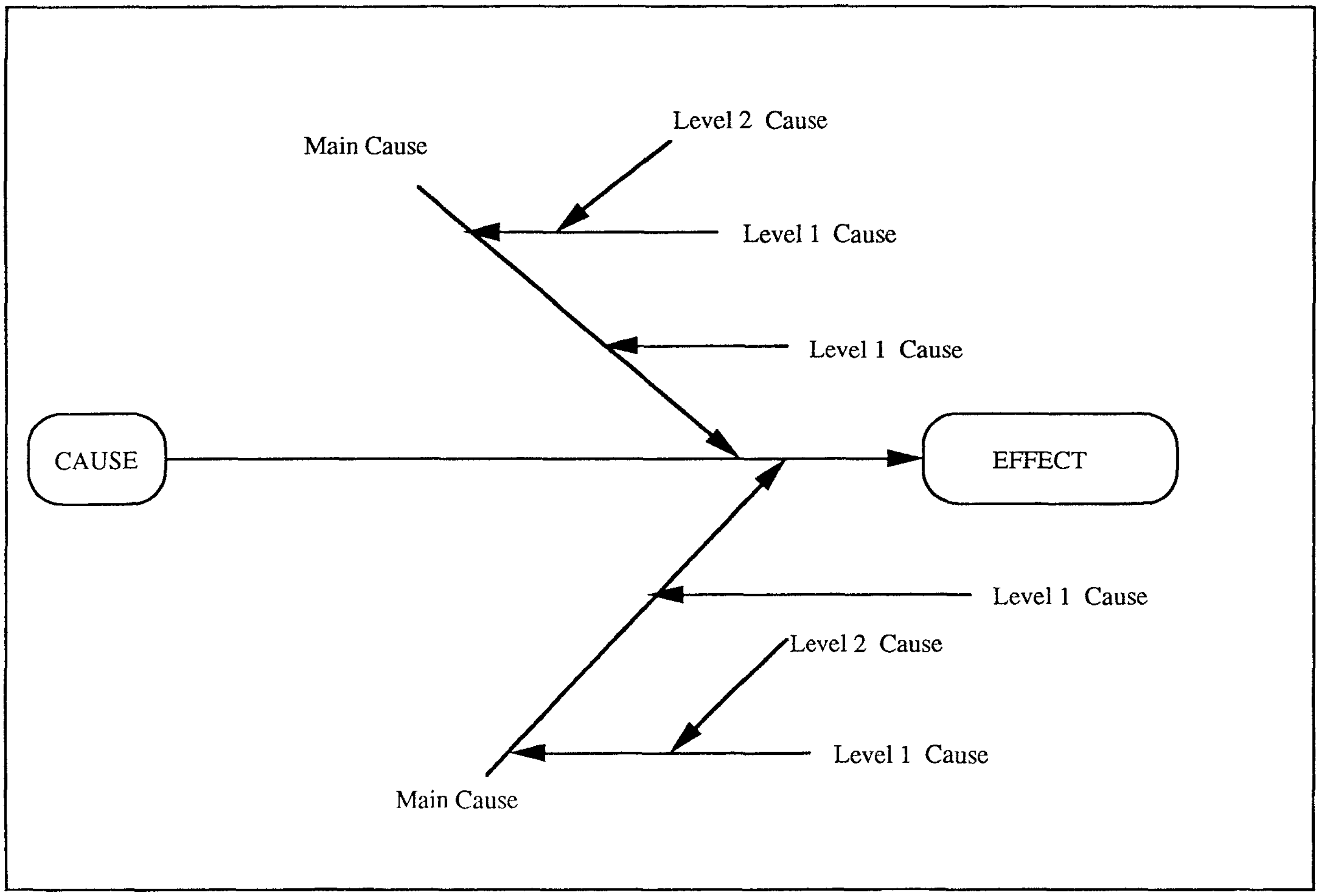

Figure 5. Ishikawa Diagrams Relating Cause to Effect

3. 3. IDENTIFICATION OF ASSEMBLY DEFECTS

Several types of defects can be caused during the process of manufacturing. This thesis is concerned only with the defects occurring at the assembly stage of manufacturing. These defects identified may not necessarily be caused due to the process of assembly. The roots of the defects may be traceable to many previous manufacturing operations. The fundamental idea is to detect defects at the assembly stage, where all the different parts both manufactured and bought from other sources, are brought together to be assembled to form a finished product. The defects at the assembly stage are most important as the variations of manufacturing and design etc., which would otherwise be ignored, gain significant importance and have a diverging effect on the defects which could have a detrimental effect on the quality of the product.

In the first part of this research we studied many different products and productions process to create a synthesized list of defects. Starting with a raw list of defects we aggregated the defects into five classes. Each of these classes is presented and discussed next.

3.3.1. Missing or Misplaced Parts

This class of defects is due to the absence, or interchange of a part which was intended to be otherwise present. This is one of the most common defects occurring in assembly. The occurrence of this defect is influenced by more than one factor. These are the most common defects when fasteners, parts, locking mechanisms, lining material, gaskets, spacers etc. are found to be missing in the assembly. The mispositioning of the part is also included in this class of defects. Often times a part is missed or misplaced during assembly which is never detected immediately. Until and unless the effect of the error is tangible or instantaneous, the defect is overlooked. This however is going to affect the quality of the product at a later stage. These defects need not occur necessarily due to assembly operator error. This can also be a secondary defect. Figure 6 illustrates this class of defects.

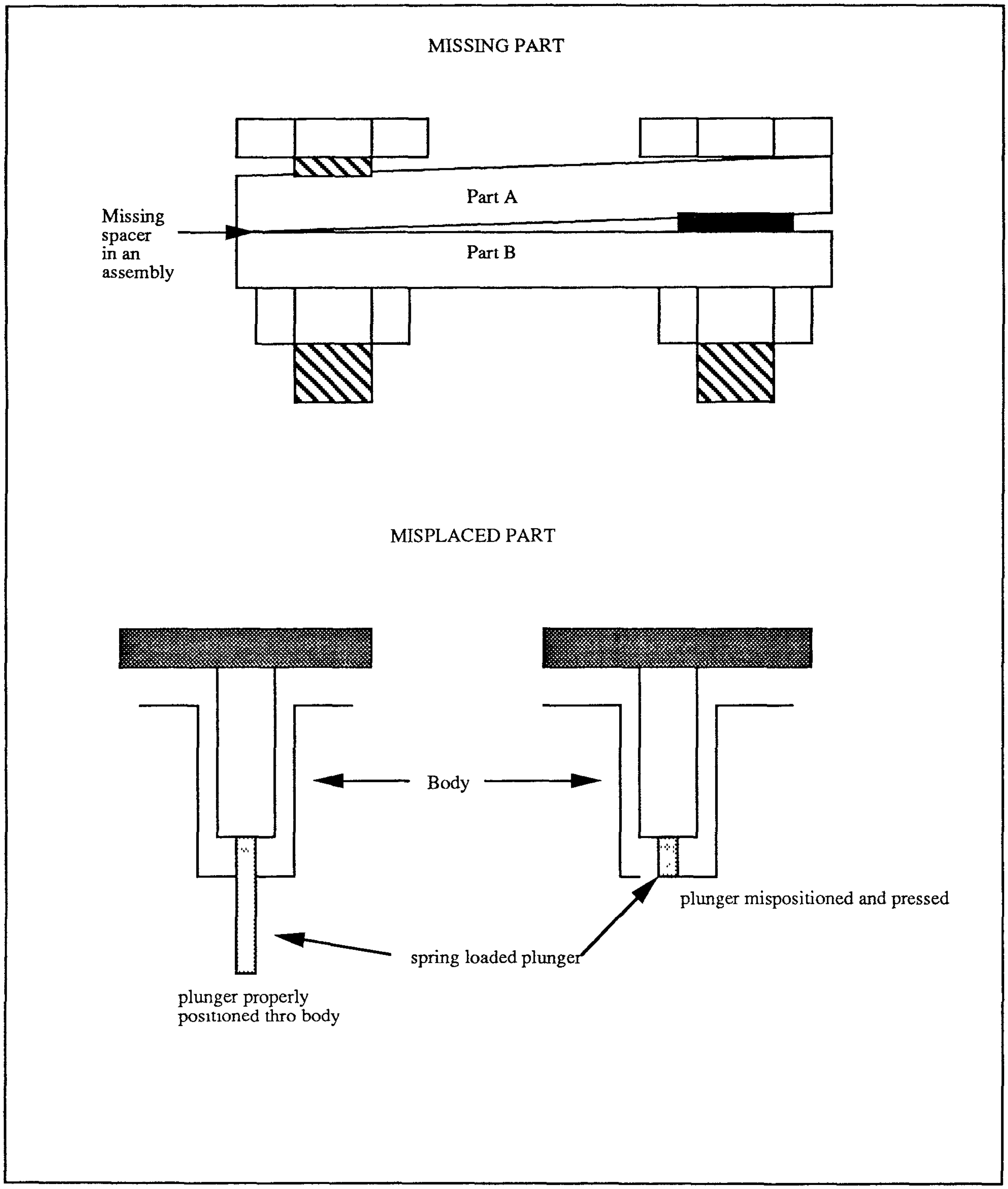

Figure 6. Specific Types of Missing and Misplaced Parts

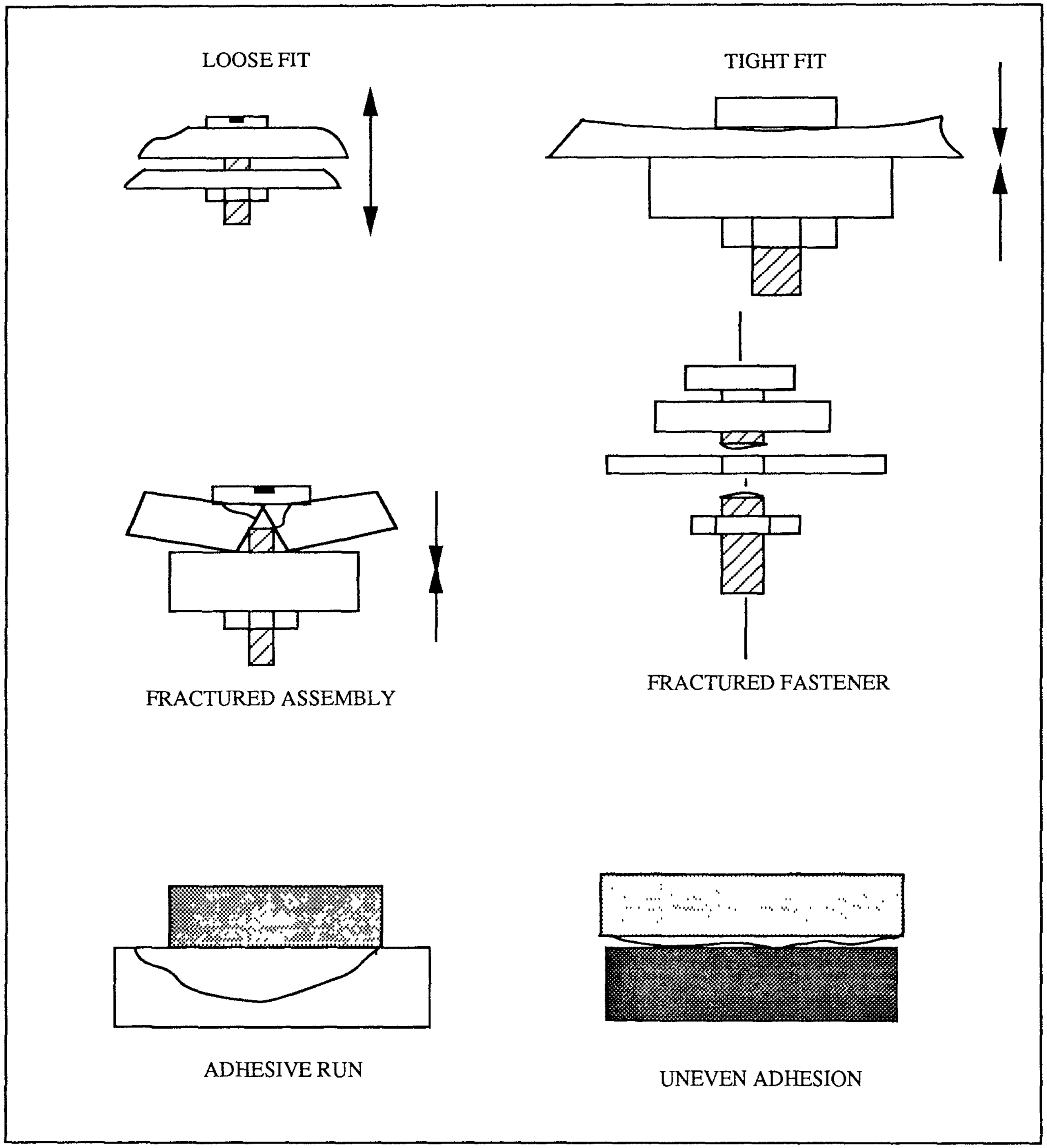

Figure 7. Specific Types of Fastener Related Defects

3.3.2. Fastener Related Defects

This class of defects are dependent on the nature of the fastening system used. These are to a large extent generally dependent on the characteristics, features and type of the fastener used in the assembly. The defects due to fasteners are sometimes easily recognizable. These defects produced can have a large influence on the occurrence of other secondary defects. These defects are identifiable as classes depending on the fastener used. Examples of the defect classes for some of the fasteners are described below and illustrated in figure 7.

A. Threaded Fasteners and Rivets - The most common defects occurring when threaded fasteners and rivets are used are:

- Loose fastening leading to vibration of assembled parts or missing parts.
- Overtight fastening leading to buckling and other deformities of the assembly.
- Failure of the fastener itself.
- Fracture of the assembly due to uneven load distribution.

B. Liquid fasteners and adhesives - The defects occurring as a result of the use of liquid fastener or adhesive are:

- Adhesive run
- Uneven adhesion

3.3.3 Misalignment Between Mating Parts

Misalignment is defined as the defect found due to two related mating parts not in alignment with each other, either functionally or aesthetically as intended in the design. It can also be defined as the defect due to the presence of uneven clearances between parts, not found in the design. Clearances which cannot be classified into the misalignment defects are categorized under the other types of defects. Misalignment is very often the most easily noticeable external defect, but it can also be an internal defect. Four general types of misalignments were identified. An illustration of these types is provided in figure 8, and a brief description follows:

A. *Axial misalignment* - This is a misalignment in the horizontal plane, when the vertical axes of the mating parts are parallel to each other.
B. *Radial misalignment* - This is the rotation which results in a misalignment in a plane perpendicular to the axis of the two mating parts.
C. *Linear misalignment* - This is a misalignment in the common horizontal axial direction of the two mating parts.
D. *Angular misalignment* - This misalignment occurs when the angle between any one axis of any one part is not at the desired angle to the corresponding axis of the second part.

The misalignments are identified with a particular reference axis which is the direction in which the parts are mated together or assembled. It should be noted than the misalignments may be identified differently if a different reference axis is chosen.

3.3.4. Part Interference Defects

Interference is caused between two parts due to the unprecedented or unexpected physical contact between two moving parts. This can occur due to several factors at different stages of the product manufacturing cycle. The interferences may be absorbed by the parts due to the nature of the material or may be magnified, thus causing several secondary defects to occur as a result of the interference defect. This kind of unprecedented contact can be classified based on the frequency of occurrence as follows:

A. *Constant Interference* - This interference is one which is observed during the entire cycle time of the movement of the assembly.

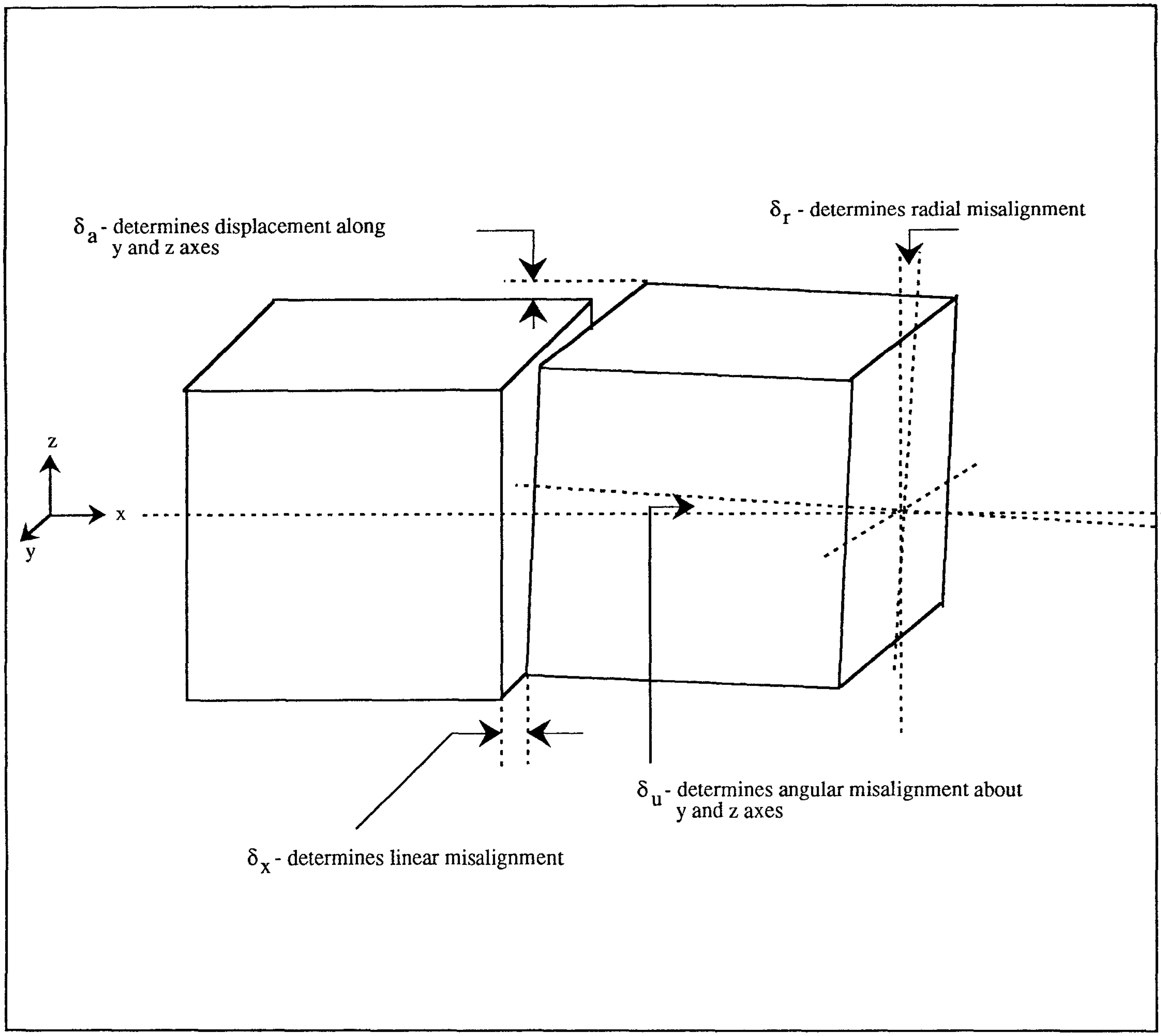

Figure 8. Specific Types of Misalignment Defects

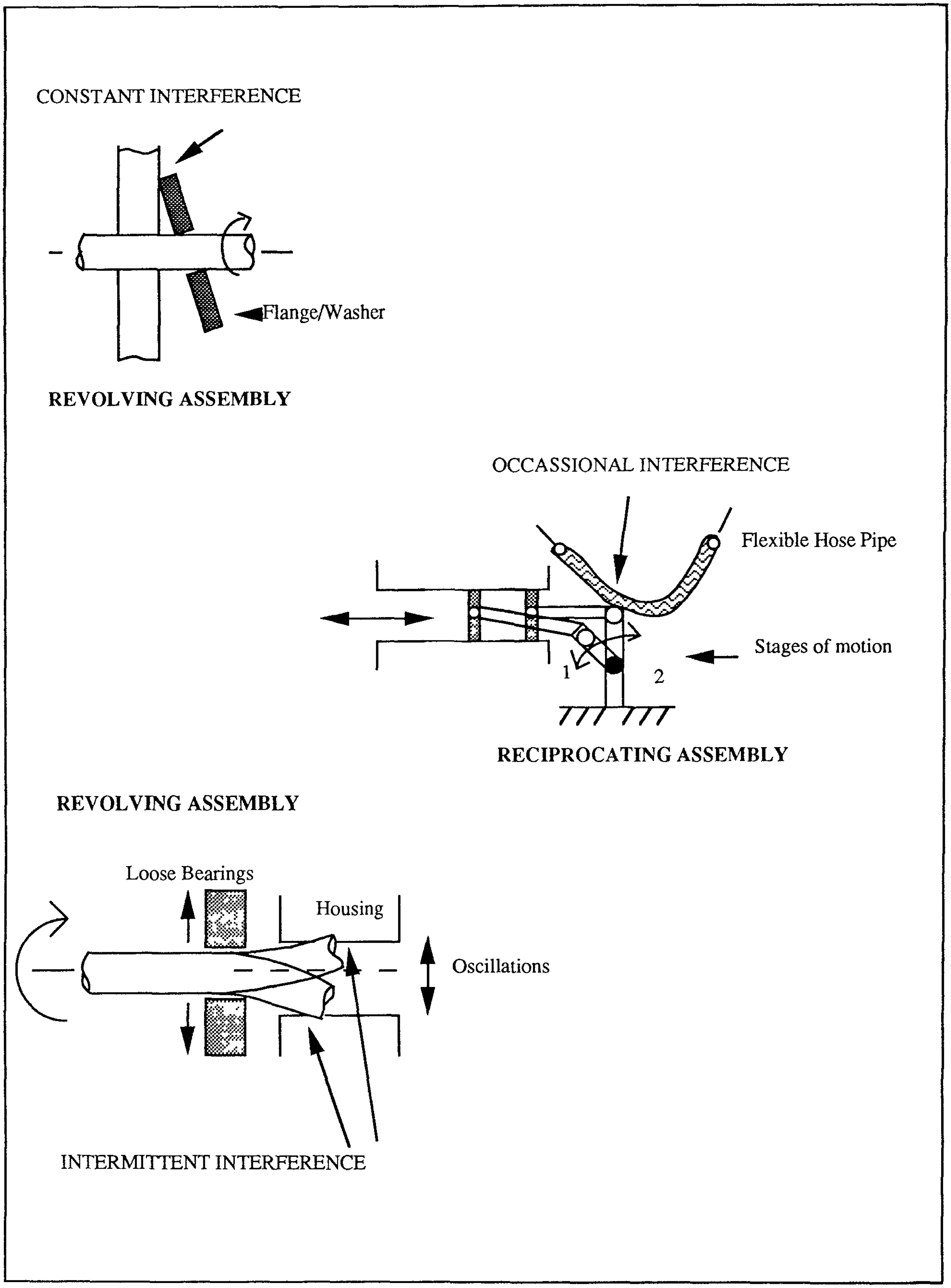

Figure 9. Specific Types of Interference Defects

B. *Occasional or Random Interference* - This interference is observed in the assembly at varied points in time not following any particular pattern.
C. *Intermittent or Periodic or Cyclic Interference* - This is observed in the assembled product at specific intervals of time, each observation related to the previous by the duration of occurrence.

Each of these types of interferences is illustrated in figure 9.

3.3.5. Total Nonconformity

The total nonconformity is a defect occurring due to the influence of another factor first. The effect of the first factor causes a misalignment, deformity, or fracture of the part which then leads to this type of defect. This defect shown in figure 10 is such that it cannot be classified as belonging to any of the above category of defects. Total nonconformity is when two parts totally different in finish or size or composition, cannot be assembled together at all. The total nonconformity between related components can be classified as follows:

A. *Surface Nonconformity* - This is the nonconformity of the surfaces of the two related components. This can be in the texture, grain, finish, shape etc. , of the two surfaces in contact.
B. *Dimensional Nonconformity* - This nonconformity occurs due to the discrepancy between the dimensions of the two related components to be mated. The dimensions are such that they do not produce misalignments, but they still don't conform to the needs of the assembly.
C. *Design Nonconformity* - This nonconformity occurs either due to a flaw in the basic design or in the processing of the components. This is observed when the components don't conform to the design and is noticed only in the assembly stage of the product manufacturing cycle.

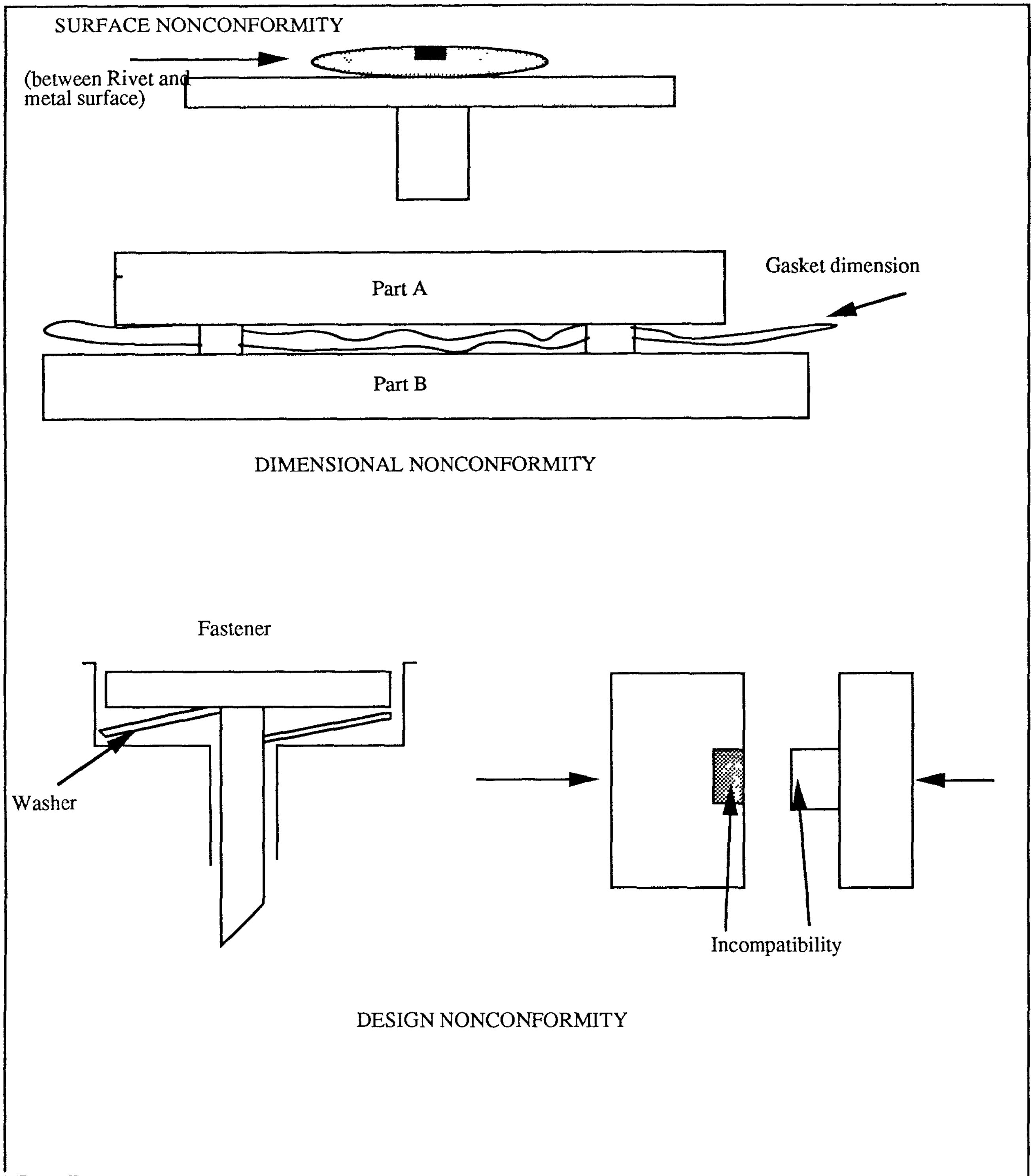

Figure 10. Specific Types of Nonconformities

The defects in an assembly can be primary defects, or secondary defects brought about by the influence of primary defects. This can be termed relative occurrence. The concept of relative occurrence can be defined as the influence one defect has over the occurrence of another related or unrelated defect. Very often in an assembly, the role played by each and every feature of a part increases in importance as the quality of the product increases. Any small variation in one feature of a part can bring about a change in one or more features of the adjoining or related part. As all the parts in an assembly are very closely related to each other, a defect in one part can get magnified and it can have a diverging effect thus increasing the defects occurring in the assembly. A primary defect like loose fastening can cause the secondary defect or missing or misplaced part. A primary defect like uneven adhesion can lead to misalignments and nonconformity when several closely finished parts are assembled together.

3. 4. IDENTIFICATION OF CAUSE FACTORS

The several types and classes of defects found to occur in manufacturing and assembly of a product are very often traceable as originating in the different stages of manufacturing. The origin can be in the previous operation or in the very operation the product is currently being subjected to. Depending on the seriousness and nature of the defect, more than one cause for the defect can be traced. This involves understanding of the various manufacturing techniques involved in the process of production. This study focuses mainly on the defects occurring at the assembly stage. The defects as identified earlier can be due to the influence of one or more "Cause factors" in any of the different operations in the manufacturing.

In this research we analyzed each of the previously identified defect classes in detail. From this analysis we were able to synthesize seven general classes of "cause factors". Each of these cause factors is discussed in detail next.

3.4.1. Geometrical Features

Geometrical features are those standard and nonstandard geometrical shapes, both internal and external, which are found in each and every part that goes into an assembly. The geometrical features like edges, corners, surfaces etc., play a very important role in the assembly of the parts. The position of the 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 the assembly. This also includes the standard features like holes, grooves, slots, keyways and other nonstandard features like curves, of the parts. The variables of the geometrical features are also identified to better explain the direct role played by the features in the occurrence of assembly defects.

3.4.2. Assembly Interrelationships

A relationship exists between each and every part that goes into an assembly. The relationship can be in the form of a functional relationship, a positional relationship or a fitting relationship. Functional relationship deals with the function of one part with respect to the other, positional relationship deals with the physical orientation of one part with respect to another and the fitting relationship deals with the nature of fit of one part to another. The relationship features among other things the boundary characteristics of two parts (a part inside a second part is bounded by the second part). This factor group also deals with the needs of the assembly of the parts like orientation of the different axes, holes etc. ,the contact relationship between every pair of components in the assembly and also include the nature of the assembly and fit like Interference fit or Conformance fit. This would also include the number and design of the parts to be oriented for assembly of the product. This group is further broken down to identify the variables which are directly responsible for causing the various defects identified earlier.

3.4.3. Material Interrelationships

An assembly consists of several parts. These parts can be made of different materials. The use of parts of more than one base material gives rise to this factor. This includes the physical properties like shear strength, tensile and compressive strength, density, hardness, malleability, ductility etc. , of the material, chemical properties like resistance to corrosion, conductivity etc. , and other material properties inherent of the material of the part. This would also include the interference, interaction and interfacing characteristics like friction, resistance to wear, lubrication needs, cooling needs, etc which are due to the properties of the material. These properties are further pronounced when two different materials incorporated in an assembly are subjected to various environmental factors. The variables actually responsible for the defects are also investigated.

3.4.4. Assembly Procedure

This deals with the various factors like the setup for the assembly (Jigs, fixtures, clamps), type of assembly method employed(manual, automatic, robotic), the type of parts presentation systems (pallets, vibratory feeders), the type of parts disposal systems (gravity chutes, bins), the orientation needs of the subsystems (not parts) used for the manufacture. This also deals with the different sequences (physical order of assembly) available for assembly of the product and the cycle times. This factor also deals with the different monitoring needs of the process and the different types of material handling devices used for the parts presentation and disposal. A very important variable in this category is the location of the center of gravity of the part. This may seem like a variable which would be grouped under geometrical features, but the location of the center of gravity has a direct bearing on the design of the assembly procedure. The design of the jigs and fixturing devices are dependent on the mass and center of gravity of the part during the different motions of the assembly process.

3.4.5. Fastening System Employed

This group is one of the most important factor groups in the assembly process. Any assembly invariably has more than one fastening system employed for the assembly of the product. The subassemblies that go into the final assembly themselves will be fastened using a fastening system. As the number of parts in the assembly increases, the role played by the fastening system becomes more and more important. Fastening systems differ from product to product depending on several factors like material, finish, nature of assembly etc. When a particular system of fastener is employed in an assembly, several associated properties are brought into effect. The quality of the product depends on the fasteners used. Some of the fastener systems considered are threaded fasteners and rivets, liquid fasteners like adhesives and glue, pressure fasteners like press fit, snap fit and force fit systems, hard fastening systems like welding (plastic and metal), soldering etc. ,The various characteristics associated with these different systems are studied to identify the variables actually responsible for the various assembly defects.

3.4.6. Process by Which Part is Manufactured

As an assembly consists of more than one part of more than one material, the process for manufacturing each of these parts varies according to individual needs. Each manufacturing process has certain properties associated with it. When different parts are manufactured at different locations, the quality of these parts is dependent on the source of manufacture. When these different parts are assembled together, any defect that is involved with a very intrinsic property of the part will be traced to the source of manufacture. This warrants the inclusion of this factor. This factor includes the characteristics both internal and external, associated with the actual manufacture of the components of the assembly. These characteristics would depend on the various manufacturing processes like welding, forging, forming, extruding, injection molding, stamping, casting, milling, turning, boring, electrical discharge machining etc. which are employed in the manufacture of the parts of varying material properties. This would also include the various quality management programs employed by the different manufacturers in the production of the subassemblies.

3.4.7. Tolerance Interrelationships

Due to the nature of the assembly, any two parts which are to form an assembled part together, will have a specific tolerance relationship between them which determines the type of fit, the positional and functional relationship between the two parts. Any deviation of the tolerances out of the specified range would mean that the part is unfit for use. It is also possible that there is a mismatch between the two parts which are at different points in their tolerance range which leads to different assembly defects. So the tolerance relationship between two parts related to each other in an assembly must be carefully evaluated, matched and designed in order to prevent problems like part mismatch and tolerance stackup. As the number of parts increases in the assembly this factor becomes more important. This factor includes the interrelationship between the tolerances (both internal and external) of the various components of the assembly. The various variables associated with this factor are identified in order to better understand the implications of this factor.

3. 5. DERIVING THE QM-INDEX RELATIONSHIP FUNCTION

The QM-Index relationship function is a function which helps in evaluating the Design for Quality Manufacturability of a particular product. This is done after an initial analysis of the defects and the cause factors. A schematic for the calculation of this index is shown in figure 11. The following notation is used to define the QM-Index function:

- i,j counter identifying the 'i'th factor variable belonging to the 'j'th factor class
- n,m counter identifying the 'n'th specific defect belonging to the 'm'th defect class

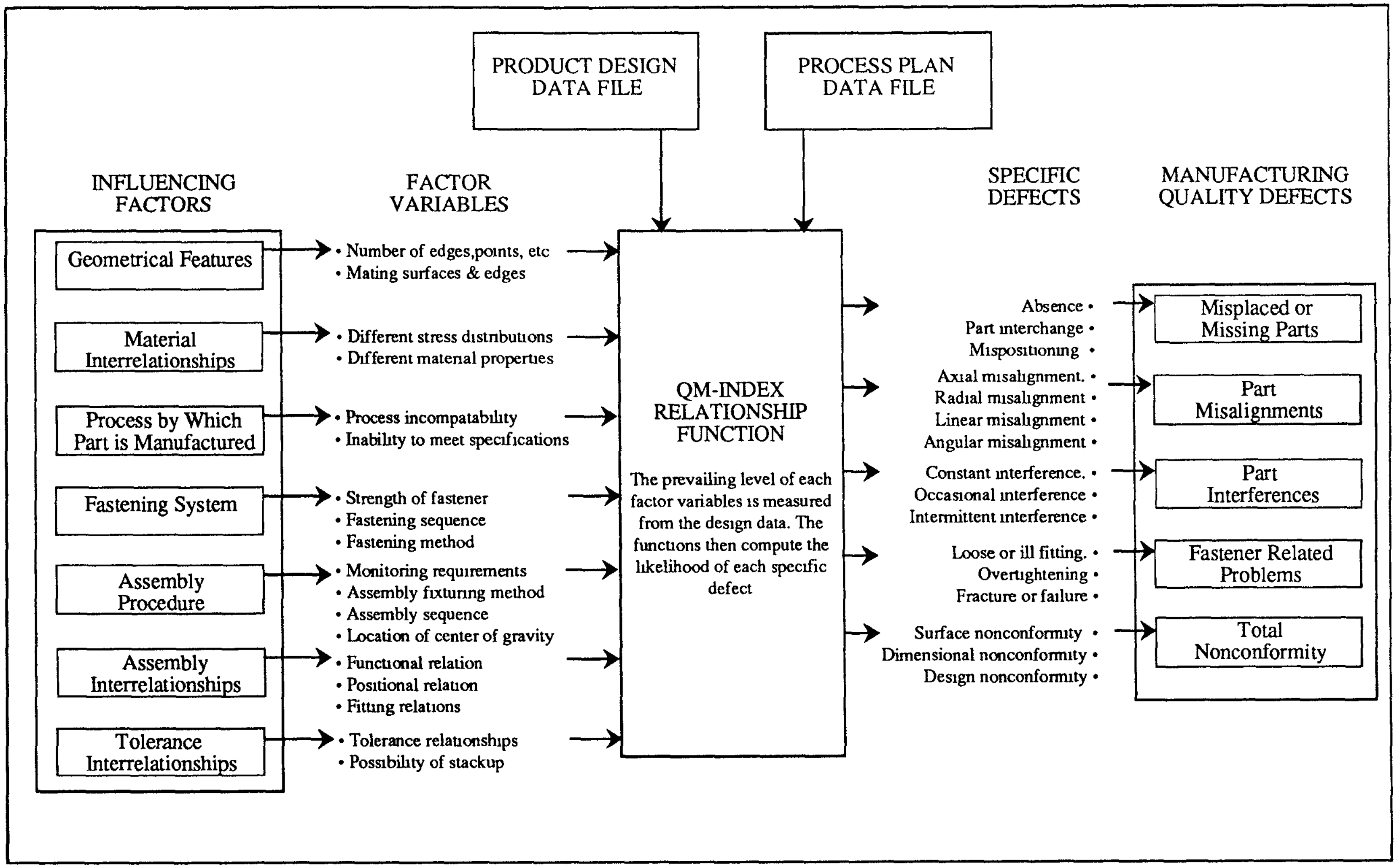

Figure 11. Initial Schematic for Estimating the Quality Manufacturability of a Design

$X_{i,j}$ current state or measure of a factor variable

w_i the perceived importance of factor 'i'

Let, $\Phi_i^{n,m}$ [$X_{i,j}$ | for all $j \in i$] represent a function for deriving the likelihood defect n,m will occur in a standard facility, due to the current level of all variables belonging to factor 'i'. Then the QM measure for a specific defect class would be:

$$QM_m = \Psi^m \left[\Phi_i^{n,m} \left[\ldots \right], w_i \;\middle|\; \text{for all 'i', and } n \in m \right]$$

The function Ψ^m would be the QM relationship function for a defect class. The QM-Index for the design would then be computed as:

$$\text{QM-Index} = \sum_{m \in M} QM_m$$

Ψ^m would be designed such that the QM-Index is defined on a logarithmic scale in the 0 to 10 range. If we assume that 5% is a global upper bound on acceptable defect rates, then a QM-Index of 1 would indicate at most one product in twenty is defective, while a score 10 would indicate at most one product in a million is defective. Scores below 1 would correspond to defect rates greater than 5%. The QM-Index will be representative of both the likelihood of defects and the effort expended in avoiding them. This can be used a comparative study in evaluating the Quality Manufacturability of a product.

CHAPTER FOUR

DEVELOPMENT OF FUNCTIONAL RELATIONSHIPS FOR QUALITY DEFECT ANALYSIS

4. 1. INTRODUCTION

The different defects identified in chapter three need to be properly analyzed before a relationship can be built with the cause factors. The analysis is carried out by developing a broad based macro loop. This loop is explanatory of the process by which these defects originate, and hence pave the way for quantifying the probability of their occurrence. The loops are analyzed to justify the presence of each element in the loop.

Care is taken to analyze the effect of more than one factor to the occurrence of the defects. When more than one factor contributes to the occurrence of the defect, the factors are investigated to identify a dominant factor. The dominant factor being the one that has a more prominent role in the occurrence of the defect. Once the macro loops are developed, the loop is exploded in order to arrive at the micro loop. This loop consists of the different factors and the stages at which these variations can be measured. This helps in the development of the functional relationships between the different factors and the defects associated with them.

4.1.1. Development of Macro Analysis Loop

The macro analysis loop consists of very few blocks. The blocks are related to one another by a series of steps and relations. The blocks are such that there is a sequential progress from the first block to the last. At the end of the macro analysis loop will be a simple relationship linking the major (dominant) blocks of the macro loop. The relationship gives an indication of the behavior of the different cause factors over the occurrence of the particular defect. The macro loop also gives a bird's eye view of the progress of the relationships between the factors and the defects. One macro analysis loop is developed for each defect class. This macro loop can be used as a rough estimating tool for the occurrence of the particular defect class. A graphical representation of the behavior of the various factors which affect the occurrence of the defect is also given. This loop is later on exploded to form the micro loop. The macro loops developed for each of the defect class is explained to further emphasize the importance of the analysis.

4. 1.2. Development of the Micro Relationship Loop

The micro relationship loop is the detailed, exploded form of the macro analysis loop. This involves the analysis of each block of the macro loop on a very detailed level. The various interactions between the different factor groups and factor variables is brought about in this loop. This justifies the presence or absence of particular factors and factor variables in the macro loop. The micro relationship loop serves as a set of guidelines which aid in understanding the macro loop. The micro loop also justifies the presence of the macro loop. It serves as a reference table for the identification of the the sources of the defect. The initial investigations towards quantification are done on the basis of the micro relationship loop. This also gives the user a chance to add and delete blocks as and when the situation demands. The micro relationship loop serves as a strong tool in the application of these techniques to actual models.

4.2. DEVELOPMENT OF THE DEFECT LOOPS

4.2.1. Fastener Related Defects

The macro loop for the estimation of the occurrence of fastener related problems is given in figure 12. The loop consists of three blocks and a computation. In the case of fastener related problems the problem of identification of the dominant factor is not there. The macro loop starts with

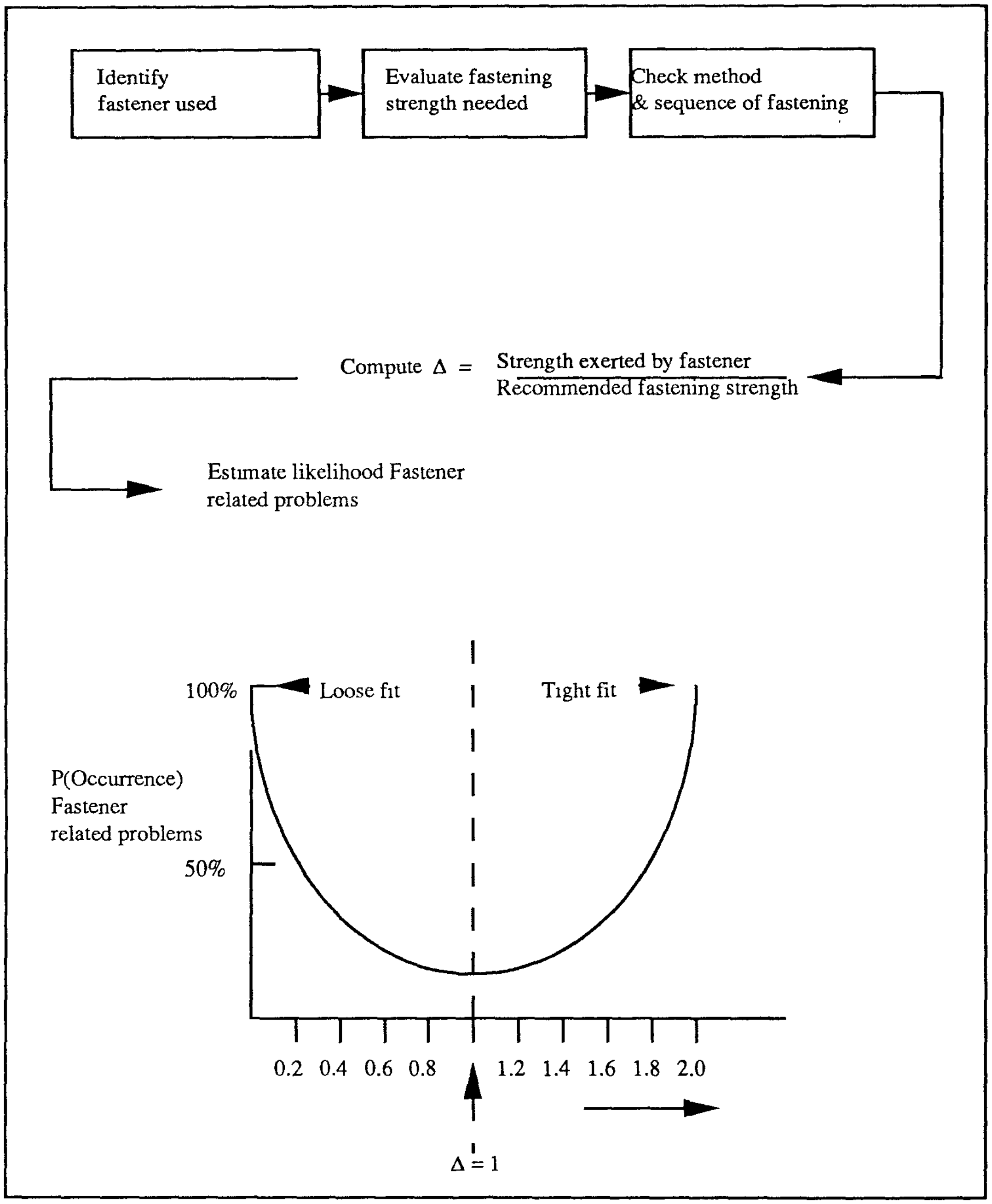

Figure 12. Macro Loop for Estimating Occurrence of Fastener Related Problems

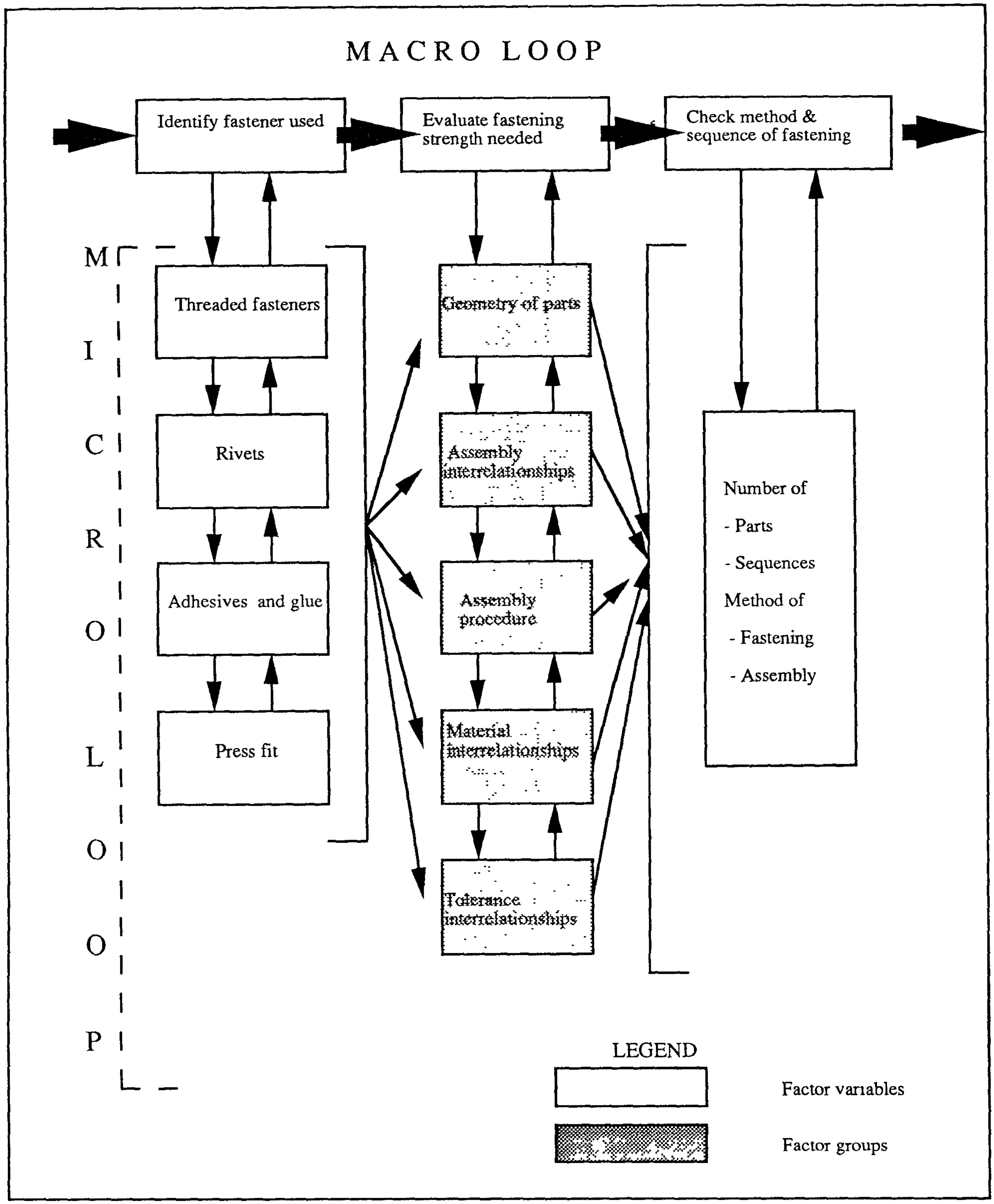

Figure 13. Micro Loop for Estimating Occurrence of Fastener Related Problems

the first block which is the block whose function is to identify the type of fastener used. The second block deals with a slightly more complex function of evaluating the fastening strength needed for the assembly. This is a function of several factors which will be explained in the micro loop. The third block deals with the identification and analysis of the different methods and sequences employed for the fastening of the different parts of the assembly. The three blocks determine two basic values. These are then used to compute a simple ratio which works as an estimator for the occurrence of the fastener related defects.

The micro loop for the fastener related defects shown in figure 13. The three blocks in this loop are identified and described next.

A. *Identification of the fastener used* - This is split up into the four types of commonly used fasteners. They are threaded fasteners, rivets, adhesives and glue and pressure fit systems. This gives an indication of the nature of the defect that can be expected. Certain types of defect can be ruled out depending on the type of fastener used. Eg. Fastener fracture when liquid adhesives are used, Adhesive run when threaded fasteners are used.

B. *Evaluation of fastening strength* - The fastening strength needed to assembly a set of parts is dependent on several things. Some of the more prominent ones among them are geometry of parts, assembly interrelationships, assembly procedure, material relationships and tolerance relationships. The geometry of the parts determines where and when a particular fastener must be used. As the size of the parts reduces the use of threaded fasteners and rivets decreases as the inherent strength of the parts themselves reduces. The assembly interrelationships and procedure determine the nature of fit and thereby influence the selection of fasteners. The materials chosen for the parts determine the type of fastener as some materials cannot be assembled by glues or by fasteners etc. , depending on the strength of the material. The tolerance relationships also determine the use of fasteners as closely fitting parts cannot be stuck with glue and self locking parts must have the right tolerance between them. Thus the fastening strength needed for an assembly depends on one or more of the above variables.

C. *Checking of the method and sequence of fastening* -- The method of fastening can be robotic, automatic, manual with or without power assist tools and the sequence of fastening can be one or more depending on the type of assembly. These influence the occurrence of defects as the torque exerted by automatic or robotic fastening systems is more or less constant compared to a manual fastening setup. Thus the reliability of the strength exerted depends on the method and sequence of fastening.

The micro loop identifies the fastener used, the fastening strength needed and the reliability or constancy of the fastening process to deliver the required fastening strength. The simple computation value Δ deals with measuring the variation of the fastening strength from the required level. This gives an indication of the type of defects that could occur due to a variation of the computed ratio. From the graph of the macro loop, it can be understood that when the value Δ increases, i. e, the strength exerted by the fastener increases when compared to the required strength, the probability of occurrence of overtight fastening increases and vice versa. The ideal ratio would be of $\Delta = 1$, where fastening strength exerted is equal to fastening strength needed.

4.2.2. Total Nonconformity

The macro loop for the estimation of the occurrence of total nonconformities is shown in Figure 14. The loop consists of three blocks and a simple computation. The first block deals with the identification of the types of nonconformities that can occur in the assembly. The second block involves the identification and isolation of the different processes by which the various parts of the assembly are manufactured. The third block deals with the evaluation of the different tolerance needs and relationships of the parts. The three blocks are then utilized to develop a simple ratio which gives the behavior pattern of the defects due to the factors.

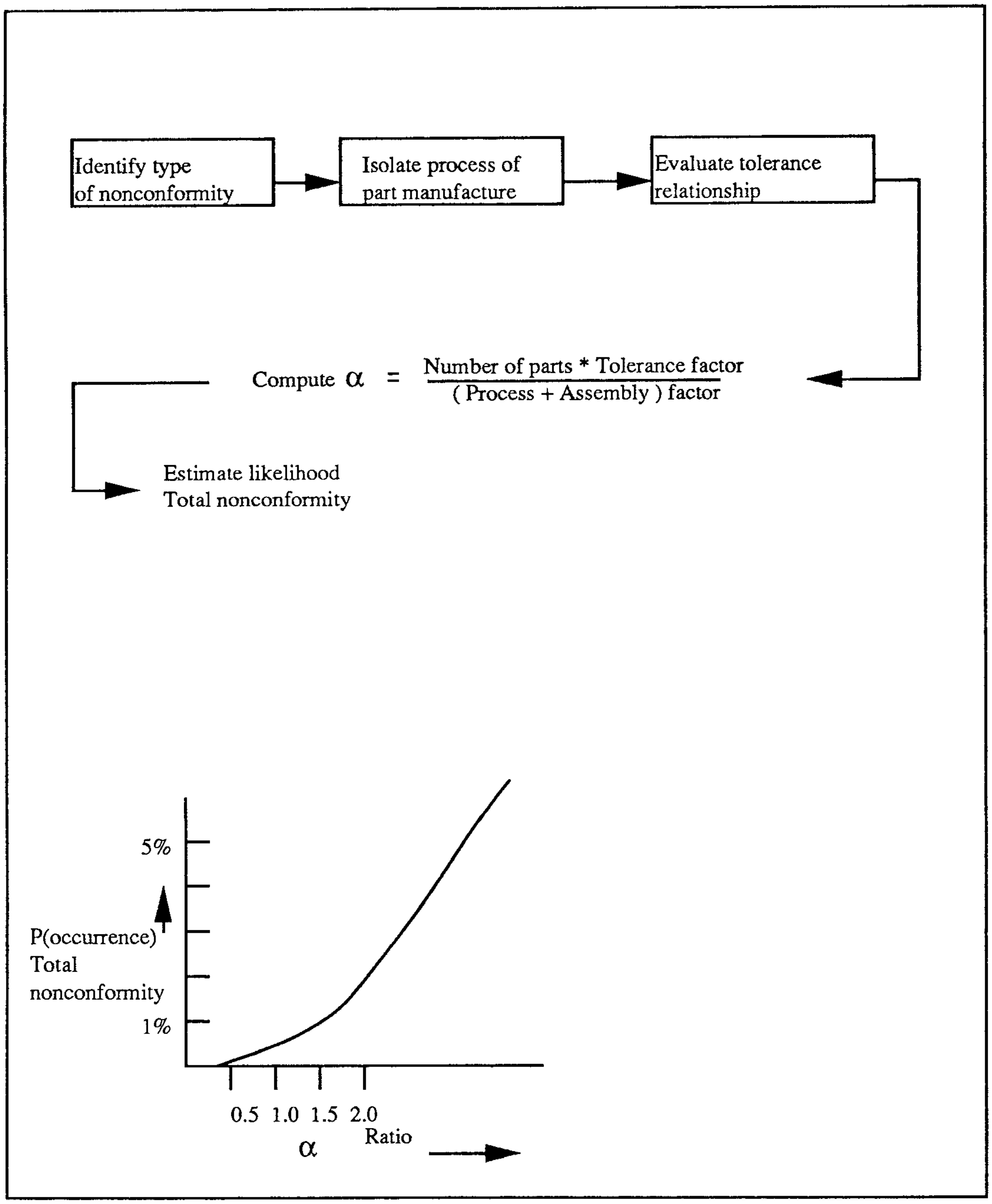

Figure 14. Macro Loop for Estimating Occurrence of Total Nonconformity

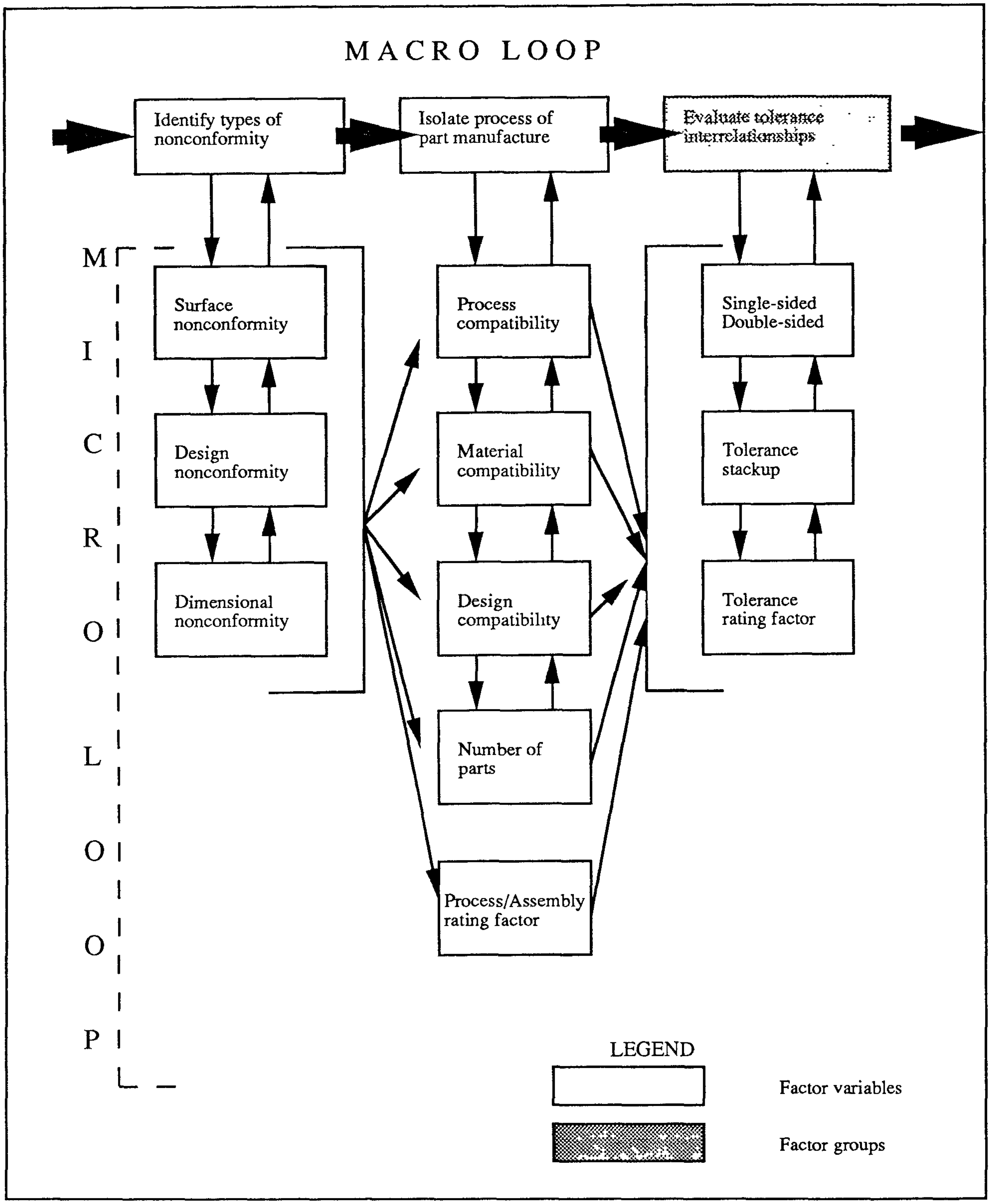

Figure 15. Micro Loop for Estimating Occurrence of Total Nonconformity

The micro loop for the total nonconformity defects shown in Figure 15. The three blocks in this loop are identified and described next.

A. *Identification of the types of nonconformity* - This block consists of the different types of nonconformities that have been identified as design nonconformity where correlation between the designs of the two mating parts is nonexistent, surface nonconformity where the surfaces of the parts mating don't conform to each other, dimensional nonconformity where there is a discrepancy in the dimensions of the mating parts. These are brought about by several factors that act on at different stages of the assembly process.

B. *Isolation of the process of manufacture of parts* - This involves the several factors associated with the process of manufacturing. This deals with the factors of process incompatibility, material incompatibility and design incompatibility. These are factors where an error that goes undetected surfaces at the assembly stage which results in one or more types of nonconformities. The occurrence of these defects also is a function of the number of parts that are involved in the assembly. As the number of parts increases, the chances of nonconformities increases as each and every part is more or less manufactured by a different process. The incompatibility in materials may not come into effect till the assembly process is started. Several materials cannot survive the handling and environmental factors that the parts are subjected to during assembly. These can lead to several more pronounced secondary defects like misalignments, missing parts etc. The efficiency of the process of manufacture of the parts of the assembly can be developed into a process rating factor for the process and assembly rating factor for the assembly. The use of automation, inspection, advanced techniques , robotics and computers are some of the variables to be considered for the general rating of the process and assembly. This rating is used in the computation of the ratio for estimation of defects.

C. *Evaluation of the tolerance relationships between the parts* - This block deals with the study of the nature of the tolerances employed on the various parts that go into an assembly. They are studied as single-double sided tolerancing, the tolerance stackup relationships etc. These are then used to arrive at a rating of the tolerance on a scale depending on the ease with which that tolerance can be met at the process.

Thus the micro loop identifies the type of nonconformity, the process and assembly rating and finally the tolerance rating. The closer the tolerances to be held, the higher the tolerance rating factor. As the tolerance becomes tighter and the process and assembly efficiency rating reduces, the occurrence of the defects increases. This is brought about in the computation of a and the graphical representation shown in the macro loop.

4.2.3. Interference Defects

The macro loop for the estimation of interferences shown in figure 16, and consists of three blocks, a computation and one more block after that. The first block deals with the identification of the different parts subjected to interference. The second block deals with the task of identification and isolation of the different internal and external factors which contribute to the occurrence of interference defects. The various factors that contribute are explained in detail in the micro loop. The third block deals with the evaluation of the frequency of occurrence of the defect so as to enable categorization of the defect. These are used then to calculate a ratio to identify the nature of interference. The fourth block deals with the task of relating the external and internal factors to the frequency of occurrence to evolve a match for the factor and frequency.

The micro loop for the interference defects shown in figure 17. The three blocks in this loop are identified and described next.

A. *Identification of the parts subjected to interferences* - This is split up into four factor groups namely geometrical features, material interrelationships, assembly interrelationships and tolerance relationships. The parts that are subjected to interference depends on the factors mentioned above. The geometrical features are indicative of the weak and strong areas of the

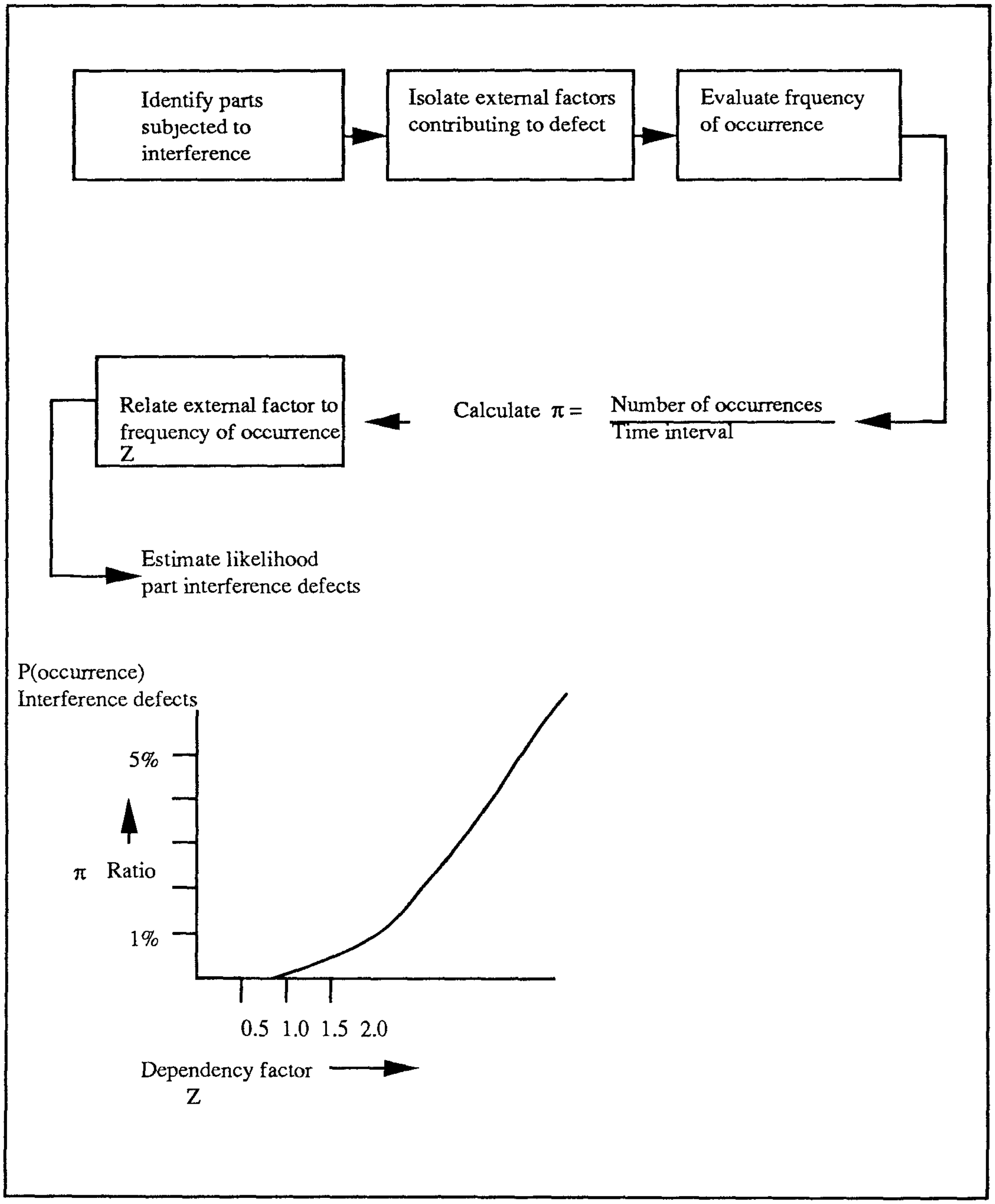

Figure 16. Macro Loop for Estimating Occurrence of Interference Defects

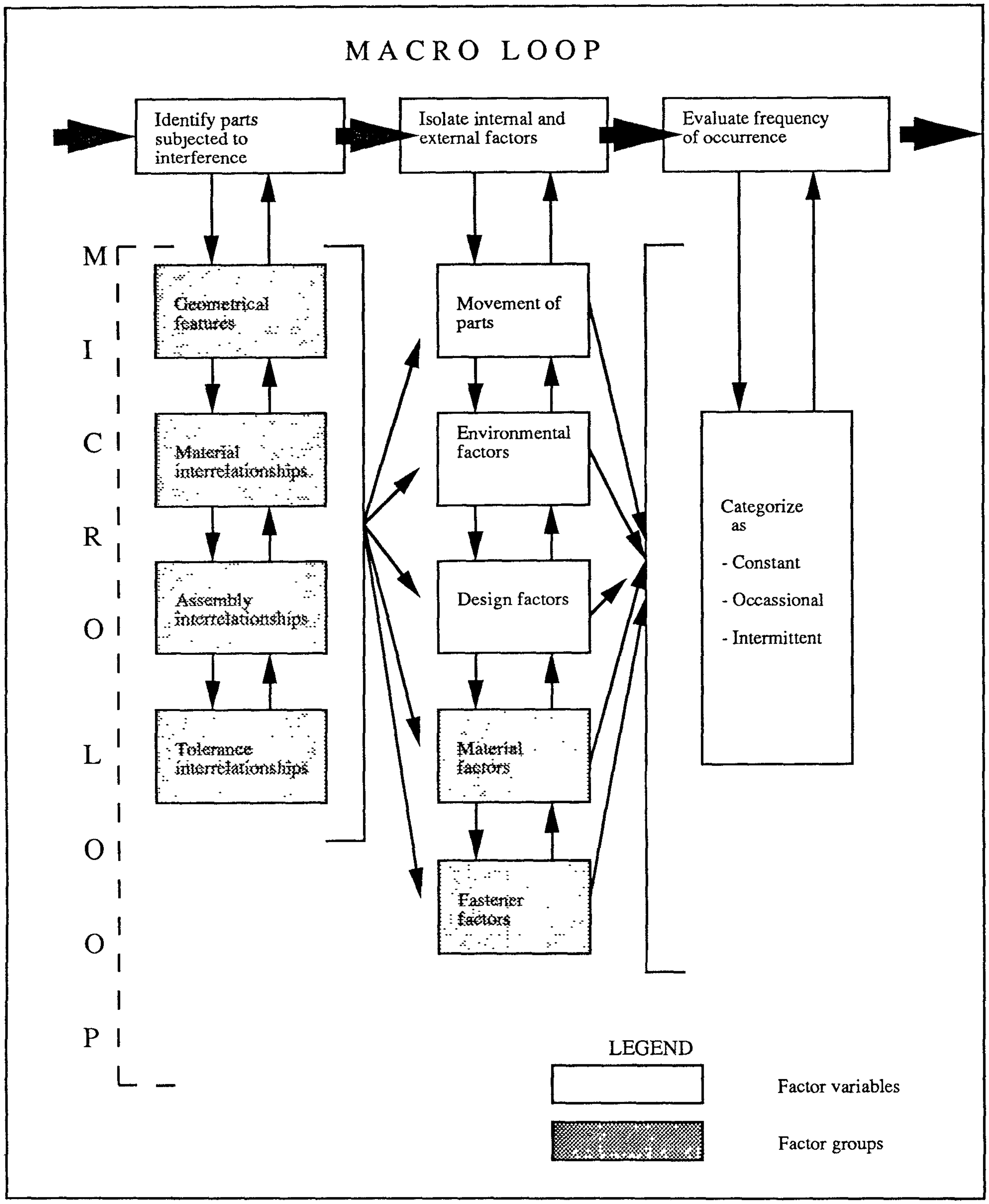

Figure 17. Micro Loop for Estimating Occurrence of Interference Defects

physical structure of the design, where flexing can occur thereby causing interference. The material interrelationships are indicative of the material weaknesses when subjected to various factors. Assembly and tolerance relationships are indicative of the nature of assembly and the degree of difficulty that is associated with the assembly.

B. *The isolation of the internal and external factors* - This deals with the analysis of the several internal factors related to the part itself and the external factors like temperature changes, humidity changes, static electricity etc. This is broken down into movement and environmental factors in the external factors group and design, material and fastener factors as the internal factor group. The occurrence of the defects is very greatly dependent on these factors. The study focuses on the exact nature of each defect caused by the factors.

C. *Evaluation of frequency of occurrence* - The frequency of occurrence is evaluated on the basis of the number of occurrences per unit time. This evaluation aids in the next stage of analysis. The frequency is evaluated as constant, occasional and intermittent as identified earlier.

Once these values are utilized to evaluate the ratio, then further analysis is done to relate the frequency of the factors to the frequency of the defect. This gives a clear indication on the effect of the various factors to the direct occurrence of these defects. As the relationship of dependency increases in strength, i.e, external factor frequency approaches defect frequency, the occurrence becomes a linear function. Then every time the factor occurs the defect can be expected to occur. this is shown graphically in the macro loop.

4.2.4. Missing or Misplaced Parts

The macro loop for the estimation of the occurrence of missing or misplaced parts is shown in figure 18. This loop consists of three blocks and a computation. The first block deals with the identification of similar parts. The similarity here does not involve the group technology approach to

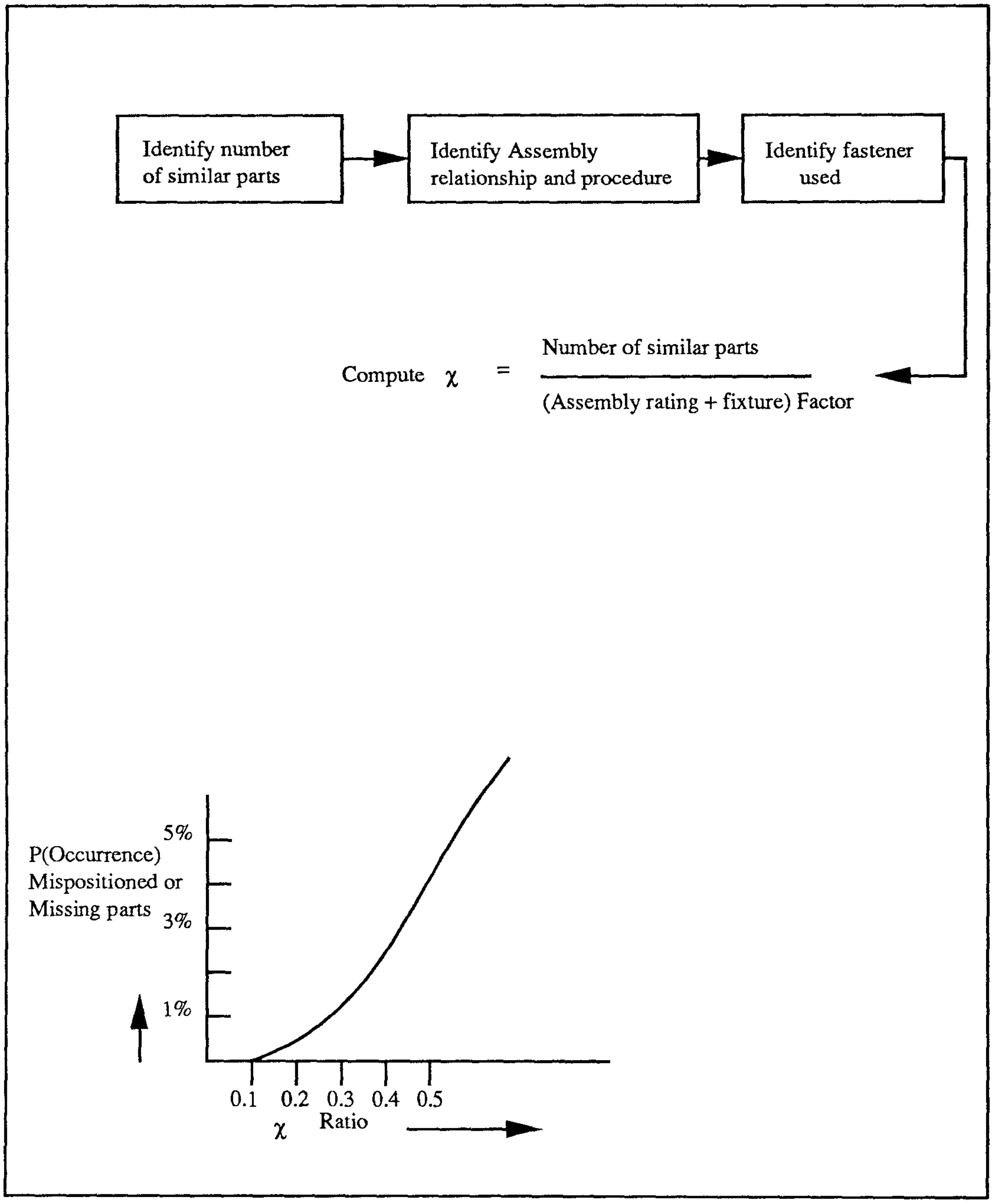

Figure 18. Macro Loop for Estimating Occurrence of Misplaced or Missing Parts

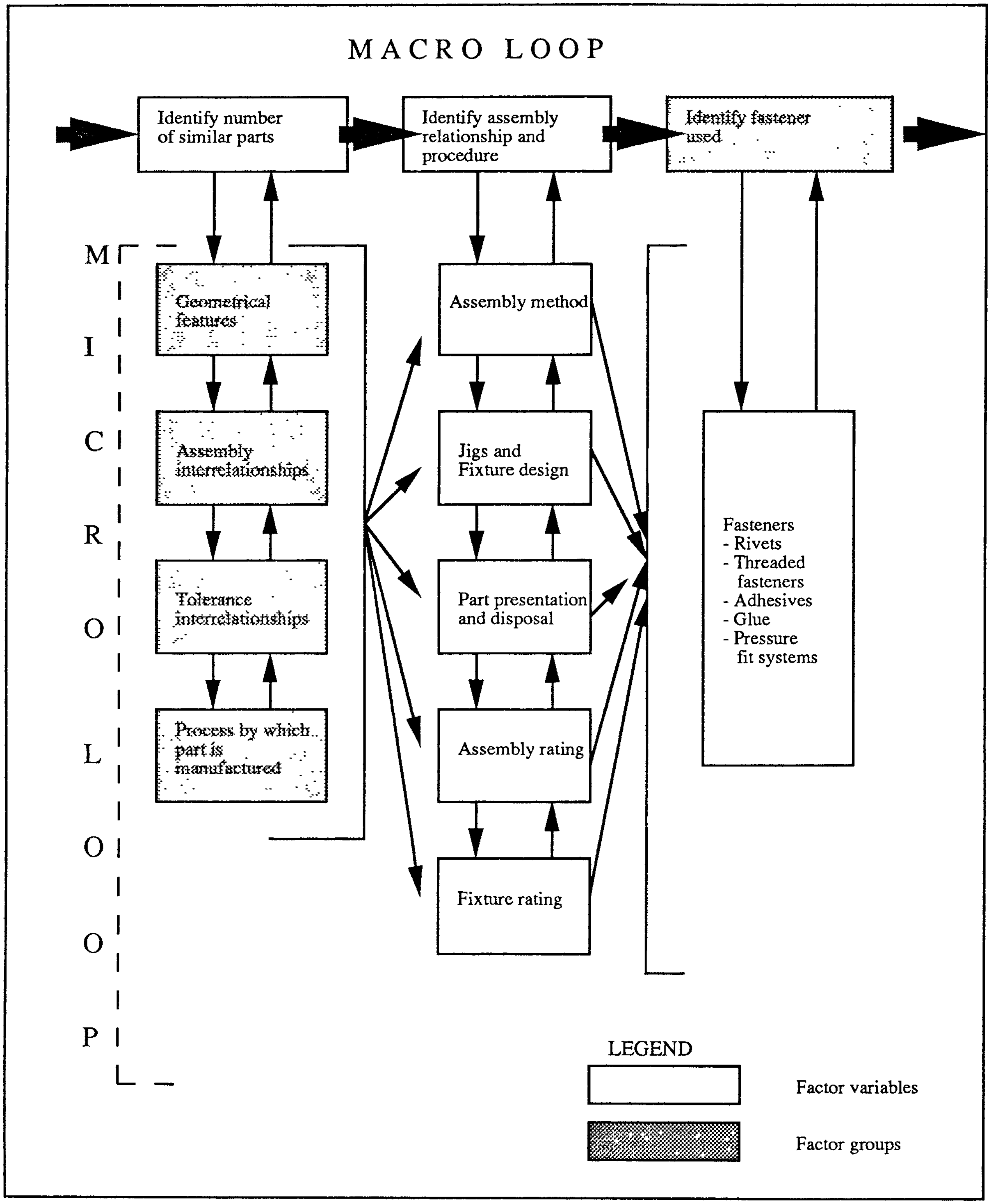

Figure 19. Micro Loop for Estimating Occurrence of Misplaced or Missing Parts

identification. The second block deals with the identification of the different relationships existing between the parts of the assembly and the procedure followed to assembly the parts. The third block deals with the identification of the fastener employed in the assembly. The output of the three blocks explained in the micro loop is then used to compute χ, which serves as an estimator for the occurrence of the missing or misplaced part defect.

The micro loop for the missing or misplaced parts shown in figure 19. The three blocks in this loop are identified and described next.

A. *Identification of the number of similar parts* - This is split up into four factor groups namely geometrical features, assembly interrelationships, tolerance relationships, process of manufacture of the parts. The similarity of the parts depends on the above factors. The geometrical features determine the common surfaces and dimensions between the parts to be similar, the assembly relationships determine the positions in which both similar and dissimilar parts can go into an assembly, the tolerance relationships determine the nature of fit and thereby the different ways in which two parts can be assembled and the process of manufacture controls the likeness in texture, surface finish, material characteristics etc. The similarity in one or more of these features can cause misplaced parts or missing parts. Smoother and smaller parts are difficult to handle.

B. *Identification of the assembly relationships and procedure* - This block deals with the analysis of the different factor associated with assembly. The study deals with the assembly method, jigs and fixtures used, parts presentation and disposal systems. These determine the efficiency of the assembly process. The assembly method deals with the robotic, automatic and manual assembly processes and the nature of jigs and fixtures used determines the quality of the assembly process, and the parts presentation systems determine the reliability of the presentation system to deliver the parts in the right orientation for assembly. The use of robotic systems must be fool proof and be capable of detecting wrongly oriented parts and missing parts. This is however easier in a manual assembly process but human error comes into the picture. The use of self locking fixtures can help assembly thereby reducing the occurrence of missing or misplaced parts. These different factors are used to come up with an efficiency rating for both the assembly process and the fixtures employed which are reflective of the reliability of the system to assembly without defects.

C. *Identification of the fastener employed* - This consists of identifying the particular type of fastener employed for the assembly. The nature of the fastener used determines the type and strength of the assembly and the resistance it offers to the occurrence of missing parts. The type of fastener used is also considered in evaluating the rating of the particular assembly process.

Thus the micro loop identifies the number of similar parts, the assembly relationships and procedure to develop a rating and the specific type of fastener used. As the number of similar parts increase and the assembly rating and the fixture rating reduces, the ratio χ increases and the variation of χ with respect to the defects is shown graphically in the macro loop.

4.2.5. Misalignment Defects

The macro loop for the estimation of the occurrence of misalignment defects is shown in figure 20. This loop consists of three blocks and the computation of a simple estimator. The first block deals with the identification of the mating surfaces of the two parts in contact. The second block deals with analysis of the geometry of the parts to identify constraining surfaces. The third block deals with the categorization of the different types of misalignments for analysis. The output of these blocks is used to compute d which serves as a simple estimator of the occurrence of misalignments.

The micro loop for the misalignment defects shown in figure 21. The three blocks in this loop are identified and described next.

A. *Identification of mating surfaces* - This block is split up into four factor groups. The mating surfaces can vary depending on the nature of the geometrical features, assembly relationships, fastening system and material

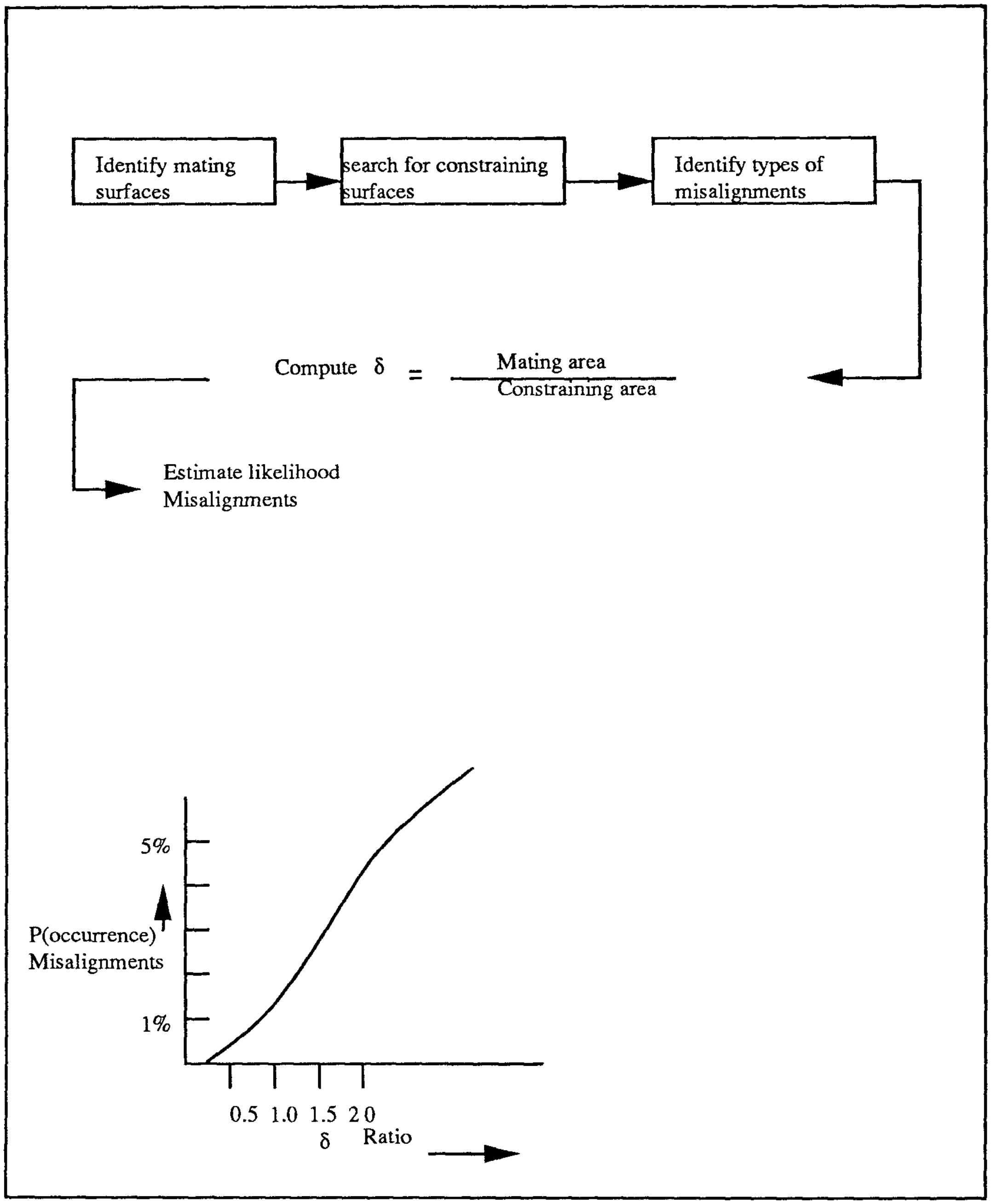

Figure 20. Macro Loop for Estimating Occurrence of Misalignments

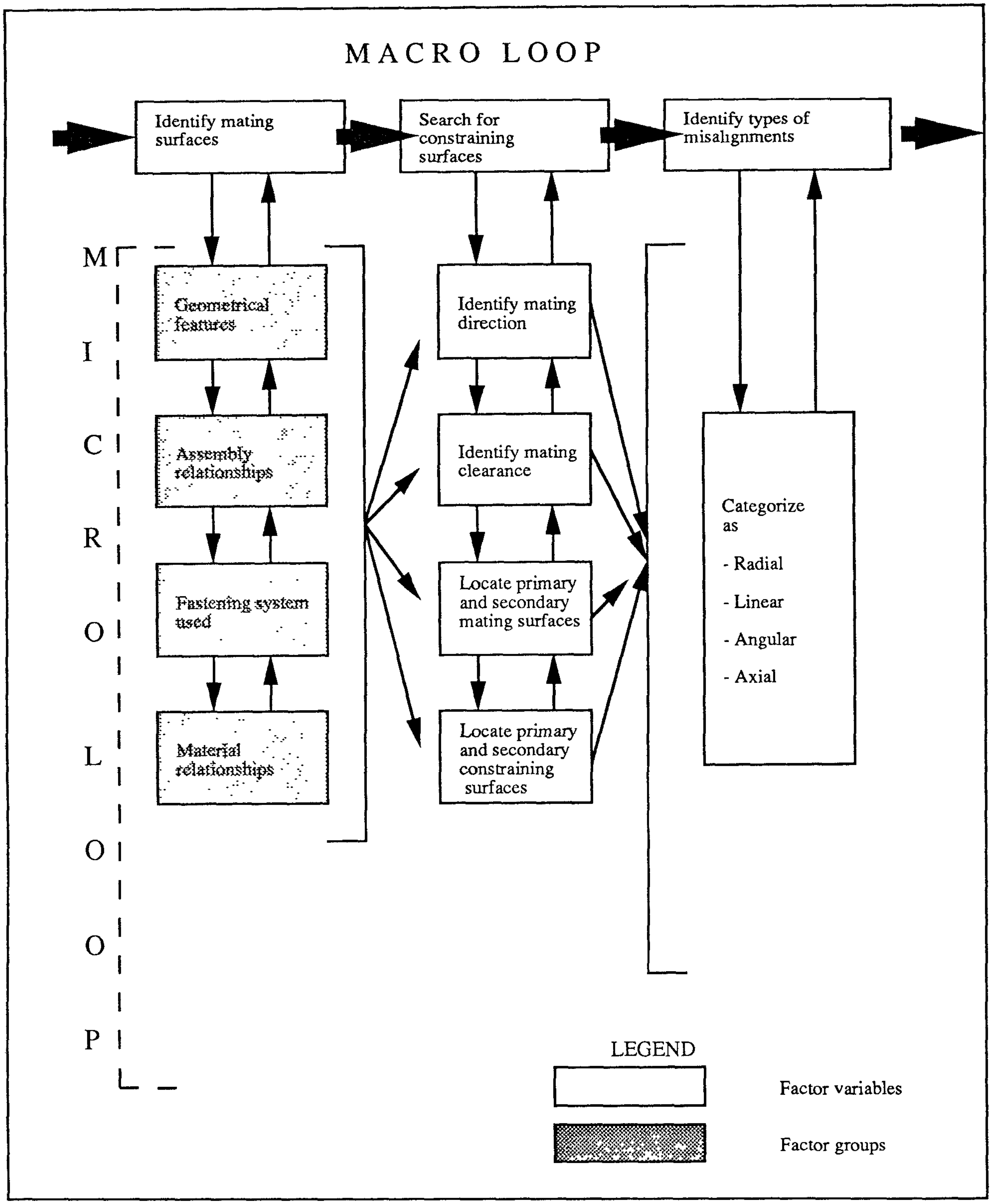

Figure 21. Micro Loop for Estimating Occurrence of Misalignments

relationships. The mating surfaces must be identified in only one direction to aid in easy analysis. The assembly relationships determine the number of surfaces that come into contact at the time of assembly. The fastening system determines the number and area of the surfaces needed for assembly. The material relationships play an important role in the location of the mating surfaces, as certain material characteristics restrict the location of the mating surfaces in certain areas of the surface of the parts.

B. *Analysis for constraining surfaces* - This analysis block consists of identifying mating direction, identifying mating clearance and locating the primary and secondary mating and constraining surfaces. The mating direction is identified as the direction in which the two parts are brought together or assembled. This is taken as the reference axis X, and all the further analysis is done based on this reference axis. The mating clearances between the surfaces actually in contact and around the surfaces in contact must be analyzed as this is very important to the occurrence of the defects. The mating surfaces are identified as primary and secondary depending on which comes into contact first. Similarly the constraining surfaces (surfaces which restrict movement in one or more directions) are also identified.

C. *Identification of the different types of misalignments* - This involves identification of the different types of misalignments like radial, linear, angular and axial depending on the mating direction. The analysis is done on the basis of proper identification of the mating direction.

Thus the micro loop identifies the mating surfaces, constraining surfaces and the different types of misalignments. The results are then used to evaluate a simple measure d which serves as an estimator for the occurrence of misalignment defects.

CHAPTER FIVE

ILLUSTRATION OF FUNCTIONAL RELATIONSHIPS FOR MISALIGNMENT DEFECTS

5. 1. ILLUSTRATIVE EXAMPLE

The application of the techniques developed in the previous chapters involves working on an object which can be easily related to. In this chapter we use an example to illustrate the working of the developed DFQM methodology. In the example, an assembly consisting of two parts, A and B is used to analyze the application of the techniques for developing a measure for the quantification of the occurrence of the defects. The parts are shown in the figure 22. The part A is placed on part B from the top. The dimensions of the parts are shown to better understand the nature of clearances between each pair of adjoining surfaces. The complete analysis is done after the identification of the various specific clearances and dimensions. The completed assembly is shown in figure 23. This example can be used as a standard in the determination of the relationships between this pair of factor and defect.

5. 1.1. Identification of Factor Defect Pair

This analysis relates the geometrical features factor group to the occurrence of misalignment defects. The pair wise analysis helps in understanding the role played by each and every factor variable towards the occurrence of the specific defects. The factor group in this example consists of edges, corners, surfaces, grooves, vertices etc. The misalignments consist of axial, radial, linear and angular, which are so defined based on the reference axis. The analysis tries to relate one or more factor variables to one or more specific defects.

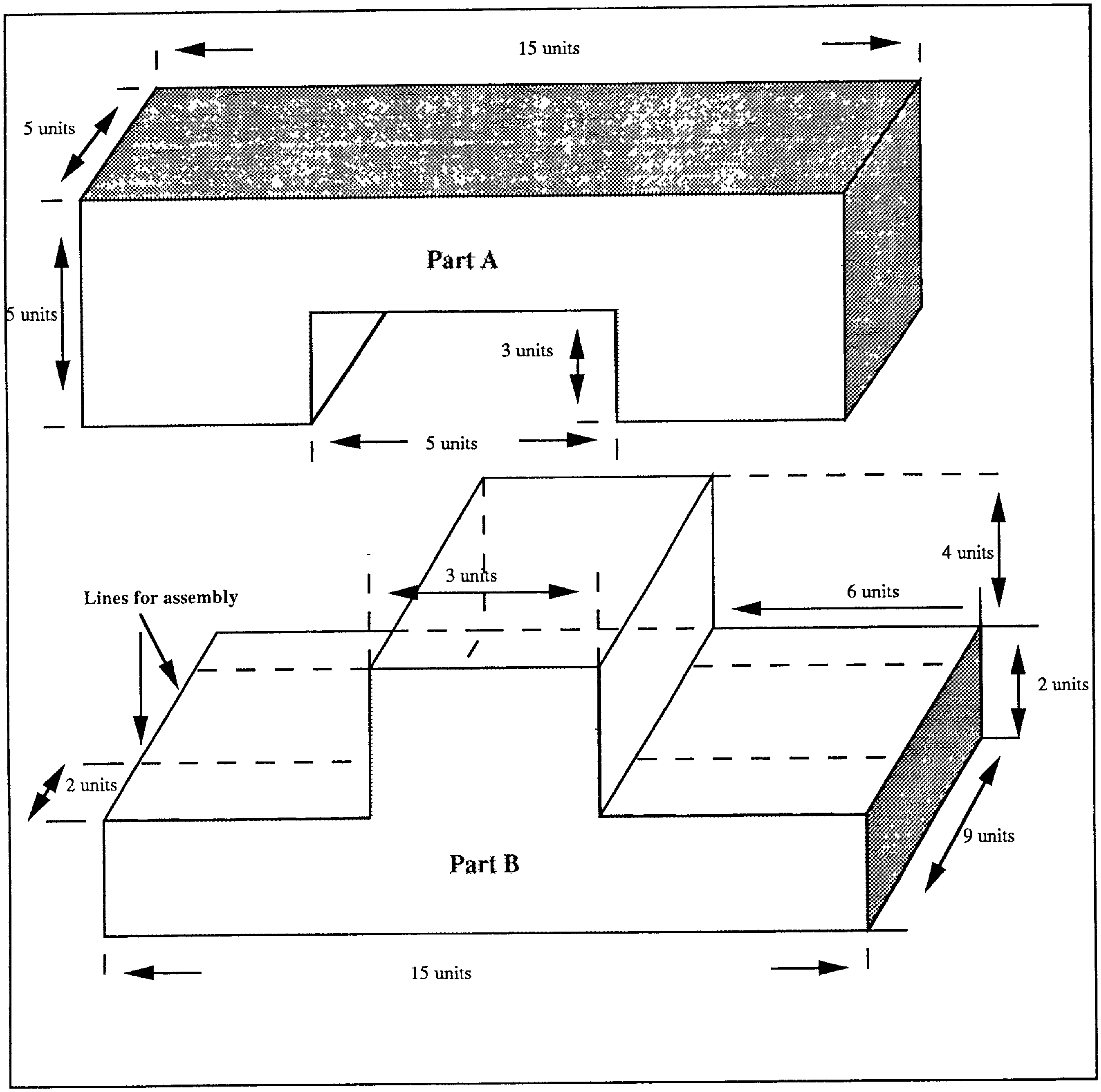

Figure 22. Example Assembly Consisting of Parts A and B

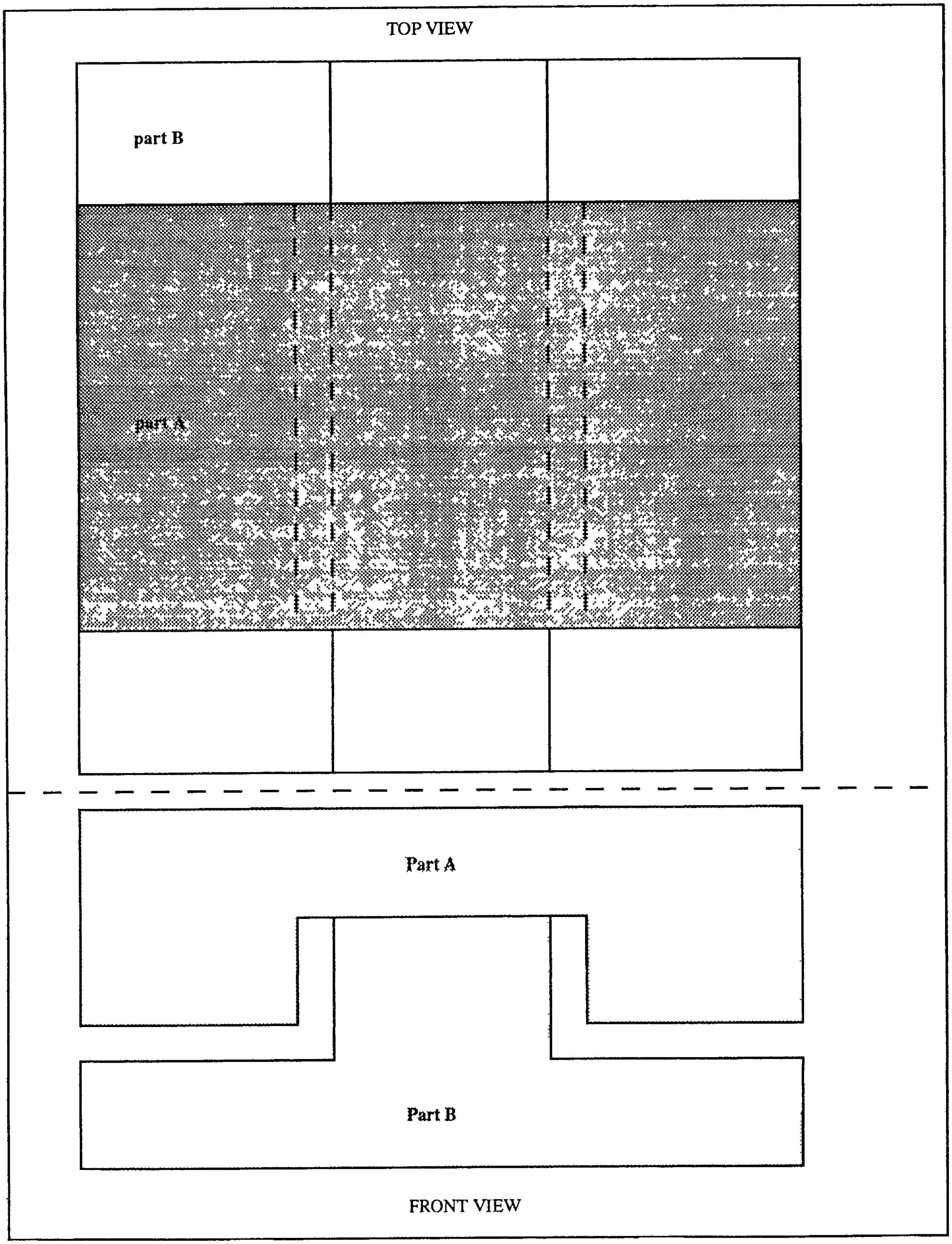

Figure 23. View of Completed Assembly

5.2. ANALYSIS OF MACRO AND MICRO LOOP

The macro and micro loop for the estimation of the occurrence of the misalignments has already been presented in chapter 4. The detailed analysis of the micro loop consists in defining the various types of surfaces and edges that are to be identified for the development of the probability functions. The following geometrical features are defined for this exercise.

Mating direction - This is defined as the direction in which the two parts are brought together for assembly. This is identified properly as the rest of the analysis of the misalignments is done based on this. The reference directional axis chosen determines the specific type of misalignments that are to be identified. This axis is referred to as X-axis for all further analysis.

Mating surface - This is defined as the surface of the part that comes into actual contact with the other part. The mating surfaces are identified for both the parts.

Mating length - This is the maximum dimension of the area of contact between the two parts. This is defined with respect to each part.

Constraining surface - This is defined as the surface of a part which prevents movement of the other part in one or more directions. It should be noted that all mating surfaces are constraining surfaces but the converse is not true. The constraining surface can be either internal or external depending on the positioning of the parts during assembly.

Primary and secondary mating surfaces - The primary mating surface is the surface that comes into contact first and the secondary mating surface comes into contact only after the primary has come into contact.

Primary and secondary constraining surfaces - The primary constraining surface is the surface which causes a restriction for movement first and the secondary constraining surface is the surface which can prevent movement either in the other direction or only if the primary were to be absent.

Axial clearance - This is defined as the dimensional clearance between the two parts measured on one particular axis at a time.

These specific geometrical features are identified on the example assembly parts and the relationships are developed to yield a measure.

5.3. ANALYSIS OF EXAMPLE MODEL

The example model is analyzed one specific defect at a time. The different misalignments are first identified for the example model. This is shown in figure 24. The misalignments are based on the reference axis - the mating direction which is referred to as X- axis. The arrows indicate the movements possible and the different misalignment directions. The different geometrical features are shown as and when the specific defect analysis is made.

a. *Linear misalignment* - The linear misalignment as defined in figure 24, occurs due to excessive clearance in the direction of the axes. The axes Y and Z as identified with respect to the reference axis are analyzed to identify the internal and external constraining surfaces. It can be noticed that the occurrence of this defect is a function of the clearance between the parts in the axial direction and the clearance between the primary and secondary constraining surfaces either external or internal taken as a pair. The effect of another factor group, i. e, the fastening system used is also considered as the ability of the parts to be assembled effectively depends on the right system. It can be identified that the use of rivets would limit this problem the most, next would be threaded fasteners and last in efficiency would be liquid fasteners. So finally the variables contributing to this defects are:

i. The least value among the clearance between the parts,the difference between the primary and secondary internal constraining surfaces and

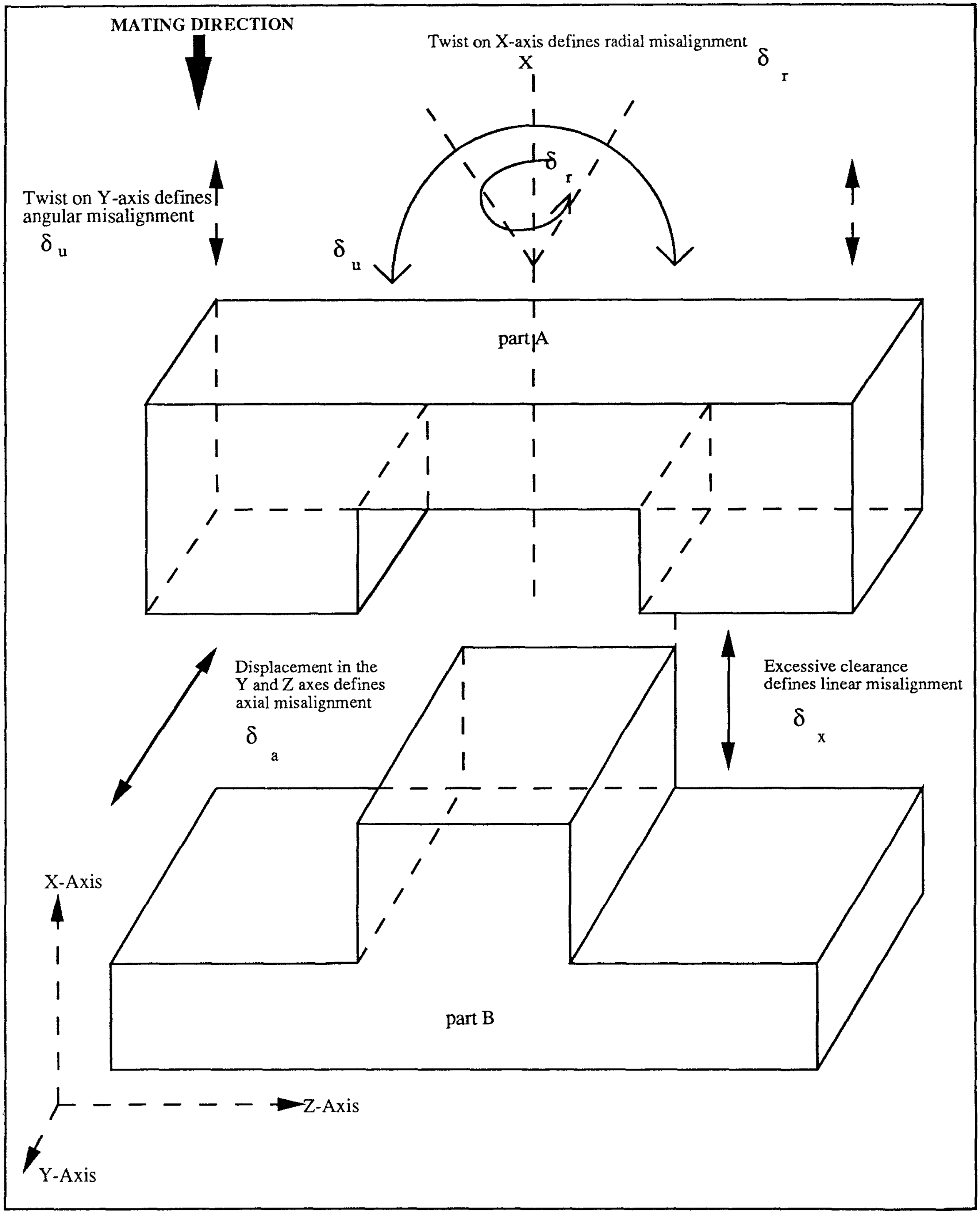

Figure 24. Misalignment Defects With Respect to The Example

the difference between the primary and secondary external constraining surfaces.

ii. The order of preference to the prevention of this defect would be to use rivets, then threaded fasteners and finally liquid fasteners. This means that the use of liquid fasteners has a higher probability of causing this defect than threaded fasteners, and that the use of threaded fasteners has a higher probability of causing this defects when compared to rivets.

b. *Radial misalignment* - The radial misalignment as defined in figure 24, occurs due to the twisting in the mating direction of part A with respect to part B. The analysis of the mating surfaces of the two parts reveals that the clearance between the two parts in the two axes other the one being considered determines the extent of radial misalignment. The clearance between the two parts can be considered in the Y and Z axes. the least of them can be used to construct an imaginary rectangle, the breadth of which is the clearance between the parts and the length is the dimension of the mating surface of the part in question. The diagonal of the rectangle would give a measure of the maximum radial misalignment angle, without the interaction of any constraining surfaces. Thus as the clearance increases, the rectangle becomes bigger and the diagonal angle increases thus indicating an increase in the misalignment angle. When there are constraining surfaces present, the pair of external or internal constraining surfaces determine the size of the rectangle and the analysis is continued. Thus the determinants of the radial misalignment are:

i. The clearance between the two parts on the mating surface in the Y and Z axes.

ii. The presence of internal and external constraining surfaces.

c. *Angular misalignment* - The angular misalignment as shown in figure 24, occurs due to a twisting movement in the Y axis of the two parts. This is brought on by the ratio ϕ of the dimension of primary mating surface of part A to part B and the ratio β of length of mating surface to the length of the part, taken on the longer side of the part and taken one part at a time. The misalignment is also a function of the difference in primary and secondary mating and constraining surfaces taken on one side of the part with reference to the reference axis. The difference measured is the maximum measure of the allowed twist for the misalignment. The variables that are thus contributing for the occurrence of the angular misalignment are:

i. The ratio ϕ and the ratio β, as the ratio ϕ approaches one , the probability of defects reduces and as the ratio β approaches one the probability of defects reduces.

ii. As the difference between the primary and secondary surfaces (mating and constraining) on the same side of the part reduces, the probability of defects reduces.

d. *Axial misalignment* - The axial misalignment as described in figure 24, occurs due to the displacement of the axes of the two parts being assembled. This is brought about by the clearance in the directions perpendicular to the reference axis. The clearances if any can be controlled if external or internal constraining surfaces are present. Thus the axial misalignment can increase or decrease depending on the clearance provided and the difference between the external and internal constraining surfaces. The variables contributing to this defect are:

i. The clearances available in the directions perpendicular to the reference axis.

ii. The presence of constraining surfaces and the difference between the internal and external constraining surfaces.

5. 4. EVALUATION OF PROBABILITY FUNCTIONS

The results of the analysis are represented in the form of functions depicting the probability of occurrence of the various defects. The nature of the

Linear Misalignment

$$P(\delta_x) \quad \alpha \quad \frac{\text{Clearance in the axial direction } + \text{ Difference between surfaces*}}{\text{Fastening strength of fastener used}}$$

* pair of internal or external constraining surfaces

Radial Misalignment

$$P(\delta_r) \quad \alpha \quad \frac{\text{Clearance in the Y and Z axes}}{\text{Difference between pair of constraining surfaces*}}$$

* pair must be of only external or internal

Angular Misalignment

$$P(\delta_u) \quad \alpha \quad \frac{\text{(ratio } \phi\text{) Difference between primary and secondary surfaces}}{\text{ratio } \beta}$$

Axial Misalignment

$$P(\delta_a) \quad \alpha \quad \frac{\text{Clearances available for movement in one axis}}{\text{Number of constraining surfaces * distance of constraining surface from the part}}$$

Figure 25. Probability Functions for the Different Misalignment Defects

behavior of the specific defects due to the variation in the factor variables is explained by these functions. The probability functions serve as an estimator and an indicator of the causes for the defects. They can be used to measure the feature by feature efficiency of one design over the other towards the occurrence of the misalignment defects. The different probability functions are shown in figure 25.

CHAPTER SIX

CONCLUSION

6. 1. CONCLUSION AND SCOPE OF FUTURE RESEARCH

Several conclusions can be drawn from the results of this thesis. The analysis conducted gives one an easily understandable methodology for evaluating a design. The feature by feature analysis of the design exposes the strengths and weaknesses of the design. This helps in bridging the gap, to a certain extent between product design,product quality and manufactured quality. This also provides the designer with important data about the different features, their interaction with other features and the need for such features, thereby enabling further improvement as and when desired. This enables the product development to take place during the prototyping stage, instead of the usual trial run and production run stages. The designer can improve on this by developing a priority index which would aid the designer in modifying the design based on the needs and the priority of the problem associated with the feature. A realistic picture of the various features and variables which are involved during the manufacture and assembly of the product is brought about. It serves as an important concurrent engineering tool by aiding the user to a certain extent in the selection of the processes, materials, fastening system, material handling system, parts presentation and disposal, jigs and fixtures etc. It must also be noted that the development of an absolutely generic methodology is not possible as no two designs are similar. This study serves as a benchmark in the product realization process thereby helping in design improvement and selection of one design over the other based on the quality needs of the market.

The macro architecture can be used as the starting point in the development of the QM-Index. The methodology developed can be used to ascertain the probability functions for the remaining sets of defects identified. Future research can concentrate on the primary and secondary occurrence of these defects. Depending on the scenario the factors and defects can be improved upon to generate more defect classes and factor groups. The probability functions of all the defects must then be integrated to develop the QM-Index for the entire design with sufficient feedback from the processes. Tests must be conducted on dummy parts to validate, correct and improve the methodology for calculation of the index. The next stage of the research would involve the introduction of guidelines for the effective improvement of the designs based on the comparative feature by feature analysis. This analysis also cannot be completely generic but the study can be used to address all features by developing an accurate set of guidelines which can tackle both existing and hypothetical issues. A set of tables must also be developed for easy reference and understanding. This tool can also be extended to address defects at other stages of production.

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