# A FUNCTION BASED DESIGN TOOL FOR FAILURE MODE IDENTIFICATION AND FAILURE-FREE DESIGN

by

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**A THESIS**

**Presented to the Faculty of the Graduate School of the**

**UNIVERSITY OF MISSOURI-ROLLA**

**In Partial Fulfillment of the Requirements for the Degree**

**MASTER OF SCIENCE IN MECHANICAL ENGINEERING**

**2002**

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# PUBLICATION THESIS OPTION

This thesis consists of the following articles that will appear or are intended for publication as follows:

a) Pages 1-23 will appear in Proceedings of DETC 2002, ASME 2002 Design Engineering Technical Conferences And The Computers and Information In Engineering Conference, Montreal, Canada, September 29 – October 2, 2002.

b) Pages 24-28 is a literature review that will serve as a transition from section 1 to section 3

c) Pages 29-55 are intended for submission to the 2002 ASME International Mechanical Engineering Congress and Exposition.

# DEDICATION

To mother, father, teachers and God.

# ABSTRACT

Knowledge of potential failure modes during design is critical for prevention of failures. Research has shown that nearly 80% of the costs and problems are created in product development and that cost and quality are essentially designed into products in the conceptual stage. Currently industries use procedures such as Failure Modes and Effects Analysis (FMEA), Fault Tree analysis, or Failure Modes, Effects and Criticality analysis (FMECA), Design of Experiments as well as knowledge and experience, to determine potential failure modes at the conceptual design stage. When new products are being developed there is often a lack of sufficient knowledge of potential failure mode and/or a lack of sufficient experience to identify all failure modes. This gives rise to a situation in which engineers are unable to extract maximum benefits from the above procedures. Though all of these methods have their own advantages, they do not give information as to what are the predominant failures that a designer should focus on while designing a product. This work describes a function-based failure identification methodology, which would act as a storehouse of information and experience, providing useful information about the potential failure modes for the design under consideration, as well as enhancing the usefulness of procedures like FMEA. Further a statistical clustering procedure is proposed to retrieve information on the set of predominant failures that a function experiences.

# ACKNOWLEDGMENTS

Firstly, I would like to express my gratitude to Dr. Robert B. Stone for giving me the opportunity to work on this interesting project and for his constant support and encouragement. Apart from being a great mentor, he has been a great source of inspiration for me to pursue a career in academia.

I would also like to thank Dr. Daniel McAdams, my co-advisor and Dr. K. Chandrashekhara for their insightful suggestions and guidance in writing this thesis and through out my stay at the University of Missouri – Rolla.

I would like to thank Dr. Irem Y. Tumer, Computation Sciences Division, NASA Ames who as a co-author for the two papers that appear in this thesis, made valuable contribution to this work.

I would like to thank all the members of the Design Engineering Lab (DELAB) for providing a great environment to do research.

This research work was supported by the NSF grant number DMI-9988817 for which I am thankful. I would also like to thank the Basic Engineering Department and its staff who have been very helpful in completing this work.

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# A FRAMEWORK FOR CREATING A FUNCTION-BASED DESIGN TOOL FOR FAILURE MODE IDENTIFICATION

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## ABSTRACT

Knowledge of potential failure modes during design is critical for prevention of failures. Currently industries use procedures such as Failure Modes and Effects Analysis (FMEA), Fault Tree analysis, or Failure Modes, Effects and Criticality analysis (FMECA), as well as knowledge and experience, to determine potential failure modes. When new products are being developed there is often a lack of sufficient knowledge of potential failure mode and/or a lack of sufficient experience to identify all failure modes. This gives rise to a situation in which engineers are unable to extract maximum benefits from the above procedures. This work describes a function-based failure identification methodology, which would act as a storehouse of information and experience, providing useful information about the potential failure modes for the design under consideration, as well as enhancing the usefulness of procedures like FMEA. As an example, the method is applied to fifteen products and the benefits are illustrated.

## KEYWORDS

Function-based decomposition; Failure mode identification; Functional modeling; Failure mode standardization; Failure-free product design.

# 1. INTRODUCTION

## 1.1.Scope

In engineering design, the end goal is the creation of an artifact, product, system or process that performs a function or functions to fulfill customer needs [1]. In today's competitive market it is important that manufacturers meet the customer requirements of a safe and reliable product that will have a minimum down time during the expected life of the product. This is true for all kinds of markets, be it the industrial markets like the highly failure sensitive aerospace industry or the consumer market which demands high reliability at low cost. This demand places a heavy burden on the shoulders of designers and manufacturers to eliminate or at least minimize possible malfunctions and failure modes from their products and processes. This necessitates a broad knowledge of the common failures encountered. This paper mainly deals with management of the declarative knowledge of recorded failure cases and their link to component function.

This paper is based on a function-failure method, developed by Tumer and Stone [2], who have hypothesized that similarities exist between different failure modes based on the functionality of each component/product. We also adopt a modified form of the matrix method developed by Collins et al. [3] to document failure data. Major emphasis has been laid on the standardization of the vocabulary in documenting the failure modes. The functions have been standardized by the functional basis developed by Hirtz et al. [1] and the failure modes by the failure classification provided by Collins, which is to be further expanded to adapt to new and advanced materials. The principles of Failure Modes Effects and Analysis (FMEA) have been adopted to quantify the failure mode documentation.

In the remainder of the paper, we present the motivation, background, approach, results and conclusions of this research. As specific motivation, we present some applications for a common function-failure design vocabulary. As background, we briefly summarize some research in the field of Failure Modes and Effects Analysis that are related to conceptual engineering design and some work related to the classification of failure modes and the methods proposed for their documentation. The methodology and approach are described and an example is provided to illustrate the methodology. The paper concludes with insights gained from the research process.

## 1.1.Motivations and Applications

Several factors motivate the creation of a function-failure method for design methodology. The following serve both as a motivation for and practical applications of the function-failure method developed in this research.

- Standardization of Vocabulary:

Often different methods are employed in recording failure data and the natural language is used for describing failure information. This makes the sharing of the valuable information difficult among different sections of the same organization or even among individuals. Though researchers have worked on the standardization of the function vocabulary and the failure modes on an individual basis, there has been little effort on the combined standardization of the two. This paper uses the functional basis developed by Stone and Wood [4] and Hirtz et al. [1] and presents a standardized failure mode vocabulary. This uniformity and consistency in the representation of function and failure knowledge provided by the function-failure method makes it an effective engineering organizational learning tool whose knowledge base can be shared not only among sections within the same organizations but across organizations with the aid of web-based technologies.

- Repeatability and Reusability:

It is very important for the failure mode data to be dynamic in nature indicating the latest status on the failure modes and its various characteristics like severity and occurrence. The dynamic nature is essential to make the method repeatable and reusable. The uniformity in the description of the function-failure data along with archival techniques employed facilitates repeatability and effortless updating of the failure modes data. This data when used with conventional FMEA techniques is envisioned to be a very useful design tool.

- Failure Data for New Products:

To design for failure in the conceptual design stage has always proved a challenge. This is because of the difficulty that arises in predicting failures at such an early stage when the structure of the component or product is hardly realized and no specifications as to its materials and the use environment are known. Beiter et al [5] developed the Assembly Quality Methodology (AQM) to predict defect levels of new products. In this research we use a functional model, which is a functional diagram of the product expressed in the vocabulary of the functional basis to predict failure modes. This will give the designer a starting point for examining the possible failure modes that the component and/or product might experience during use. Thus the method assists in specifying the component design and needed analysis methods at a very early stage and offers to minimize the cost of redesign. For instance, the indication of a high cycle fatigue for a product with a “transmit rotation” function will prompt the designer to perform a fatigue analysis to ensure that the corresponding component does not malfunction.

- A Source for Real-Time Failure Occurrence Data:

The FMEA analysis assigns a value to the Occurrence of the failure by making a reasonable guess of the probability of the occurrence of the failure. This introduces certain amount of non-uniformity in the data recorded as the probability assigned for a failure to occur depends on the experience of the designer and hence can vary from designer to designer. The function- failure method provides a realistic approach to obtain actual occurrence rates from the composite function-failure matrix.

- An Educational Tool for Novice Designers:

To design for failure or for the performance of tasks like the Failure Modes and Effects Analysis, requires a lot of experience. Today’s market is flooded with products that might not require the expertise of an experienced designer but at the same time is required to meet the customer’s demand of longevity and safety. It is quite natural to employ novice and fresh graduate designers for such products. The function-failure matrix can compensate for their lack of design experience, as it is in effect the collection of real-time data recorded in a standardized form.

These are just some of the practical applications in sight. With the continued development of the function-failure method, its usability and the areas in which it can be applied is bound to increase.

## BACKGROUND AND RELATED RESEARCH

### 1.2.Failure Modes and Effects Analysis (FMEA)

The FMEA procedure is an offshoot of the Military Procedure MIL-P-1629 [6], developed by the United States Military as a tool to determine and evaluate equipment failures. This was followed by ISO 9000 series issued by the International Standards Organization and QS 9000 series, the automotive analogy of the ISO 9000, which were a set of business management standards that focused on customer needs and expectations. In 1993 the Automotive Industry Action Group (AIAG) and the American Society of Quality Control copyrighted the industry-wide FMEA standards, which provided the general guidelines for preparing the FMEA.

A rigorously performed FMEA contains valuable information about the various components and assemblies of the product, which helps in the early detection of weaknesses in a product’s design. The FMEA procedure is still considered by most organizations as laborious and costly both in terms of money and time. More often the efforts have had poor results due to poor reusability arising from the inconsistent descriptions of the functions of the components or systems and the failures they undergo. Wirth et al. [7] have identified two fundamental weaknesses in the conventional FMEA. These are: the lack of methodological guideline to conduct an FMEA, and, the employment of natural language in recording the FMEA related information. Wirth et al. have addressed the problem of natural language in the description of functions using system and function taxonomies derived from the set of verbs and operators or fluxes provided by Roth [8] and Pahl and Beitz [9]. But there continues to be a lack of consistency in the description of failure modes. An engineer might describe different occurrences of the same failure in different ways or the same description for two marginally different failures. This lack of consistency makes the classification of failures that might manifest a particular set of symptoms difficult to identify, which otherwise would be a great source of help in diagnostic analysis [10]. Thus standardization of both the function vocabulary and failure mode vocabulary is desired.

Standardization of vocabulary aids in the effective maintenance and utilization of a knowledge base. A knowledge base is the combination of “declarative” and “procedural” knowledge [11, 12]. Bluvband and Zilberberg [11] describe “declarative knowledge” as a set of facts and statistical data about objects or events, and, “procedural knowledge” as information about courses of action and production rules. Declarative knowledge is a collection of libraries and serves as the organizations’ collective memory. Classic examples of declarative knowledge libraries include component libraries (component, failure modes and causes), corrective and preventive actions library, database description, end effect and severity library, test methods library, detectability library and current controls. The procedural knowledge consists of information regarding the effect of a failure propagated to the next higher level. For example, from the part level to the assembly level the identification of the highest effect failure mode is regarded as the end effect of the system.

FMEA has to be performed as early in the design stage as possible as it would identify potential problem areas and minimize the cost of changes to be made in the design. But if FMEA is performed earlier in the design stage then it has to be repeated whenever the design is changed. The prohibitive cost and the time consumed in repeating FMEA has pushed the FMEA procedure to a later stage in the product development cycle [13]. FMEA performed at the final stages of the product development will add little or no value to the product, as the cost involved in making design changes at this stage can be enormous. Thus this necessitates following an approach that will enable the FMEA to be performed at an early stage.

There are two main approaches to the “Design FMEA” according to the Aerospace Recommended Practice [14]: the hardware approach and the functional approach. The two approaches complement each other as they have different kinds of details and are performed at different stages in the product cycle. The hardware approach is evaluated by considering the changes that occur in each hardware and its effects on the neighboring component hardware and propagated to the next level up. As this requires specific information about the type of components and their individual properties, it can be performed only when the design has been adequately realized. The functional approach however can be undertaken in the initial stages of product development. It involves the development of functional and system schematic diagrams. This approach relies on the specification of the purposes and functions of each piece of equipment [12].

The concept of applying matrix techniques to FMEA was originally introduced by Barbour in 1977 [15]. Goddard and Dussault [16] developed the Automated Advanced Matrix FMEA, which was a refined extension of Barbour's work, mainly serving as a logistics tool. The matrix was formed with the columns comprising of outputs of the assembly under analysis, test points of analysis, comments, remarks and references and the rows comprising of inputs to the assembly being analyzed with appropriate failure modes for the inputs and the parts contained in the assembly being analyzed with their failure modes. Henning and Paasch [17] also adopt a matrix-based approach to diagnose potential failure cases in proposed designs.

## 1.3.Mechanical Failure Modes

The increasing importance of reliability metrics is fueling the advancement of reliability prediction methods, especially those used in new designs. Researchers have relentlessly worked to develop methods to classify and provide failure mode data to designers at an early stage. Peecht and Dasgupta [18] have discussed the application of the methodology of the physics of failure approach to reliable product development. In this approach the designer specifies the design requirements based on customer requirement and supplier capability and also identifies the use environment. Next, stress analysis, along with the knowledge of stress response of the design materials, is used in identifying failure sites, failure modes, and failure mechanisms. Once the potential failure modes are analyzed, a failure mechanism model is obtained which enables a reliability assessment to be conducted on the product. This information thus obtained helps to determine whether a product will survive its intended application life.

Thornton [19] classifies failures into three categories: Safety, Functional and Ancillary. Within these categories, failures are further classified into five general areas as design deficiencies, construction deficiencies, material deficiencies, administrative deficiencies and maintenance deficiencies. The paper further states that as much as 52% of the failures is due to design deficiencies, 25% due to construction, and 18% due to materials deficiencies.

Svalbonas [20] classifies failure into five general groups as design, material selection, material imperfection, material fabrication and service environment.

Failures resulting from design deficiencies are usually associated with poor structural design aspects. The design phase is divided into five stages: 1) setting design specifications, 2) providing design analysis, 3) providing proper fabrication and inspection, 4) setting required quality assurance procedure and 5) providing proper purchase specification. An error in any of the above five stages is almost certain to introduce a failure mode into the product.

Collins et al [3, 21] have introduced the matrix approach to failure modes data recording as early as 1976. They devised a three dimensional matrix in which the axes represent the failure modes, elemental mechanical functions and corrective actions. Each failed part was classified by these attributes. The Failure-Experience matrix formed a sound basis for cataloguing failure data and a potential engineering design tool. Its effectiveness as a design tool lies in its ability to accept real data and to generalize and normalize the data, which can then be used for a specific application.

In this paper we use the failure modes categorization scheme enumerated by Collins [3]. Collins has classified failures into three categories, as shown in Table 1: 1) manifestations of failure, 2) failure inducing agents and 3) locations of failure. The human category was added under failure inducing agents to account for failure due to human negligence such as improper maintenance or ignorance of processes [22].

By selecting appropriate classification from the three categories mentioned above Collins describes 23 commonly occurring failure modes, which are listed in Table 2. For example the “Thermal Fatigue” failure mode is derived as follows:

1. Manifestation of Failure – Rupture or Fracture
2. Failure Inducing Agent
    Force – Transient
    Temperature – Transient
3. Failure location – Body type

The Collins classification is used as a starting point in this research.

Table 1. Categorization of failures

| CATEGORY | SUB-CATEGORY |
|---|---|
| **Manifestation of Failure** | |
| Elastic Deformation | |
| Plastic Deformation | |
| Rupture or Fracture | |
| Material Change | Metallurgical |
| | Chemical |
| | Nuclear |
| **Failure Inducing Agents** | |
| Force | Steady |
| | Transient |
| | Cyclic |
| | Random |
| Time | Very Short |
| | Short |
| | Long |
| Temperature | Low |
| | Room |
| | Elevated |
| | Steady / Transient |
| | Cyclic |
| | Random |
| Reactive Environment | Chemical |
| | Nuclear |
| Human | |
| **Failure Locations** | |
| Body Type | |
| Surface Type | |

Table 2. Classification of Failure Modes by Collins (1981)

| CATEGORY | SUB-CATEGORY | CATEGORY | SUB-CATEGORY |
|---|---|---|---|
| | | | |
| **Force and/or temperature induced deformation** | | **Impact** | Impact Fracture |
| **Yielding** | | | Impact Deformation |
| **Brinelling** | | | Impact Deformation |
| **Ductile Rupture** | | | Impact Wear |
| **Brittle Fracture** | | | Impact Fretting |
| **Fatigue** | High-cycle Fatigue | | Impact Fatigue |
| | Low-Cycle Fatigue | **Fretting** | Fretting Fatigue |
| | Thermal Fatigue | | Fretting Wear |
| | Surface Fatigue | | Fretting Corrosion |
| | Impact Fatigue | **Creep** | |
| | Corrosion Fatigue | **Thermal relaxation** | |
| | Fretting Fatigue | **Stress Rupture** | |
| **Corrosion** | Direct Chemical Attack | **Thermal Shock** | |
| | Galvanic Corrosion | **Galling and Seizure** | |
| | Crevice Corrosion | **Spalling** | |
| | Pitting Corrosion | **Radiation Damage** | |
| | Intergranular Corrosion | **Buckling** | |
| | Selective Leaching | **Creep Buckling** | |
| | Erosion Corrosion | **Stress Corrosion** | |
| | Cavitation Corrosion | **Corrosion Wear** | |
| | Hydrogen Damage | **Corrosion Fatigue** | |
| | Biological Corrosion | **Combined Creep and Fatigue** | |
| | Stress Corrosion | | |
| **Wear** | Adhesive Wear | | |
| | Abrasive Wear | | |
| | Corrosive Wear | | |
| | Surface Fatigue Wear | | |
| | Deformation Wear | | |
| | Impact Wear | | |
| | Fretting Wear | | |

## 3. GENERAL APPROACH

This section outlines the steps that lead to the formation of the function-failure matrix and concludes by describing how the function-failure method can be used in realizing the applications described earlier. The procedure is outlined in Figure 1. The function-component matrix is composed of the component vector (obtained from the bill of materials) and the function vector (obtained from the bill of materials and the functional model).

The component-failure matrix is obtained from the component vector and the failure vector. The function-failure matrix is obtained from the matrix multiplication of the two matrices. The function-failure method naturally breaks into five steps, which are described in detail in the following sections.

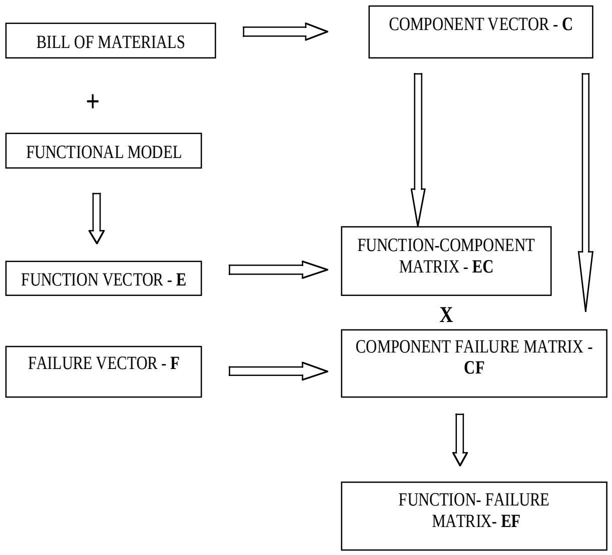

Figure 1. Procedure Flowchart

### 3.1. Documenting Functional Data

The first step is to document the function information detailing all possible functions performed by the component, assembly, or sub-system, and describe their physical characteristics. This is accomplished by preparing a bill of materials and functional model for each product under study.

The bill of materials is a list of the components making up the product [23]. It identifies the assembly to which the component is a member, the quantity of the component used in the product, its physical description, and the process by which it is manufactured along with the functions performed by the component. The set of m components for a product or a group of products is represented by an m-dimensional vector C.

The functional model is a description of a product or process in terms of the elementary functions that are required to achieve its overall function or purpose [4]. The functional model is a flow diagram indicating the various functions of the product and their connectedness through the flows of energy, material and information. In both the bill of materials and the functional model, the functional basis is used to describe the functions and the flows. The functional basis is a design language where product function is characterized in a verb-object (function-flow pair) format capable of describing the mechanical design space. Tables 3 and 4 give the function and flow classes respectively [1]. The set of functions describing the product set form an n-dimensional vector E.

Table 3. Function Classes and their Basic Categorizations

| Class | Material | Signal | Energy | | |
|---|---|---|---|---|---|
| Basic | Human | Status | Human | Electrical | Mechanical |
| | Gas | Signal | Acoustic | Electromagnetic | Pneumatic |
| | Liquid | | Biological | Hydraulic | Radioactive |
| | Solid | | Chemical | Magnetic | Thermal |
| | Plasma | | | | |
| | Mixture | | | | |

Table 4. Flow Classes and their Basic Categorizations

| Class | Basic | Class | Basic | Class | Basic |
|---|---|---|---|---|---|
| Branch | Separate | Control Magnitude | Actuate | Signal | Sense |
| | Distribute | | Regulate | | Indicate |
| Channel | Import | | Change | | Process |
| | Export | | Stop | Support | Stabilize |
| | Transfer | Convert | Convert | | Secure |
| | Guide | Provision | Store | | Position |
| Connect | Couple | | Supply | | |
| | Mix | | | | |

### 3.2. Forming the Function-Component Matrix

Next, the function-component matrix is created with the help of the bill of materials and the functional model. The components form the m columns of the matrix and the functions form the n rows of the matrix. For a given component a ‘1’ is placed in the cell corresponding to the function it performs and a ‘0’ is placed in the other cells. We call this m x n matrix the EC matrix, shown in Figure 2.

| **PRODUCT NAME** | | | | | | |
|---|---|---|---|---|---|---|
| **FUNCTION - COMPONENT** | Component - 1 | Component -2 | . | . | . | Component - n |
| Function - 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| Function - 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| . | 0 | 0 | 0 | 0 | 1 | 0 |
| . | 0 | 0 | 1 | 0 | 0 | 0 |
| . | 0 | 0 | 0 | 0 | 0 | 0 |
| Function - m | 0 | 1 | 0 | 0 | 0 | 1 |

Figure 2. EC Matrix

### 3.3. Documenting Failure Data

The third step is to record failure data in a manner similar to the bill of materials. It is recorded in a tabular format with columns representing part name, function performed and physical description (each obtained from the bill of materials and/or functional model). To this we add information about the failure modes, causes of the failure and the effects of these failure modes on the components and the severity and occurrence values of the components.

The failure modes are recorded using the descriptors provided by Collins [3]. Though this paper uses only the descriptors provided by Collins, during the course of this research we believe that more failure mode descriptors will be required to handle failure modes experienced by plastics, and products made from composite materials and other new advanced materials.

We have added primary and secondary identifiers to the Collins failure modes to resolve any ambiguity in the designer's mind as to the selection of the appropriate failure mode. The "primary identifier" provides information such as the kind of load applied, the nature of the force, the kind of material involved, the characteristic environment under which the failure mode occurs or the main characteristic of failure. These were categorized as primary identifiers as it is absolutely necessary for the failure to have been associated with the given condition to be classified under the corresponding failure mode. The "secondary identifier" provides information such as materials used, characteristics of failure, or presence of other factors or medium. The reason behind identifying this information as secondary identifiers was because it is absolutely necessary for the failure mode to fit into the description provided by the primary identifier for it to be labeled by the corresponding failure mode. Table 5 provides the primary identifier, the secondary identifier and the corresponding failure mode. The failure modes in italics indicate that they have been merged and identified by a new name. The words in bold face serve as a visual aid in identifying the prominent characteristics.

During the course of this research some ambiguity was caused by three pairs of failure modes: 1) surface fatigue wear and surface fatigue; 2) impact fatigue and impact wear; and 3) erosion corrosion and corrosive wear. The ambiguity arose due the very similar characteristics in the development and description of these failure modes. As different engineers or the same engineer might describe the net result by two different names, it was decided that these failure modes be combined into three classifications. Surface fatigue wear and surface fatigue are combined as surface fatigue wear since surface fatigue wear is a result of surface fatigue and a design to prevent the former would take care of the latter. Similarly impact fatigue and impact wear were combined under the heading impact fatigue wear, as it would address both failures simultaneously. Also, corrosive wear and erosive wear are combined as corrosive wear, since by definition there is little distinction between the two and corrosive wear encompasses erosive wear.

# Table 5. Failure Mode Identification

| PRIMARY IDENTIFIER | SECONDARY IDENTIFIER | FAILURE MODE |
|---|---|---|
| **Elastic** Deformation | | Force / Temperatire induced deformation |
| **Plastic** Deformation | **Ductile** Material | Yielding |
| **Static** Force<br>**Curved** Surfaces | 1. Permanent surface discontinuity<br>2. **Mating** members | Brinelling |
| **Plastic D**eformation<br>**Ductile** Material | 1. Separate into 2 parts<br>2. Dull fibrous surface | Ductile rupture |
| **Elastic** Deformation<br>**Brittle** Material | 1. Separate into 2 parts<br>2. Granular, multifaceted fracture surface | Brittle fracture |
| **Fluctuating** Load / deformation | 1. Sudden separation into 2 parts<br>2. Magnitude of load such that **more than 10,000 cycles** required | High cycle Fatigue |
| **Fluctuating** Load / Deformation | 1. Sudden separation into 2 parts<br>2. Magnitude of load such that **less than 10,000 cycles** required | Low cycle Fatigue |
| **Fluctuating** Load / Deformation | Caused by fluctuating **temperature** | Thermal Fatigue |
| **Fluctuating** Load / Deformation | **1. Rolling** surfaces in contact<br>2. Manifests as pitting, cracking, scaling | *Surface Fatigue*<br>Surface Fatigue Wear |
| **Fluctuating** Load / Deformation<br>**Impact** Load<br>**Elastic** Deformation | Failure occurs by nucleation or crack propagation | *Impact Fatigue*<br>*Impact Wear*<br>Impact Fatigue Wear |
| **Fluctuating** Load / Deformation<br>**corrosion** action | Corrosion creates stress raisers which accelerate fatigue which in turn exposes new layer to corrosion | Corrosion Fatigue |
| **Fluctuating** Load / Deformation | 1. **Interface** of 2 solid bodies<br>2. **Normal** force<br>3. **At joints not intended to move** | Fretting Fatigue |
| Attack by **Corrosive Media** | | Direct Chemical Attack |
| **Electrochemical** Corrosion | 2 **Dissimilar metals** in electrical contact. circuit completed by **Corrosive Medium** | Galvanic Corrosion |
| **Localized** in crevices, cracks and joints | Presence of **corrosive medium** | Crevice Corrosion |
| Development of **array of holes or pits** | Presence of **corrosive medium** | Pitting Corrosion |
| Grain boundries of **Cu, Ch, Ni, Al, Mg, Zn alloys** | **Improprly heat treated** | Intergranular Corrosion |
| Solid **Alloy** | **One element** is removed | Selective Leaching |
| Presence of **Abrasive / Viscid material** flow | Corrosive Medium | *Erosion Corrosion*<br>Corrosive Wear |
| Difference in **Vapor Pressure** | | Cavitation Erosion |
| Blistering, embritleement, decarburization | Corrosive medium | Hydrogen Damage |
| Food ingestion and waste elemination of **living organisms** | Products act as corrosive media | Biological Corrosion |
| Applied S**tresses** | **Corrosive** medium | Stress Corrosion |
| Undesirable **change in dimension** | High pressure<br>**Plastic** deformation<br>Rupture of sharp sites | Adhesive Wear |
| **Mating** Surfaces | Particles remvoved by harder mating surface or by particles entrapped | Abrasive Wear |
| **Plastic** deformation | **Impact** loading | Deformation Wear |
| Change in **dimensions** | 1**. Mating** parts<br>2**. Normal** force<br>3. Joints not intended to move | Fretting Wear |
| **Impact** load | **Separation** into 2 or more parts | Impact Fracture |
| **Plastic / Elastic** deformation | **Impact** load | Impact Deformation |
| **Impact** load | 1**.Mating** parts<br>2. **Normal** force<br>3. Joints not intended to move | Impact Fretting |
| **Plastic** deformation | 1**.Temperatute / stress** Influence<br>2**. Rupture** occurs depending on stress-time-temperatire conditions | Creep stress Rupture |
| **Prestarined or prestressed part** | **Change in dimensions** | Thermal Relaxation |
| **Thermal** gradients | **Differential** strains | Thermal Shock |
| **Sliding** surfaces | 1.**Combination loads**<br>2. Sliding velocity<br>3. Temperatures<br>4. Lubricants<br>**5. Surface destruction**<br>6. 2 parts virtually welded together | Galling and Seizure |
| Partilcle **spontaneously dislodged** from surface | | Spalling |
| Nuclear **radiation** | **Loss of ductility** | Radiation Damage |
| High and/or point load<br>Geometric configuration | Deflection increases greatly for slight increses in load | Buckling |
| **Plastic** deformation | 1. Influence of temperature / stress<br>2.Rupture<br>3.Exceed buckling limit | Creep Buckling |

### 3.4. Forming the Component-Failure Matrix

From the failure data recorded as described in the previous section, the fourth step is to form the component failure mode matrix, with p columns representing the failure modes and n rows representing the components. This n x p matrix is called the component-failure matrix, denoted by CF. As in the function-component matrix, a ‘1’ is placed for a component in the cell corresponding to the failure mode it experienced and a ‘0’ in the other cells. The component-function matrix is shown in Figure 3.

| **PRODUCT NAME** | | | | | | |
|---|---|---|---|---|---|---|
| **COMPONENT - FAILURE MODE** | Failure Mode -1 | Failure Mode -2 | . | . | . | Failure Mode - n |
| Component - 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| Component - 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| . | 0 | 0 | 0 | 0 | 1 | 0 |
| . | 0 | 0 | 1 | 0 | 0 | 0 |
| . | 0 | 0 | 0 | 0 | 0 | 0 |
| Component - n | 0 | 1 | 0 | 0 | 0 | 1 |

Figure 3. CF Matrix

This paper describes only the binary format of the CF matrix where a 1 represents the existence of a particular failure mode for a component and 0 the absence. Research is in progress wherein the cells of the CF matrices contain information like severity or the risk priority numbers, which on analysis by statistical procedures will provide some good indicators for the relationship between component functions and their associated failure modes, as well as the relationship among different failure modes or among functions.

### 3.5. Forming the Function-Failure Matrix

Finally, the function-failure matrix is obtained by the matrix multiplication of the function-component matrix (EC) and the component-failure mode matrix (CF):

$$EF = EC \times CF \qquad (1)$$

The resulting m x p matrix is called the EF matrix. The cells of this matrix provide information as to the number of occurrences of a particular failure mode for a given function.

The real advantage of the EF matrix as a design tool is obtained from the composite EF matrix from which occurrence-ranking values could be obtained using the probability of occurrence. The probability could be obtained from the ratio of the number of occurrences of a failure to the total number of instances of failure. The following section illustrates the application of the function-failure approach to a set of fifteen products.

## 4. EXAMPLE

In this section we describe the function-failure method applied to fifteen products [24]: Braun coffee grinder, Dremel engraver, Dewalt sander, Mr. Coffee-Coffee Maker, Bissell Hand-Vac, Air purifier, Ball shooter, B&D dust buster, Conair hair drier, Hunt Boston sharpener, Mr. Coffee Iced tea maker, B&D palm sander, Popcorn popper, Skill screw driver and spatula mixer and interpret the results for two functions.

Table 6 shows the composite function-failure matrix for the fifteen products. Before creating the composite function-failure matrix the function-component and the component-failure matrices are aggregated and the resulting matrices are multiplied to get the composite function-failure matrix [2]. More details on matrix aggregation are given in Stone et al. [25]. Mathematically the aggregated function-failure matrix is:

$$EF_c = \sum EC \times \sum CF \qquad (2)$$

The matrix for fifteen products gives a list of 25 failure modes occurring over 71 functions, as shown in Table 6. While designing a new product or redesigning an existing product we follow the procedure described earlier in deriving the functions of the product. Now utilizing the composite function-failure matrix we form the product specific function-failure matrix (EF) by selecting the failure modes corresponding to the derived functions. For example say the product under study has the following functions: 1) stop liquid and 2) secure solid. Its possible failure modes corresponding to its functions are shown in Figure 4. The failure modes for these functions are:

- Stop liquid – Corrosive wear, Force induced deformation and yielding.
- Secure Solid – Abrasive wear, corrosive wear, direct chemical attack, ductile rupture, force induced deformation, fretting fatigue, high cycle fatigue, temperature induced deformation, thermal fatigue, thermal relaxation, thermal shock and yielding.

| **FUNCTION / FAILURE** | ABRASIVE WEAR | CORROSIVE WEAR | DIRECT CHEMICAL ATTACK | DUCTILE RUPTURE | FORCE INDUCED DEFORMATION | FRETTING FATIGUE | HIGH CYCLE FATIGUE | TEMPERATURE INDUCED DEFORMATION | THERMAL FATIGUE | THERMAL RELAXATION | THERMAL SHOCK | YIELDING |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SECURE SOLID | 3 | 1 | 11 | 1 | 8 | 1 | 2 | 9 | 2 | 3 | 2 | 44 |
| STOP LIQUID | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

Figure 4. Function-Failure Matrix.

With the possible failure modes identified, this gives us a direction performing further analyses on candidate design solutions. In particular, solutions for the stop liquid sub-function must be analyzed for strength and appropriate wear characteristics.

We explain the above two functions and their corresponding failure modes to illustrate the interpretation of the function-failure matrix in Table 7.

Table 6. Composite Function-Failure Matrix $EF_c$.

| FUNCTION - FAILURE MATRIX | ABRASIVE WEAR | ADHESIVE WEAR | BIOLOGICAL CORROSION | BRINELLING | BRITTLE FRACTURE | BUCKLING | CORROSIVE WEAR | DEFORMATION WEAR | DIRECT CHEMICAL ATTACK | DUCTILE RUPTURE | ELECTROCHEMICAL CORROSION | FORCE INDUCED DEFORMATION | FRETTING | FRETTING FATIGUE | GALLING AND SEIZURE | GALVANIC CORROSION | INTERGRANULAR CORROSION | HIGH CYCLE FATIGUE | PITTING CORROSION | SURFACE FATIGUE WEAR | TEMPERATURE INDUCED DEFORMATION | THERMAL FATIGUE | THERMAL RELAXATION | THERMAL SHOCK | YIELDING |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ACTUATE ELECTRICITY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 5 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 15 |
| ALLOW X-Y DEGREE OF FREEDOM | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| CHANGE ELEC. ENERGY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| CHANGE ROTATION | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| CHANGE FORM SOLID | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CHANGE TORQUE | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 |
| CHANGE VELOCITY | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CONVERT ELEC. ENERGY TO ROT. ENERGY | 7 | 9 | 0 | 8 | 7 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 2 | 0 | 0 | 1 | 2 | 2 | 2 | 0 | 0 | 0 | 4 |
| CONVERT ELEC.E TO MECH.E | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 2 | 1 | 0 | 0 | 2 |
| CONVERT ELECTRICAL ENERGY TO THERMAL ENERGY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| CONVERT HUMAN ENERGY TO TRANSLATIONAL ENERGY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| CONVERT R.E. TO P.E. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 2 |
| CONVERT ROT. ENERGY TO VIBRATIONAL ENERGY | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| COUPLE MECH.ENERGY | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| DISSIPATE THERMAL E. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| DISTRIBUTE MECH. ENERGY | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 5 |
| EXPORT ELEC. ENERGY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| EXPORT GAS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| EXPORT LIQUID | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| EXPORT SOLID | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 |
| EXPORT VISUAL SIGNAL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| GUIDE GAS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| GUIDE LIQUID | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 5 |
| GUIDE SOLID | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IMPORT ELEC. ENERGY | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 1 |
| IMPORT GAS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| IMPORT HAND | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 4 |
| IMPORT HUMAN ENERGY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 4 |
| IMPORT LIQUID | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| IMPORT MECH.ENERGY | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 7 |
| IMPORT SOLID | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| MIX SOLID AND LIQUID | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| POSITION SOLID | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 4 |
| REGULATE ELECTRICITY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| REGULATE MECH.ENERGY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| REGULATE ROTATION | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| REGULATE TRANSLATION | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| REMOVE SOLID | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 |
| SECURE MECHANICAL ENERGY | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 2 |
| SECURE SOLID | 3 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 11 | 1 | 0 | 8 | 0 | 1 | 0 | 0 | 0 | 2 | 0 | 0 | 9 | 2 | 3 | 2 | 44 |
| STABILIZE MECH. ENERGY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| STOP LIQUID | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| STOP SOLID | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 5 |
| STOP THERMAL ENERGY | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| STORE LIQUID | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| STORE SOLID | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 3 |
| TRANSMIT ELEC. ENERGY | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 11 | 0 | 0 | 0 | 4 |
| TRANSMIT MECH.ENERGY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 1 | 0 | 1 |
| TRANSMIT ROTATION | 2 | 1 | 0 | 1 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 2 |
| TRANSMIT THERMAL ENERGY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 1 | 2 |
| TRANSMIT VIBRATION | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

Table 7. Interpretation of Results

| FUNCTION | FAILURE MODE | INTERPRETATION |
|---|---|---|
| Stop Liquid | | Function of a lid or cover like part that shields or insulates the liquid |
| | Corrosive Wear | Liquid itself or the suspended inpurities in the liquid act as a corrosive agent and wear the material |
| | Force Induced Deformation | Lid is hinged and carelessness on the cutomers part while opening and closing can cause it to get separated from the part |
| | Yielding | Denotes plastic deformation and is mainly due to the fact that most of the lids in the study were plastics |
| | | |
| Secure Solid | | Function of part that helps to attach, mount, lock, fasten or hold other parts. |
| | Abrasive Wear | Fasteners that come in the path of flowing material |
| | Corrosive Wear | Fasteners that may be in contact with oil or other lubricants or exposed to corrosive atmosphere |
| | Direct Chemical Attack | Fasteners outside the product and employed in places like kitchen, workshop etc. |
| | Ductile Rupture | Fastener is made of ductile material and located in a very hazardous environment |
| | Force Induced Deformation | Plastic holders that help in holding or attaching a component |
| | Fretting Fatigue | A lock formed by joining two parts and is subjected to fluctuating loads |
| | High Cycle Fatigue | Locks subjected to fluctuating loads |
| | Temperature Induced Deformation | Fasteners are located near parts that are involved in the process of generating heat |
| | Thermal Fatigue | Fasteners are located near parts that are involved in the process of generating heat and the temperature is fluctuating |
| | Thermal Relaxataion | Washers that are pre-strained but due to heat loose their straining and malfunction |
| | Thermal Shock | Washers that are pre-strained but due to heat loose their straining and thus malfunction and the failure is due to a sudden and dramatic change in temperature |
| | Yielding | Plastic fasteners that undergo plastic deformation |

## 5. CONCLUSION

In this paper, the function-failure method, first introduced by Tumer and Stone [2], has been standardized by implementing a standard vocabulary for the description of functions and the failure modes of components. The method is meant to provide designers with an analytical tool to identify potential failure modes in the conceptual design stage. Additionally, a major contribution to the failure modes literature is presented in the failure mode identification table with primary and secondary identifiers to aid in selecting the appropriate failure mode. The method is applied to five products and the composite function-failure matrix is formed to illustrate its potential as both an analytical tool and an educational tool. It is meant to aid the development of new products that do not have failure data and aid in the repeatability and usability of procedures like Failure Modes and Effects Analysis.

As ongoing and future work, we plan to apply the function-failure method to a number of products and apply statistical procedures to determine similarity between functions and/or among failure modes. This paper dealt with the binary form of the component-failure matrix. We plan to augment the function-failure matrix with crucial parameters like severity ratings or risk priority numbers and determine if they can be of any help in relating functions and failure modes.

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# EXPANSION AND STANDARDIZATION OF FAILURE MODE CLASSIFICATION

## 1. FAILURE MODES – EXPANDING THE WORK OF COLLINS

The Collins failure classification was used a starting point in this research and in this section we expand the failure modes list to include failure modes characteristic of newer materials and components. We have included new failure modes for those components that were encountered during the course of this work and whose failure mode could not be identified under the Collins classification. The new failure modes encountered dealt with components composed of plastics, elastomers (rubber), printed circuit board (PCB) and glue joints. The derived failure modes for each of the new classifications are described in the following sections.

## 2. FAILURE MODES – PLASTICS

Plastics were one of the most frequently encountered materials in this work. It was felt that the Collins classification could not accurately describe all the failures encountered by plastics. As the use of plastics is growing every day we classified the failure modes of plastics based on the list created by Spoormaker [1]. This classification along with Collins classification can describe most of the failure modes of plastics. Table 1 gives the failure modes of plastics. The failure modes in bold are the additional failure modes for the plastic, while the other failure modes are a part of Collins classification.

Table 1. Failure Modes – Plastics

| PRIMARY IDENTIFIER | SECONDARY IDENTIFIER | FAILURE MODE |
|---|---|---|
| Plastic | Stress Concentration, Creep | CREEP STRESS RUPTURE |
| Plastic | Low mass and/or mould | **STRESS RELAXATION** |
| Plastic | Caused by Temperature | WEAR |
| Plastic | Highly stressed weld lines | Fatigue |
| Plastic | Faulty Ribbing | **AGEING** |
| Plastic | Too high stiffness | **UV-DEGRADATION** |
| Plastic | Incorrect joining | **CRACKING** |

## FAILURE MODES – ELASTOMERS

Elastomers or rubber was another material whose failure modes were not adequately described by the Collins classification. The following failure modes list was prepared from the failure modes identified by Greene Tweed [2]. The failure modes in bold indicate new failure modes that were not a part of the Collins classification.

Table 2. Failure Modes – Elastomers

| **PRIMARY IDENTIFIER** | **SECONDARY IDENTIFIER** | **FAILURE MODE** |
|---|---|---|
| **Elastomer** | Produces a **flat surface** at the cross-section of the polymer and system **temperature too high** | **COMPRESSION SET** |
| Elastomers near **reciprocating, oscillating or rotary mechanism**, less lubrication, excessive temperature, surface too rough or smooth, presence of contamination | **Flattened surface** on one side of cross-section with axial or radial score marks depending on whether it is reciprocating or oscillatory/rotary | WEAR / ABRASIVE WEAR |
| Elastomer is **swollen and softer**, deteriorates and increases possibility of extrusion | chemical composition of elastomer not resistant to fluids in contact | DIRECT CHEMICAL ATTACK |
| Elastomers near **pneumatic** or air systems | appears **pitted or cracked** accompanied by flatness produced by compression set | **HEAT HARDENING** |
| **Excessive temperature**, elastomer hardens and plasticizer vaporizes and elastomer is less resistant to tensile stress and cracks | **cracks** on surface | **HEAT CRACKING** |
| **Sharp edges** on mating metal, no lubrication, improper use of installation tools | short cuts , notches or skinned or **peeled surface** | **INSTALLATION DAMAGE** |
| At **high pressure systems**, excessive clearance, excessive pressure, degradation of elastomer | elastomer forced through clearance gaps | **EXTRUSION** |
| **Tensile stress** exceeds tensile strength of elastomer, places where there is high breakaway friction | micro-tensile breaks on the surface | **POCK MARKS** |

## 4. FAILURE MODES – PRINTED CIRCUIT BOARDS (PCB)

The Collins classification is essentially a classification of mechanical failures. We managed a few electrical failures by identifying it with temperature induced deformations, where an excess of current caused a temperature increase and ultimately lead to the malfunction of the component. Thus electrical and electronic failure modes are areas where a lot of failures are to be classified. Here we describe only the failure modes experienced by Printed Circuit Boards that are frequently encountered in products like printers, VCR and other electronic devices. The classification is developed from the work of Vishwanadham and Singh [3]. Table 3 gives the failure modes for a printed circuit board. All the failure modes are new and have never been addressed in the Collins classification.

# Table 3. Failure Modes – Printed Circuit Board

| PRIMARY IDENTIFIER | SECONDARY IDENTIFIER | FAILURE MODE | |
|---|---|---|---|
| **PCB**- Material related failure | **Cracks** developed in epoxy-fiber interface under very high stresses during **lamination** and via **drilling**. | PREPREG DEFECT | MATERIAL RELATED DEFECTS |
| **Bundles of glass fiber** cross each other and usually there is **epoxy starvation** and **loss of adhesion** between glass fiber and epoxy caused by thermal, high pressure or mechanical impact | Appearance of **white spots** or crosses that look like plus signs | MEASLING | |
| Measling spots merge together | Found around **drilled holes** | CRAZING | |
| Localized **microcrazing** | Found around a **drilled or a punched** hole | HALOING | |
| **Separation** of prepreg and copper layers | Localized - **small area** | BLISTERING | |
| **Separation** of prepreg and copper layers | Over a **large area** | DELAMINATION | |
| **Remains of silver of resist** that should have been etched away, which protects the copper from being etched | Causes a **Short** | COPPER ETCH SHORTS | SIGNAL/POWER PLANE PLATING SURFACE DEFECTS |
| **Resist is removed** from the area where copper is not to be etched | **open type** of defect occurs due to removal of the desired copper | COPPER ETCH OPENS | |
| **Handling** of thin circuit cores and composites, exposing them to mechanical damage | Lead to **open circuit** | MECHANICAL CIRCUIT DAMAGE | |
| **Fingerprints** on clean plated copper surface | can cause oxidation and skin oil contamination leading to **adhesion problems** | HANDLING DEFECTS OF PLATED COPPER SURFACE | |
| **Contaminants** such as Grease, dust, fibres,hair, skin flakes | cause plating deposition and adhesion problems | PARTICULATE CONTAMINATION | |
| Deep pits or scratches, metal chips caused by **scratching** | can cause circuit shorts or reduce minimum distance between the conductors | PITS AND SCRATCHES | |
| **Blooming or copper nodules or residual copper** from incomplete etching | reduce insulation distance between two conductors | REDUCED CONDUCTOR SPACING | |
| Hole does not go through all the layers of composite and produces **blind hole** condition due to incorrect drilling spindle height | For Leaded or through holes component lead cannot be inserted and soldered and in interconnection via an open will occur owing to lack of metal to metal bond at foil copper interface | PARTIALLY DRILLED HOLES | THROUGH-HOLE DEFECTS |
| **Drill bit is dull** and speed/feed ratio is not optimized, instead of cutting drill stars to extrude and punch through PCB material. The **epoxy becomes soft** due to excessive heat and is dragged across copper interface and hole wall creating a thin layer of epoxy smear | the smear creates a poor bond between plated copper and the hole wall including the inner plane copper interface. This condition may cause weak joints that may cause opens during component assembly and thermal stress test failures during reliability evaluation | EPOXY SMEAR | |
| In **multilayer** boards expansion of inner plane(IP) copper layer occurs caused by mechanical deformation of IP copper when drill bit does not perform a clean cutting action | Incorrect speed/feed ration, worn bit, incorrect drill geometry. Leads to weak points in the plated copper, leading to stress cracks. | NAILHEADING | |
| **Delamination of IP copper** from epoxy laminate during drilling | causes voids and discontinuities in plated copper whose fatigue properties are poor | INNER PLANE DELAMINATION | |
| **Brittle copper** with horizontal grain structure is weak in tensile force exerted on the barrel during wave solder process | develops cracks and fissures | PTH COPPER GRAIN STRUCTURE | |
| During **hole drilling** burrs on drilled holed corners, rough hole wall, exposed glass fibers, expose smear, copper nodules, brittle copper, **contaminations** are created | reduce the uniformity and mechanical strength of plated copper | PTH COPPER PLATING DEFECTS | |
| **poor hole fill** during the wave solder process | 1. **Barrel copper crack** at the IP interface prevents the solder from filling the hole. 2. Copper tries to plate into void cavity bit was unable to bridge the gap. **Outgassing** during wave solder prevents solder from filling the PTH. 3. Exposed **glass fibers** cause discontinuity in copper plating along the circumference of drilled hole which prevents solder flow | PTH SOLDERABILITY | |
| **Adhesion** of copper to prepreg is poor, **localized delamination** occurs at the interface due to drilling. | processing, cleaning, plating chemicals attack the oxide layer dissolving the oxide. This region around the hole looks pink | PINK RING | |
| Inaccurate and imprecise **registration of solder mask** | exposes underlying copper circuitry to etch ants, solder, plating chemicals, atmospheric corrosion, degradation, handling damage and provide electromigration barrier. | SOLDER MASK RELATED DEFECTS | |

## 5. FAILURE MODES – GLUE JOINT

The failure of a glue joint by themselves may not be a matter of great concern but when combined with other factors they can be of enormous concern. The following failure modes of a glue joint are from the list provided by Wengert [4].

Table 4. Failure Modes – Glue Joint

| PRIMARY IDENTIFIER | SECONDARY IDENTIFIER | FAILURE MODE |
|---|---|---|
| **Low spread rate**, too much **pressure** squeezing all adhesive out, too much **penetraion** into prorous surface | Insufficient adhesive | STARVED JOINT |
| The adhesive **solidifies** before spreading,trasnfering to **mating** surface,**penetrating** and before bonding with the surface | | PRE-CURED JOINT |
| The adhesive flowed , transferred onto mating surface and penetrated corners but **failed** to from **strong bonds** with surface | | UNANCHORED JOINT |
| The adhesive fails to **solidify** | | UNDER-CURED JOINT |

## 6. SUMMARY

The failure modes classification has been extended to include materials and components like elastomers, plastics, printed circuit boards and glue joints. This classification is used in future work and has been employed in the next section.

# A CLUSTERING-BASED APPROACH FOR FAILURE MODE IDENTIFICATION

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## ABSTRACT

Research has shown that nearly 80% of the costs and problems are created in product development and that cost and quality are essentially designed into products in the conceptual stage. Currently failure identification procedures (such as FMEA, FMECA and FTA) and design of experiments are being used for quality control and for the detection of potential failure modes at the conceptual design stage. Though all of these methods have their own advantages, they do not give information as to what are the predominant failures that a designer should focus on while designing a product. This work uses a functional approach to identify failure modes, which hypothesizes that similarities exist between different failure modes based on the functionality of the product/component. In this paper, a statistical clustering procedure is proposed to retrieve information on the set of predominant failures that a function experiences. The various stages of the methodology are illustrated using a hypothetical design example.

## 1. INTRODUCTION

Identification of potential failure modes during the product design process is critical for creating failure-free designs. Currently industries use procedures such as Failure Modes and Effects Analysis (FMEA), Fault Tree analysis, or Failure Modes, Effects and Criticality analysis (FMECA), as well as prior knowledge and experience, to determine potential failure modes. These procedures require designers to have a broad knowledge of commonly occurring failure modes and to understand any connections (causality) between failures for successful implementation. If there is a lack of sufficient knowledge to predict all of the realistically possible failure modes, then the current failure prevention procedures may fail.

To increase the effectiveness of failure identification and prevention procedures, we build on a function-failure method introduced by Tumer and Stone [1] where functionality is used to guide the determination of potential failure modes a product may be subject to, once placed in its operating environment. In this paper, this work is extended to explore the statistical characteristics of failure modes by means of clustering methods, using the set of failure modes and functions generated in Arunajadai et al. [2]. Using the results of the cluster analysis, a methodology is proposed for failure-free design in the conceptual design stages. The following subsections first describe the function-failure method briefly, followed by a discussion of how failure is documented, and some background on statistical means to retrieve failure information. Then, a detailed discussion of a functional approach to study potential failure modes is presented, where an investigation of failure distributions is used as the basis for the proposed clustering approach. The main contribution of this paper is the clustering approach to study potential failure modes, which is presented in detail next, including some background on clustering techniques, and application to a hypothetical design example.

## 2. THE FUNCTION-FAILURE METHOD FOR FAILURE-FREE DESIGN

Standardization of product function vocabulary in the effective maintenance and utilization of a product design knowledge base has been a primary research area for many years now [3-6]. In this work we use the functional basis developed by Hirtz et al [3] and Stone et al. [6] to link failure back to the more abstract product function. Similar work has been suggested for the classification of failure modes. Collins [7] has described 23 different mechanical failures based on the characteristics of the manifestation of failure, the failure inducing agent and the location of failure. There are other classifications like those based on the end effect of the failure [8] and the design stage in which the failure mode might have been introduced [9]. Our current work starts with the Collins classification and augments it such that each failure mode is identified with the help of a primary and secondary identifier [1, 2].

This work employs a functional approach first introduced by Tumer and Stone [1], and explored further by Arunajadai et al. [2] and Roberts et al. [10]. It involves the use of matrices to record data and the use of the functional basis to describe functions and the failure classification to describe failure modes. The schematic of the approach is shown in Figure 1, with the input information including a product's bill of material and functional model.

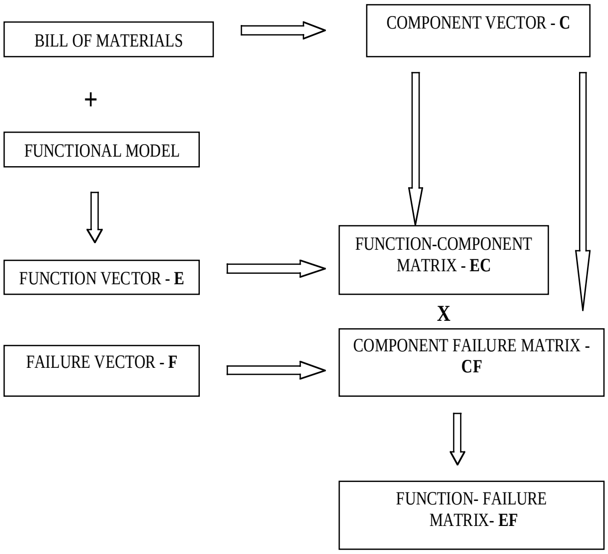

Figure 1. Schematic of the Functional Approach.

## 3. DOCUMENTING FAILURE

Over the years many procedures have been developed to document failure data. Notable among them are the Failure Mode and Effects Analysis (FMEA), Failure Modes Effects and Criticality Analysis (FMECA) and the Fault Tree Analysis (FTA). In this work we take a new look at the principles of FMEA and present a methodology for failure-free design of products.

The FMEA procedure is an offshoot of the Military procedure MIL-P-1629 [11] developed by the United States Military as a tool to determine and evaluate equipment failures. Many industries have developed their own standards of performing the FMEA like the AIAG (1993) of the Automotive Industry Action Group, MIL-STD-1629A (1984) of the US Department of Defense, SAE J1739 (1994) of the Society of Automobile Engineers and the VDA 96, Heft4, Teil 2 (1996) of the Verband der Automobileindustrie, Germany.

The Traditional FMEA when performed rigorously contains valuable information about the failures of various components but has two fundamental weaknesses – lack of a methodological guideline to conduct the FMEA and the employment of natural language in recording the information [12]. Current Industrial FMEA practice is severely restricted in its usefulness and analytical power because of limitations of spreadsheet based approaches to acquiring, representing and reasoning with system failure knowledge. Thus the standardization of the failure mode vocabulary would make the procedure more useful and repeatable.

In this work, we use a matrix-based method to help sort through the failure modes associated with products. A matrix approach to recording failure data was introduced as early as 1976 by Collins et al. [13] and the concept of applying matrix techniques to FMEA was introduced in 1977 by Barbour [14] and subsequently developed by Goddard and Dussault [15]. More recently the matrix technique has been employed by Henning and Paasch [16] to represent the failure and replacement characteristics of a system.

## 4. RETRIEVING FAILURE INFORMATION – THE STATISTICAL APPROACH

Statistical tools have been employed for quite some time now in quality control and reliability measurement. The need to meet the intense global competition where manufacturers are challenged to design and manufacture high reliability products in shorter product cycle times with stringent cost constraints has lead to the increased use of statistical principles in design and manufacturing.

A structural approach based on probability theory for the design and safety analysis of aircraft began in the early 1960's [17]. The use of numerical probabilities may not be a prerequisite for carrying out system safety analyses but it provides valuable guidance to the designer in determining the architecture required and is a useful tool in assessing its failure tolerance. The prediction of system failure probabilities is not a precise science, however the process does provide an extremely good framework on which to hang engineering experience [17] and the final decision being made on the basis of engineering judgment. Lee [18] has employed the Bayes networks, which constitute a mathematically sound method for representing and reasoning with joint probability distributions in an internally consistent manner, to account for the conditional dependencies between states and events in the causal chain and across causal chains. Traditional FMEA ignores these connections and implicitly assumes that all failure states and events, together with their causes and effects, are probabilistically independent.

Probabilistic design is concerned with the probability that a system will realize the function assigned to it without failure. Onyebueke et al. [19] give an overview of the Probabilistic Design Methodology (PDM) with emphasis on the quantification of the effects of uncertainties for the structural variables and the evaluation of failure probabilities. PDM takes into consideration reliability, optimization, cost parameters and the sensitivity of design parameters, which is ignored by the deterministic method and is extremely useful in designs characterized by complex geometry, sensitive loads and material properties. The method is limited in use due to three identifiable factors: 1) most people are unaware of the capabilities of the PDM and the available computer codes; 2) there is not yet a universal decision as to what constitutes an acceptable risk; and 3) there is very little information on most design parameters [19].

Bhonsle et al. [20] have developed a statistical distribution function called adaptive distributive function model, which is compatible with collected data and produces conservative designs at low tail ends. Meeker and Hamada [21] discuss the role of statistical process monitoring and designed experiments as tools for design engineers in their quest for quality improvement and their application to conceptual degradation based reliability model. They also differentiate between the traditional reactive approach where the reliability requirements are not met at the time of delivery of the product which can lead to additional expense, increased inconvenience, loss of revenue and goodwill, delay of product introduction, uncertainty of future product reliability, and delay of efforts in the next generation of product development and the proactive reliability assurance approach which emphasizes the use of reliability tests and experiments and the use of past field data to meet reliability requirements early in the design stage. Yang and Xue [22] describe the application of the fractional factorial design of experiment method to degradation testing and reliability design. Marco et al. [23], while describing the integration of the FMEA and serviceability design, raise the need for calculating statistical and probabilistic occurrence measures for each type of failure mode depending on component type, operational environment or duty cycle.

## 5. KEY ISSUES

The functional approach to failure-free design, used in this paper, provides a systematic methodology for storing and exploring function and failure data in an informative way. Apart from providing a means to store data in a standardized vocabulary it also helps in storing data that is more conducive to statistical or other kind of analyses. Most statistical tools developed over the years for reliability design have been important tools in designing reliable products. But their use and repeatability has been severely hampered by their non-standardized ways of describing failure modes or their effects or causes. This difficulty is aggravated by the often powerful but complex statistical computations.

This paper addresses these key issues by proposing a statistical cluster analysis approach, described in the following sections.

## 6. FAILURE MODES STUDY – A FUNCTIONAL APPROACH

The failure-function approach described in [1, 2, 10] is used as a starting point in this research work. This method provides a standardized vocabulary to record failure data and a matrix approach to store failure information, which helps in easy retrieval of data and aids in further calculations of similarities between designs and failure modes, with the purpose of eliminating operational failures. In this paper we go one step further to show how the matrix approach aids in identifying critical failure modes and functions, by making use of the probabilistic characteristics of the observed failure modes.

### 6.1. General Observations

We know by experience that certain failure modes occur more frequently than the others. The question we want to answer is: are there functions that are more critical than other functions? Stated another way, are there functions that typically experience more failures than other functions? Such information would be of immense importance in the conceptual design stage so that the designer can take appropriate measures to ensure the best possible design. It is our hypothesis that if the failure mode occurrence knowledge is easily accessible, the designer can focus on the appropriate analyses to prevent the failure modes.

To test this hypothesis we examined a set of 41 consumer products. The following observations were made from the three resulting matrices: 1) EC, the function-component matrix; 2) CF, the component-failure matrix; and 3) EF, function-failure matrix that are generated as a part of the functional approach.

**Distribution of Failure Modes**: The total number of occurrences of each failure mode was calculated from the component-failure (CF) matrix. A Pareto chart was plotted for the occurrence of the failure modes and is shown in Figure 2.

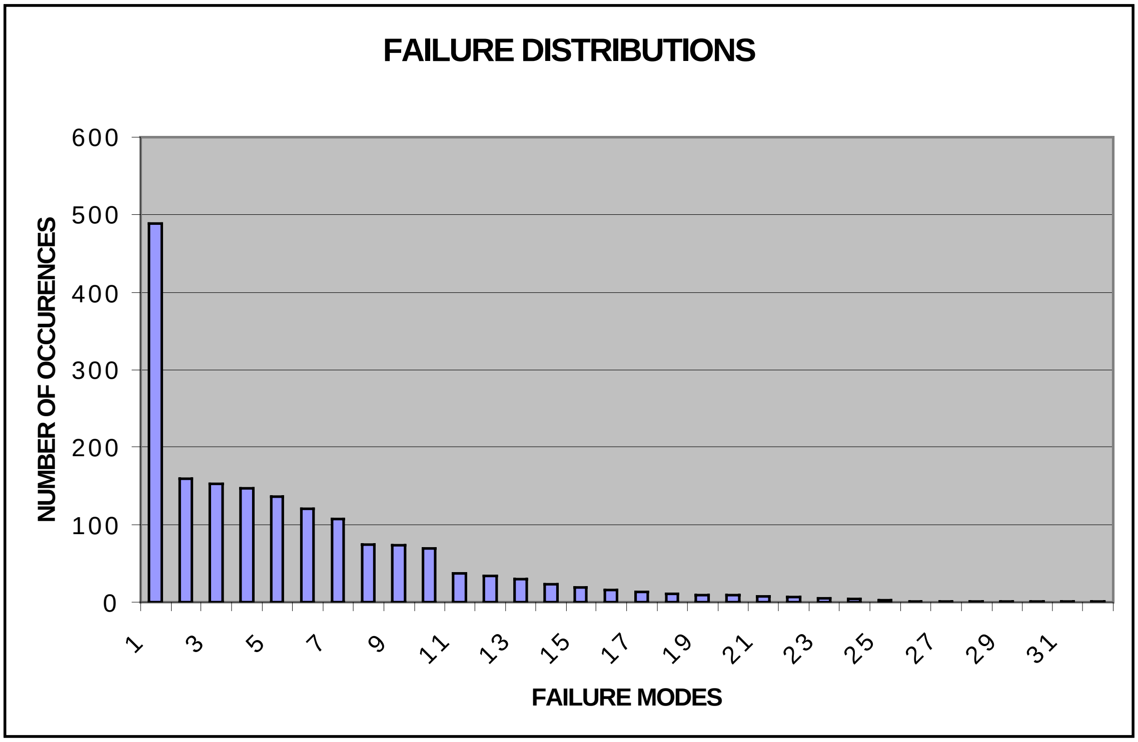

Figure 2. Failure Mode Distributions.

It is evident from the graph that certain failure modes occur more frequently than the others. In fact 92% of the failures were accounted by just 40% of the failure modes, i.e., 92% of the failures were contributed by just 13 of the 32 failure modes. Thus by concentrating on these failure modes, the designer can be assured that the major failure types have been taken care of. To verify this fact we checked the component-failure matrix to see the number of failure modes that were overlooked per component. Of the 1001 components in the matrix only 134 of them exhibited failure from the 19 infrequently occurring failures. Of these 134 components only 8 of them exhibited 2 of these 19 failure modes and the rest just 1 of the 19 failure modes. Thus, on an average for the 1001 components, we overlooked 0.141failure mode per component belonging to the 19 less frequently occurring type. This was calculated by determining the number of failure modes that were not addressed for a component after taking into account the 13 primary failure modes. Then the average was calculated for the 1001 components.

**Distribution of Failures Across Functions:** The sum of each row corresponding to the given function in the function-failure (EF) matrix gives the number of failures experienced by the function for the time period observed. A Pareto chart was plotted for the number of failures for a given function and is shown in Figure 3.

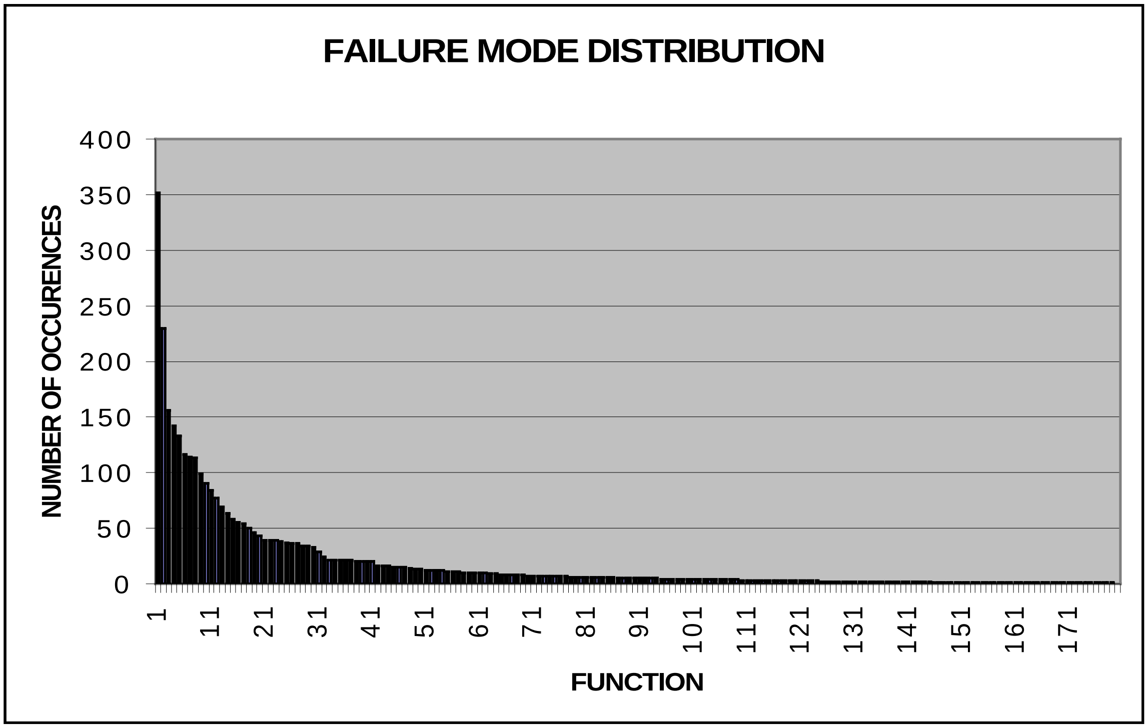

Figure 3. Failure Modes for a Given Function.

As seen from Figure 3, there are certain functions that exhibit more failures both in type of failures and the number of occurrences. Only 42 of the 180 functions experienced at least 1% of the failures. Thus the designer can focus his time and money on these functions that are more critical in design than the others.

**Number of distinct failure modes with increasing functions:** As the number of functions increase, the number of distinct failure modes that are contributed by the new function decreases. That is, there is a limit after which the addition of a new function does not contribute a new distinct failure mode. This fact reinforces the hypothesis that the designer can concentrate on a particular set of failure modes, as the additional functions are very unlikely to add a substantial number of new distinct failure modes. Figure 4 shows the plot of the number of distinct failure modes with increasing number of functions. It is seen that that there are no new failure modes observed after 9 functions.

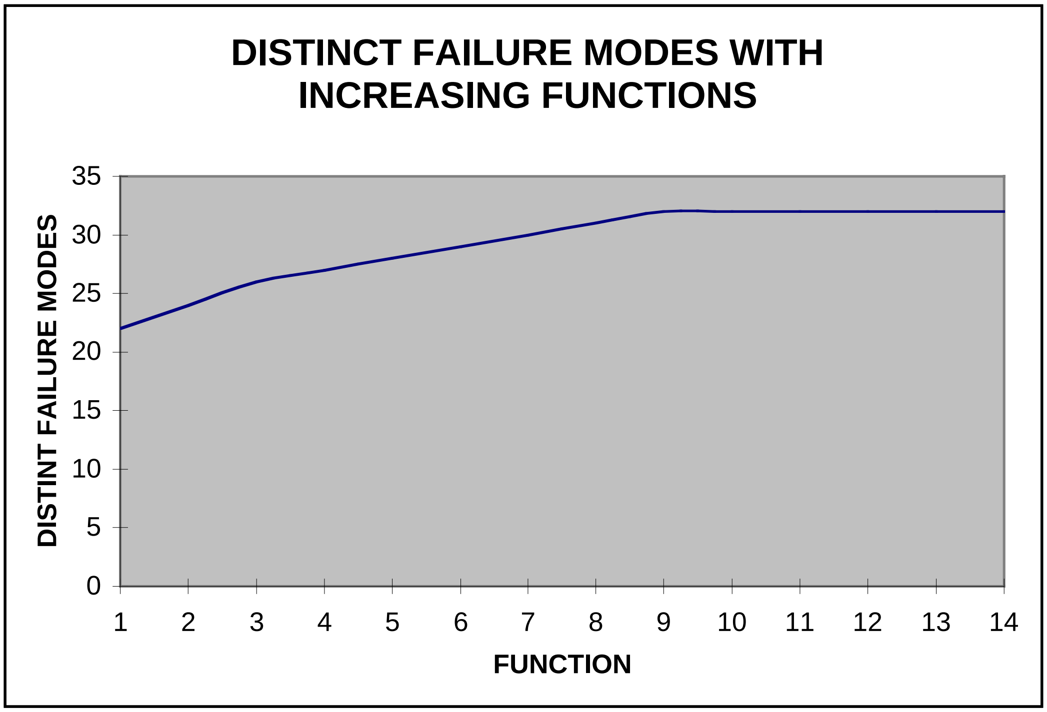

Figure 4. Distinct Failure Modes with increasing functions.

**Number of distinct failure modes with increasing components:** As with the functions, as the number of component increase, the number of new distinct failure modes observed in a component decreases. That is, as the number of components increase, the probability that it would experience a new distinct failure decreases. As shown in Figure 5, the number of distinct failure modes observed decreases as the number of components increase.

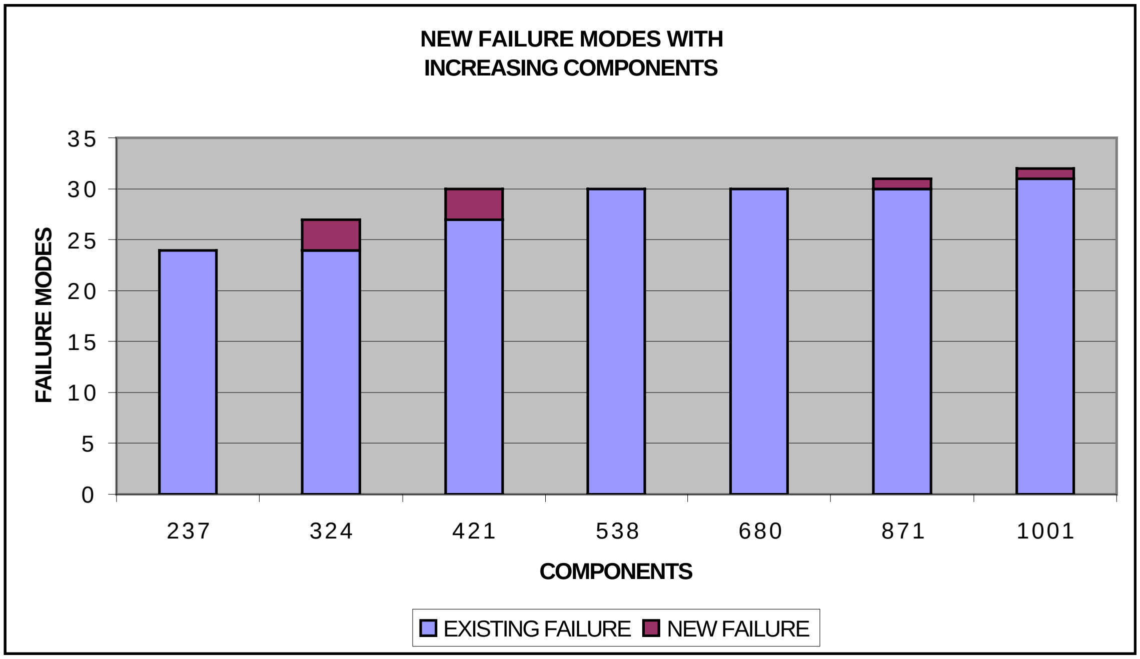

Figure 5. Distinct failure modes with increasing components.

## 7. PRESENT SCOPE OF RESEARCH

To summarize, our empirical study of 41 products provides a reliable knowledge base on which to propose a new statistically –based failure free design approach. The addition of new components or new functionality is not expected to significantly alter our findings. For this paper, we only focus on the failure mode occurrence data. While typical FMEA approaches also include severity and detectability data, we will be confined to occurrence data and the inherent statistical knowledge it holds.

## 8. FAILURE MODES STUDY-- A CLUSTERING APPROACH

Time is money and this all the more true for product development especially in today's highly competitive market. Thus the key to success is to get the product to the customer in the shortest possible time ensuring maximum performance and safety. The issue is whether this can be accomplished without a substantial increase in cost of product development.

Let us examine a simple hypothetical design situation. Assume a product in which the function *Stop Gas* is involved. Using the concept generator approach, by pre-multiplying the function-component (EC) matrix by an appropriate filter matrix, we obtain the morphological matrix containing possible component solutions to the function [1, 2]. We present here the morphological matrix pertaining to the function *Stop Gas* alone in Table 1.

Table 1. Morphological Matrix for the Function *Stop Gas.*

| FUNCTION / COMPONENT | RUBBER PISTON SEAL | O-RING | RUBBER SEAL PLUG | AIR TUBE CAP | RUBBER PRESSURE GAUGE RING | SPACER | RUBBER BARREL SEAL |
|---|---|---|---|---|---|---|---|
| STOP GAS | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Though it is not necessary for a designer to use the component solutions obtained from the morphological matrix, here we select the solution of using some kind of a rubber seal to accomplish the function *Stop Gas*. The designer's decision of which failure modes should be the focus of the analysis depends on the application– it could be a simple home-product where the seal just acts as an obstruction for stagnant air or the highly complex aerospace industry products where the seal might have to stop the flow of gas at high pressure and temperature. Let us refer to the function-failure matrix (EF) to know what kind of failure modes are exhibited by the function *Stop Gas*. The reduced EF matrix with the failures corresponding to the function Stop Gas alone is shown in Table 2.

Table 2. EF Matrix for the function *Stop Gas.*

| FUNCTION / FAILURE MODE | ABRASIVE WEAR | BRITTLE FRACTURE | COMPRESSION SET | CORROSIVE WEAR | CRACKING | DEFORMATION WEAR | DIRECT CHEMICAL ATTACK | FORCE INDUCED DEFORMATION | HEAT CRACKING | HIGH CYCLE FATIGUE | INSTALLATION DAMAGE | TEMPERATURE INDUCED DEFORMATION | YIELDING |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STOP GAS | 1 | 0 | 3 | 0 | 1 | 0 | 0 | 4 | 0 | 0 | 1 | 0 | 0 |

We see that the function *Stop Gas* has experienced 5 distinct failure modes for the time period observed. The question now is whether the designer should concentrate on all the failures during design. In this rather simple case, the difference between designing for 5 failures and 3 failures may seem trivial. But consider cases where a function exhibits 15 different kinds of failures or for multiple functions of a product. It would be of great advantage to know if there is a particular set of failures that a designer could concentrate on which could ensure safety of the product and, at the same time, save cost and reduce time of product development. The next section explains a cluster analysis approach that would help extract the information as to the set of failure modes that a designer can concentrate on.

### 8.1. Background: Cluster Analysis

Cluster analysis is a multivariate statistical procedure that starts with a data set containing information about a sample of entities and attempts to reorganize these entities into relatively homogeneous groups. It is helpful when a researcher tries to classify or group data into categories or groups when neither the number of groups, nor the members of the group are known. Clustering has proved to be good technique to be used in exploratory data analysis when it is known that the sample is not homogeneous [24].

There are two main methods by which clustering analysis is performed – Hierarchical clustering and K-means clustering. In this paper we have used the hierarchical clustering as the number of cases is small (32 failure modes); the K-means method is more advantageous when there are a large number of cases (greater than 200). In the hierarchical method, clustering begins by finding the closest pair of objects, according to a distance measure and combines them to form a cluster. The algorithm continues one step at a time, joining pairs of cases, pairs of clusters, or a case with a cluster, until all the data are in one of the clusters. The method is hierarchical because, once two cases or clusters are combined, they remain together until the final step. The hierarchical clustering offers several methods for combining or linking clusters. In this work we have used the complete linkage method [24].

The complete linkage method rule states that any candidate for inclusion into an existing cluster must be within a certain level of similarity to all members of that cluster. This rather rigorous rule of the complete linkage method has a tendency to find relatively compact, hyperspherical clusters composed of highly similar cases.

The disadvantage of the cluster analysis is that, though the algorithm helps in forming the clusters, the final decision as to how many clusters and the membership of the cluster is dependent on the researcher’s judgment. Most algorithms cluster the cases according to the number of clusters input by the user. The user performs this a number of times and with the help of other indicators like dendograms, a tree diagram that depicts the clustering sequence, decides which is the best set of clusters. However the method acts a useful starting point for grouping data, especially when the data space is too large to analyze.

## 8.2. Technical Approach

As described in the previous sections, the cluster analysis is a multivariate statistical procedure that helps to group or categorize data. Our attempt is to group failure modes based on their occurrence data – i.e., we would like to have the information as to whether the failure is to be considered by itself or whether it has a tendency of accompanying other kinds of failure. The cluster analysis is performed using the SPSS software. The software gives different cluster combinations and the research team interpreted the clusters and decided upon the best number of clusters and their membership. To get the failure mode groupings, the cluster analysis is performed on the failure similarity matrix, which is obtained by pre-multiplying the component-failure matrix (CF) by its transpose [1]. The similarity matrix is shown in Figure 6.

$$\Lambda = CF^{T} \times CF \qquad (2)$$

The hierarchical clustering algorithm using the complete linkage method was performed on the data. The software grouped the data into clusters ranging in from 6 clusters to 15 clusters with minor variations at each stage. The different cluster combinations were studied and the number of clusters for this set of data was fixed at 9 based on engineering judgment. Thus we have grouped the 32 failure modes identified in this work into 9 groups as shown in Table 3.

Table 3. Cluster Grouping of Failure Modes.

| CLUSTER | MEMBERS |
|---|---|
| **Cluster - 1** | Abrasive Wear |
| | Compression Set |
| | Heat Cracking |
| | Installation Damage |
| **Cluster - 2** | Adhesive Wear |
| | Deformation Wear |
| **Cluster - 3** | Ageing |
| | Biological Corrosion |
| | Blistering |
| | Ductile Rupture |
| | Fretting Fatigue |
| | Galvanic Corrosion |
| | Impact Fretting |
| | Impact Fatigue Wear |
| | Intergranular Corrosion |
| | Starved Joint |
| | Thermal Fatigue |
| | Thermal Relaxation |
| | Thermal Shock |
| **Cluster - 4** | Brittle Fracture |
| | Temperature Induced Deformation |
| **Cluster - 5** | Corrosive Wear |
| | Yielding |
| **Cluster - 6** | Cracking |
| | Creep Stress Rupture |
| | Galling and Seizure |
| | High Cycle Fatigue |
| | Surface Fatigue Wear |
| **Cluster- 7** | Creep Buckling<br>Impact Deformation |
| **Cluster - 8** | Direct Chemical Attack |
| **Cluster - 9** | Force Induced Deformation |

## 8.3. Interpretation of the Cluster Groups

Cluster-8 and cluster-9, which have *direct chemical attack* and *force induced deformation* respectively, are single member clusters. This is because of the fact that these two failures have a very high frequency of occurrence and occur along with a variety of failure modes. Hence they are placed in an individual group so that they will be considered in all design situations. We shall call such clusters Type-I clusters.

Clusters 1, 2, 4, 5, 6, and 7 comprise failure modes that have a tendency to occur together. In cluster-1 *abrasive wear* has 74 occurrences while the other members of the cluster have a maximum of about 5 occurrences. They are still being placed in a single cluster because abrasive wear on most occasions occurred by itself; if it did occur with other failure modes they predominantly occurred with failure modes in cluster-1. Similarly, the failure modes in clusters 2, 4, 5, 6, and 7 have a tendency of occurring together. We will call such clusters Type-II clusters.

Cluster 3 is the group of failure modes that will be dealt with on an individual basis. These are failure modes that have a very low occurrence rate and do not show any particular characteristic of occurring along with another failure. Thus for a failure mode in cluster-3 we will consider only that particular failure mode for design. We shall call such clusters Type-III clusters. The following section explains the general steps involved in using the cluster information.

### 8.4. Rules for Using the Cluster Information

For deciding the failure modes to be considered for initial short-listing of the failures the following steps are followed:

1. Clusters with single membership, that is, Type-I clusters that have only one failure mode are always considered during the initial design stage.
2. For the given function (E) under consideration, we identify the maximum occurring failure mode. This is identified from the function-failure matrix (EF). In selecting the maximum occurring failure mode from the EF matrix, the failures belonging to Type-I clusters are not considered as they are already taken into consideration in Step 1.
3. After having identified the maximum occurring failure mode, the cluster to which it belongs is identified. If the failure mode belongs to a Type-II cluster we consider the entire cluster for the design; if the failure mode belongs to a Type-III cluster only that failure mode is considered and others are ignored.

We claim that by following Steps 1 through 3 we will identify a set of failure modes, of which the failure modes corresponding to the design in hand would be a subset. Let us denote the set of failure modes corresponding to the design under consideration by $F_{d,}$ and the set of failure modes obtained from Steps 1 through 3 by $F_{1\text{-}3}$. We claim that

$$F_d \subset ( F_{1\text{-}3} \cup \varepsilon_d ) , \tag{3}$$

where $\varepsilon_d$ is the set of failures that the Steps 1 through 3 did not yield for the design under consideration. For this work, the number of failure modes that was overlooked for a given component was on average 0.295. That is $n (\varepsilon_d) = 0.295$. This shows that by following the failure mode clustering approach we can identify a superset of failure modes corresponding to the failure modes of the design under consideration by overlooking just about 0.295 failure mode per component. Thus Equation 3 can be written as:

$$F_d \subset F_{1\text{-}3} \tag{4}$$

The schematic representation of the cluster approach is shown in Figure 7.

### 8.5. Application to the ‘Stop Gas’ Function

We now apply the 3-step method described in the previous section to the Stop Gas function component.

1. We take into consideration Type-I clusters. In this case they are clusters 8 and 9 corresponding to failure modes direct chemical attack and force induced deformation.
2. For the given function we identify the maximum occurring failure mode from the function-failure matrix (EF). We find that the maximum occurring failure mode is compression set. Here as we had mentioned in the previous section the designer can use his/her discretion in selecting the failure mode. We select the compression set failure modes, as we know that it is associated with

rubber failures (since we have chosen rubber seals as a solution from the morphological matrix.)

3. Next we identify the cluster to which the failure mode compression set belongs. It is cluster-1. As it is a Type-II cluster we consider the entire cluster for the design.

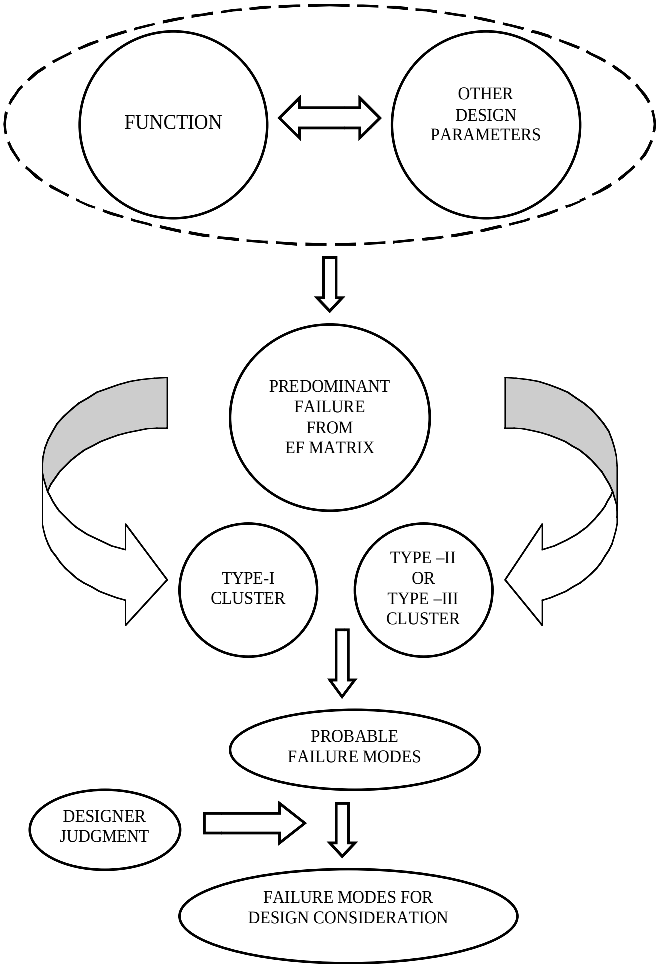

Figure 7. Schematic of the Cluster Approach.

Thus our superset F1-3 comprises *force induced deformation, direct chemical attack, abrasive wear, compression set, heat cracking and installation damage*. Now the designer can use his/her judgment in analyzing the failure modes that pertain to the design from the given set.

We did a cross check with the component–failure matrix (CF) for the components identified solving the function *Stop Gas* to see what failure modes they had exhibited and if we had the value of n ($\varepsilon_d$) < 0.295. Table 4 shows the failure modes in the components identified and the number of failures modes that were not identified by the cluster approach.

Table 4. Verification of Failure Modes for Hypothetical Design.

| **COMPONENT / FAILURE MODE** | ABRASIVE WEAR | COMPRESSION SET | CRACKING | FORCE INDUCED DEFORMATION | INSTALLATION DAMAGE | **UNACCOUNTED FAILURE** |
|---|---|---|---|---|---|---|
| RUBBER PISTON SEAL | 0 | **1** | 0 | 0 | **1** | 0 |
| O-RING | 0 | 0 | 0 | **1** | 0 | 0 |
| RUBBER SEAL PLUG | 0 | **1** | 0 | 0 | 0 | 0 |
| AIR TUBE CAP | 0 | 0 | 1 | **1** | 0 | 1 |
| RUBBER PRESSURE GAUGE RING | 0 | 0 | 0 | **1** | 0 | 0 |
| SPACER | 0 | 0 | 0 | **1** | 0 | 0 |
| RUBBER BARREL SEAL | **1** | **1** | 0 | 0 | 0 | 0 |
| **AVERAGE UNACCOUNTED FAILURE/COMPONENT** | | | | | | 0.143 |

As seen from Table 4, we missed just one failure mode for a single component. A careful consideration would reveal that the air tube cap was a plastic component and had we decided on a plastic component, we would have selected cracking as our major failure in Step-2 of the cluster approach and we would have still found all the failure modes for the component. This also has another advantage. We see that while all the rubber seals experienced the failure mode *compression set*, just one of them experienced *abrasive wear* and *installation damage*. Thus clustering helps in retraining collective information of failure history for given functions spanning the various components. Thus the designer would now have considered all the failure modes that such a component solving a particular function had experienced. As mentioned before if the seal is just in a home-product, then it might not be necessary to design it for *force induced deformation* or *direct chemical attack*. However, if it is in some aerospace application it would be necessary to consider these failures indicated by the Type-I clusters as seal might come in a very reactive environment with the gas possessing tremendous velocities.

Table 5 shows the values of n ($\varepsilon_d$), the number of overlooked failures. We see that on an average we overlooked about 0.295 failure mode per component. The table is interpreted as follows. First we determine the predominant failure mode for the given function. For example, take *abrasive wear*. *Abrasive wear* belongs to cluster-1. Now the component, which delivers the desired function, is designed to withstand failures belonging to cluster-1, cluster-8 and cluster-9. That is, the component is designed to counter *abrasive wear*, *compression set*, *installation damage*, *heat cracking, direct chemical attack* and *force-induced deformation.* (As described in the previous section, it is not necessary to consider all the failure modes provided by the clusters and engineering judgment may be exercised in choosing the required failures from the given set of failures). Thus, when a component is designed to counter the failures in the 3 clusters, on average, we would have overlooked about 0.55 failure per component. For failures belonging to cluster-3, only that individual failure along with cluster-8 and cluster-9 are considered and other failures in cluster-3 are not considered (Type-III cluster), as this is a group of failures that have either occurred very infrequently or have not exhibited any particular association with another kind of failure mode. Thus the n ($\varepsilon_d$) values of failure modes corresponding to cluster-3 were not calculated. So the designer may design the component for that particular failure mode, force induced deformation, direct chemical attack and any other failure he thinks is pertinent to the case. As more failure mode observations are recorded in the function-failure matrices, n ($\varepsilon_d$) is expected to decrease.

## 9. CONCLUSION AND FUTURE WORK

A clustering-based failure-free design method has been described to help the designer during the conceptual design stage in identifying potential failure modes and deciding which failure mode analyses are needed. The standardized vocabulary coupled with the matrix approach, introduced in Tumer and Stone [1], is used here as a basis for analyzing the statistical characteristics of failure mode data. A discussion of the advantages of using a clustering-based approach to failure mode identification and analysis planning is presented in detail including the technical approach and a hypothetical example.

Further research is needed to expand the failure mode classification to include more material specific failures such as the failure of composite materials and to include more failures pertaining to the variety of electrical components. The current work focused only on the occurrence data of the failure modes. The performance of the methodology with the severity and detectability data is a part of the ongoing research.

Table 5. n ($\varepsilon_d$) Values.

| **FAILURE MODE** | CLUSTER 1 | CLUSTER 2 | CLUSTER 3 | CLUSTER 4 | CLUSTER 5 | CLUSTER 6 | CLUSTER 7 | **CLUSTER 8** | **CLUSTER 9** | **OVERLOOKED FAILURE** |
|---|---|---|---|---|---|---|---|---|---|---|
| ABRASIVE WEAR | × | | | | | | | × | × | 0.550 |
| ADHESIVE WEAR | | × | | | | | | × | × | 0.115 |
| AGEING | | | × | | | | | × | × | × |
| BIOLOGICAL CORROSION | | | × | | | | | × | × | × |
| BLISTERING | | | × | | | | | × | × | × |
| BRITTLE FRACTURE | | | | × | | | | × | × | 1.147 |
| COMPRESSION SET | × | | | | | | | × | × | 0.000 |
| CORROSIVE WEAR | | | | | × | | | × | × | 0.275 |
| CRACKING | | | | | | × | | × | × | 0.190 |
| CREEP BUCKLING | | | | | | | × | × | × | × |
| CREEP STRESS RUPTURE | | | | | | × | | × | × | 0.026 |
| DEFORMATION WEAR | | × | | | | | | × | × | 0.156 |
| DIRECT CHEMICAL ATTACK | | | | | | | | × | × | × |
| DUCTILE RUPTURE | | | × | | | | | × | × | × |
| FORCE INDUCED DEFORMATION | | | | | | | | × | × | × |
| FRETTING FATIGUE | | | × | | | | | × | × | × |
| GALLING AND SEIZURE | | | | | | × | | × | × | 0.473 |
| GALVANIC CORROSION | | | × | | | | | × | × | × |
| HEAT CRACKING | × | | | | | | | × | × | 0.000 |
| HIGH CYCLE FATIGUE | | | | | | × | | × | × | 0.666 |
| IMPACT DEFORMATION | | | | | | | × | × | × | × |
| IMPACT FRETTING | | | × | | | | | × | × | × |
| IMPACT FATIGUE WEAR | | | × | | | | | × | × | × |
| INSTALLATION DAMAGE | × | | | | | | | × | × | 0.000 |
| INTERGRANULAR CORROSION | | | × | | | | | × | × | × |
| STARVED JOINT | | | × | | | | | × | × | × |
| SURFACE FATIGUE WEAR | | | | | | × | | × | × | 0.100 |
| TEMPERATURE INDUCED DEFORMATION | | | | × | | | | × | × | 0.360 |
| THERMAL FATIGUE | | | × | | | | | × | × | × |
| THERMAL RELAXATION | | | × | | | | | × | × | × |
| THERMAL SHOCK | | | × | | | | | × | × | × |
| YIELDING | | | | | × | | | × | × | 0.365 |
| **AVERAGE** | | | | | | | | | | **0.295** |

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# APPENDIX A.

# COMPOSITE FUNCTION – FAILURE MATRIX

# EF MATRIX

The following pages provide the composite function-failure matrix (EF) for the 41 products discussed in Section 3. The method of deriving the composite matrix is discussed in Section 1 of this thesis. The 41 products used in this study are given in table A1. The EF matrix gives the count of 32 failure modes occurring across 181 functions.

Table A1. List of 41 Products

| No. | PRODUCT |
|---|---|
| 1 | AIR PURIFIER |
| 2 | AIRPLANE |
| 3 | AIRPUMP |
| 4 | B & D ELECTRIC KNIFE |
| 5 | B & D SANDER |
| 6 | BALL SHOOTER |
| 7 | BISSEL HAND VAC |
| 8 | BRAUN COFFEE GRINDER |
| 9 | CONAIR HAIR DRYER |
| 10 | DAZEY STRIPPER |
| 11 | DEWALT SANDER |
| 12 | DIRT DEVIL VACCUM |
| 13 | DREMEL ENGRAVER |
| 14 | DUSTBUSTER |
| 15 | ERGONOMIC CHAIR |
| 16 | FLOORJACK |
| 17 | GE FRIDGE |
| 18 | HUNT BOSTON SHARPENER |
| 19 | JIGSAW |
| 20 | JUICER |
| 21 | KENMORE DRYER |
| 22 | KRUPS CAFÉ TRIO |
| 23 | LEAF BLOWER |
| 24 | LENNOX CD PLAYER |
| 25 | METRO BATH SCALE |
| 26 | Mr. COFFEE ICE TEA MAKER |
| 27 | Mr. COFFEE COFFEE MAKER |
| 28 | PAINT ROLLER |
| 29 | PATTON ROOM HEATER |
| 30 | PRESTO POPCORN POPPER |
| 31 | INKJET PRINTER |
| 32 | PROCTOR SILEX IRON |
| 33 | PROCTOR SILEX TOASTER |
| 34 | RICE COOKER |
| 35 | SALTON WOK |
| 36 | SKILL SCREW DRIVER |
| 37 | SPATULA MIXER |
| 38 | WASHER |
| 39 | WATER PURIFIER |
| 40 | WESTBEND WOK |
| 41 | WESTINGHOUSE TOASTER |

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# VITA

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