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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.

INTRODUCTION

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

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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.

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

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.

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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.

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

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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.

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	

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.

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.

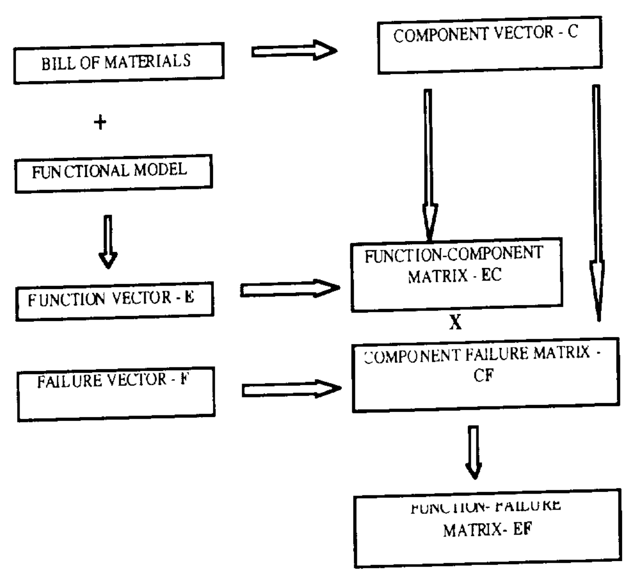

FIGURE 1. Procedure Flowchart

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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		

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.

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

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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				

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 the 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.

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 $n \times p$ matrix is called the component-failure matrix, denoted by CF. As in the

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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

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.

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.

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 $m \times p$ 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.

TABLE 5. Failure Mode Identification

PRIMARY IDENTIFIER	SECONDARY IDENTIFIER	FAILURE MODE
Elastic Deformation		Force / Temperatire induced deformation
Plastic Deformation	**Ductile** Material	Yielding
Static Force **Curved** Surfaces	1. Permanent surface discontinuity 2. **Mating** members	Brinelling
Plastic Deformation **Ductile** Material	1. Separate into 2 parts 2. Dull fibrous surface	Ductile rupture
Elastic Deformation **Brittle** Material	1. Separate into 2 parts 2. Granular, multifaceted fracture surface	Brittle fracture
Fluctuating Load / deformation	1. Sudden separation into 2 parts 2. Magnitude of load such that **more than 10,000 cycles** required	High cycle Fatigue
Fluctuating Load / Deformation	1. Sudden separation into 2 parts 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 2. Manifests as pitting, cracking, scaling	*Surface Fatigue* Surface Fatigue Wear
Fluctuating Load / Deformation **Impact** Load **Elastic** Deformation	Failure occurs by nucleation or crack propagation	*Impact Fatigue* *Impact Wear* Impact Fatigue Wear
Fluctuating Load / Deformation **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 2. **Normal** force 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

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TABLE 5. Failure Mode Identification, Contd.

PRIMARY IDENTIFIER	SECONDARY IDENTIFIER	FAILURE MODE
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* 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 **Stresses**	**Corrosive** medium	Stress Corrosion
Undesirable **change in dimension**	High pressure **Plastic** deformation 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 2. **Normal** force 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 2. **Normal** force 3. Joints not intended to move	Impact Fretting
Plastic deformation	1.**Temperatute / stress** Influence 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** 2. Sliding velocity 3. Temperatures 4. Lubricants **5. Surface destruction** 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 Geometric configuration	Deflection increases greatly for slight increses in load	Buckling
Plastic deformation	1. Influence of temperature / stress 2.Rupture 3.Exceed buckling limit	Creep Buckling

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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:

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

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:

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.

- 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.

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.

COMPOSITE FUNCTION-FAILURE MATRIX																									
FUNCTION / FAILURE	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	HIGH CYCLE FATIGUE	INTERGRANULAR CORROSION	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	2	0	0	2	0	1	0	15
ALLOW X-Y DOF	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 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 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 TORQUE	0	0	0	0	0	0	5	0	0	0	0	0	0	0	3	0	0	1	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	7	0	0	0	0	1	5	2	7	0	4	0	6	7	7	1	0	0	10
CONVERT ELEC.E TO MECH.E	2	1	0	1	2	0	2	0	0	0	0	0	1	0	1	0	1	0	1	1	2	1	0	0	2
CONVERT ELECTRICAL ENERGY TO THERMAL ENERGY	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	5	0	0	1	0

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TABLE 6. Composite Function-Failure Matrix EF_c Contd.

FUNCTION / FAILURE	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	HIGH CYCLE FATIGUE	INTERGRANULAR CORROSION	PITTING CORROSION	SURFACE FATIGUE WEAR	TEMPERATURE INDUCED DEFORMATION	THERMAL FATIGUE	THERMAL RELAXATION	THERMAL SHOCK	YIELDING
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 ROT. ENERGY. TO PNEU. ENERGY	1	0	0	1	1	0	1	0	2	0	0	5	1	0	2	0	5	0	1	1	7	1	0	0	9
CONVERT ROT. ENERGY TO VIBRATIONAL ENERGY	1	0	0	1	1	0	1	0	0	0	0	5	1	0	2	0	4	0	1	1	5	1	0	0	5
CONVERT SOLID TO LIQUID	1	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	1	0	0	1	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
COUPLE SOLID	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
DISSIPATE THERMAL ENERGY	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	1	1	0	0	1	1	1	0	4
DISTRIBUTE LIQUID	0	0	0	0	0	0	0	0	4	0	0	4	0	0	0	0	0	0	0	0	4	0	0	4	3
DISTRIBUTE MECH. ENERGY	1	0	0	0	1	0	0	0	4	0	0	1	0	0	0	0	0	0	0	0	2	0	1	0	11
DISTRIBUTE MOTION	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
DISTRIBUTE TORQUE	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
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	1	0	0	0	1	1	0	0	4
EXPORT LIQUID	0	0	0	0	2	0	0	0	4	0	0	4	0	0	0	0	0	0	0	0	5	0	0	4	8
EXPORT SIGNAL	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	1	0	0	0	3
EXPORT SOLID	2	0	0	0	1	0	0	0	3	0	0	1	0	0	0	0	1	1	0	0	1	1	2	0	13
GUIDE GAS	1	0	0	0	1	0	3	0	7	0	0	2	0	0	0	0	1	0	0	0	4	1	0	0	7
GUIDE LIQUID	0	0	0	0	0	0	0	0	10	0	0	3	0	0	0	0	0	0	0	0	9	0	0	3	8
GUIDE SOLID	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	4
IMPORT ELEC. ENERGY	0	0	0	0	0	0	0	0	6	0	0	2	0	0	0	0	0	0	0	0	10	0	0	0	4
IMPORT GAS	2	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	5
IMPORT HAND	2	0	0	0	0	0	1	0	6	0	0	1	0	0	0	0	1	0	0	0	3	1	0	0	10
IMPORT HUMAN ENERGY	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	5
IMPORT LIQUID	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3
IMPORT MECH.ENERGY	3	0	0	0	4	0	0	0	6	0	0	2	0	1	0	0	0	0	0	0	5	0	0	0	18
IMPORT SOLID	4	0	0	0	1	0	2	0	7	0	0	3	0	0	0	0	2	0	0	0	3	2	0	3	18
MEASURE THERMAL ENERGY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
MIX GAS AND LIQUID	0	0	0	0	0	0	0	0	1	0	0	2	0	0	0	0	0	0	0	0	2	0	0	0	0
MIX LIQUID	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0
MIX SOLID	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
MIX SOLID AND LIQUID	0	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	3	0	0	2	1
MIX SOLID AND LIQUID	0	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	3	0	0	2	1
POSITION SOLID	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	1	1	1	0	17
REFINE GAS	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
REFINE LIQUID	0	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	2	0	0	2	2
REGULATE ELECTRICITY	0	0	0	0	0	0	0	0	1	0	0	2	0	0	0	0	0	1	0	0	2	0	0	0	7
REGULATE GAS	0	0	0	0	0	0	0	0	2	0	0	3	0	0	0	0	0	0	0	0	3	0	0	1	1
REGULATE MASS FLOW	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
REGULATE MECH.ENERGY	0	0	0	0	1	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	3
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	2	0	0	1	1	0	0	0	1	0	0	1	0	0	0	0	0	1	0	0	2	1	1	0	2
ROTATE 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	1
SECURE MECHANICAL ENERGY	1	0	0	0	4	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	8
SECURE SOLID	3	0	0	0	0	0	1	0	11	1	0	8	0	1	0	0	2	0	0	0	9	2	3	2	44
SEPARATE SOLID	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
STABILIZE MECH. ENERGY	0	0	0	0	0	0	0	1	3	0	0	0	0	1	0	0	0	0	0	0	2	0	0	0	7
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	3	0	0	0	0	0	1	1	6	0	0	2	0	1	0	0	0	0	0	0	2	0	0	0	15
STOP THERMAL ENERGY	1	0	0	0	5	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	2	0	0	0	3
STORE ELEC. ENERGY	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1
STORE LIQUID	0	0	0	0	2	0	0	0	1	0	0	4	0	0	0	0	0	0	0	0	5	0	0	4	6
STORE SOLID	4	0	1	0	0	0	4	1	11	0	0	3	0	0	1	0	0	0	0	0	5	0	0	3	12
SUPPLY ELEC. ENERGY	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
TRANSMIT ELEC. ENERGY	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	2	0	4	0	0	21	0	0	0	11
TRANSMIT FORCE	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	1	0	0	1	2	1	0	2
TRANSMIT MECH.ENERGY	1	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	3	1	0	0	1	0	1	0	0	0	0	0	1	1	1	0	2	0	1	1	1	1	0	0	4
TRANSMIT THERMAL ENERGY	0	0	0	3	0	1	2	0	5	0	0	1	0	0	0	0	0	0	0	0	4	0	0	1	9
TRANSMIT TORQUE	2	0	0	0	0	0	3	0	0	0	0	0	0	0	2	0	1	1	0	0	0	0	0	0	9
TRANSMIT VIBRATION	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	2
TRANSPORT SOLID	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1	2

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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

CONCLUSIONS

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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