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THE FUNCTION-FAILURE DESIGN METHOD

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ABSTRACT

To succeed in the product development market today, firms must quickly and accurately satisfy customer needs while designing products that adequately accomplish their desired functions with a minimum number of failures. When failure analysis and prevention are coupled with a product's design from its conception, potentially shorter design times and fewer redesigns are necessary to arrive at a final product design. In this article, we explore the utility of a novel design methodology that allows FMEA-style failure analysis to be conducted during conceptual design. The Function-Failure Design Method (FFDM) guides designers towards improved designs by predicting likely failure modes based on intended product functionality.

1. INTRODUCTION

A company specializing in electric power transformers rolls out a new high capacity transformer. Knowing that the high electricity handling capabilities of this new transformer will necessitate increased heat transferring capacity, the designers add large horizontal cooling fins to the sides of the transformer case. However, shortly after installation, the transformers begin to fail due to overheating after the oil used to cool them leaks out of the casings through cracks that develop at the welded connection points of

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the cooling fins. It is determined that the cracks developed due to fatigue stresses induced during shipping. [1]

If the designers of these transformers had been more aware of the common failures that befall large heat transferring components, is it likely that these failures could have been avoided? In this paper we report on a method and its potential in preventing costly problems like the one discussed above with emphasis on addressing failures at the functional level.

The research presented here is motivated by two engineering maxims: 1) Design organizations seek to derive a successful design solutions with minimal effort; 2) The less likely that a failure will occur within a product's life cycle, the more the consumer will appreciate it. The methodology presented here seeks to capitalize on these two maxims by keeping the designer(s) of a new product cognizant of failure modes during the function definition stage of design. The Function-Failure Design Method (FFDM) offers a new approach for coupling failure analysis with product design during the conceptual stage. The research builds upon the function-failure method developed by Tumer and Stone [2], which allows for historical failure data to be collected and related to the failed artifact's functionality. These relations are used to build knowledge bases of past failures that can be used by designers to avoid these failures in future designs. Like other expert systems development efforts, a considerable amount of work is involved in developing the knowledge base on the part of researchers. The function-failure analysis method was developed and tested using household products in Arunajadai et al. [3] and using NTSB rotorcraft accident data in Roberts et al. [4]. Research using spacecraft historical problem and failure data is also currently underway to develop a comprehensive function-failure knowledge base for NASA missions [5]. In this paper, the function-failure analysis approach is formalized specifically to address the issue of conceptual design, and extended to combine with a concept generator approach [6] to develop new designs with fewer failures.

At this point, several basic characteristics of the FFDM are noted below in order to describe in general terms the capabilities and performance of the method developed in this work in comparison with other relevant techniques as shown in Table 1. Since CFMA, AFMEA, and WIFA are all closely related to FMEA in approach, these are collectively referred to as FMEA type approaches. A more complete discussion of these other methods is given in the Section 2.

Table 1. FFDM Assessment Overview.

Method	Reduces high user workload	Uses archived failure knowledge base	Indicates the physical cause of failure	Accounts for failure interactions and dependencies	Usable during functional design	Uses a formalized failure language	Practical for mechanical systems
FFDM	✓	✓	✗	✓	✓	✓	✓
FMEA	✗	✗	✓	✓	✗	✗	✓
CFMA	✗	✗	✓	✓	✓	✗	✓
AFMEA	✗	✗	✓	✓	✓	✗	✓
FLAME	✓	✓	✗	✗	✓	✗	✗
WIFA	✓	✓	✓	✓	✗	✗	✓

Many advantages can be gained by beginning the failure analysis of a new design at the conceptual design stage and in particular during functional design. The main advantage comes from arriving at a more reliable product without the need for multiple redesigns in order to eliminate failure modes in advanced stages of the design process, as happens in the traditional FMEA approach. FFDM as well as FLAME and WIFA derive potential failures based on historical data in a knowledge base rather than through direct human recollection as in the FMEA type processes. As a result the FFDM approach requires less overhead in terms of personnel when performing an analysis. Unfortunately this knowledge base comes at a price due to the logistics of populating the knowledge base with relevant data. For techniques not using a knowledge base, this information ultimately is still necessary although it is maintained as personal knowledge by the engineering team or as other documented forms of corporate or general knowledge such as best practices, standards, and processes. In either case however, design reviews with an appropriate team of engineers is still required to ensure that potential failures do not fall through the cracks of a given failure method.

Furthermore, the FFDM is currently missing some of the analysis that is present within FMEA approaches. The FFDM does not diagnose or address the "cause" of failure modes nor does it have any conditions for manufacturability. Archiving historical failure "causes" and manufacturing problems in knowledge bases similar to the function-failure knowledge base could address both of this deficiencies. These knowledge bases could then be integrated into the FFDM, allowing the designer to use this historical data to guide their design as well. The FFDM is also currently devoid of analysis that would be analogous to the severity and detectability rankings that are present within FMEA methods. As the function-failure knowledge base grows and is refined, this information will be added and will then be accessible with the FFDM. With respect to failure interactions, the FFDM can identify failures that tend to occur together using similarity matrices. This particular aspect is not addressed here, but it is covered in previous papers [2, 7]

One key advantage of FFDM and certain others is they can be utilized during the functional stage of design without the need for any physical solution choice. A consequence of this benefit is that potential failures can be identified and addressed in the functional model. Specifically, this allows a designer an opportunity to add, change, or delete functionality so that the identified potential failures can be addressed before the design progresses to embodiment design tasks. Of course, certain failures may not be avoided by this change in functionality.

In this light, the paper first reviews related research and background of the function-failure analysis and the function-failure knowledge base required for the analysis in Section 2. In Section 3, an example function-failure knowledge base and its development are shown. Then, a formalized methodology and general guidelines for using the methodology in conjunction with a concept generator method are presented in Section 4. An evaluation of the FFDM is covered in Section 5 which includes both a broad assessment and a systematic method evaluation. A discussion of the method followed by recommendations and future work round out this paper.

2. BACKGROUND AND RELATED RESEARCH

2.1 Background: Traditional Failure Analysis in Design

Failure Modes and Effects Analysis (FMEA) has been the industry standard failure analysis method for many years and therefore serves as a reasonable benchmark for comparing other failure analysis techniques. Originally developed from the US military standard MIL-P-1629A [8], FMEA has been widely tested and enhanced by many organizations, most notably the United States' auto manufacturers. In a joint undertaking by Chrysler, Ford, General Motors and the Automotive Industry Action Group a reference manual for conducting FMEA was published in 1993 [9]. This manual was intended to guide the FMEA activities of these companies and their suppliers. Despite this effort to formalize a single FMEA procedure, there are still many different methods for undertaking an FMEA analysis. Another shortcoming of FMEA methods is that they are not well suited for the conceptual design of a product, since details of the physical design are rarely known [10]. This leads to time-consuming redesigns that must also be evaluated with FMEA methods, leading to even longer total design times. Also, the FMEA procedure requires the input of a concurrent engineering team of five to nine cross-functional and multi-disciplinary individuals [11], thus making it not only time consuming, but also quite expensive. In industry, "engineers consider FMEA to be laborious and time-consuming (and thus expensive) to carry out" [12].

Wirth et al. [12] state that FMEA has two fundamental weaknesses: the lack of methodological guideline and the use of natural language. The AIAG manual [9] has addressed the lack of a methodological guideline for conducting FMEA, but it is still common for FMEA practices to vary between different fields, companies and even FMEA teams. The criticism of FMEA for using natural language originates from the description of functions and failure modes within their analysis. Wirth et al. expand their criticism to state that the descriptions of systems and functions are often incomplete. The problems associated with the use of natural language can lead to ambiguity, or uncertainty when conducting FMEA. This problem is amplified when the FMEA results are viewed by outside parties or after time has passed. This deficiency inhibits attempts to reuse information from FMEA in new design cases since the description of the same failure can differ between two FMEA practitioners. For example, failures may differ in terms of the level of abstraction used to describe the failure mode. This difficulty suggests that a consistent and well-defined vocabulary be used in order for failures to be classified in an effective and reusable manner.

Another drawback of FMEA is its reliance on the FMEA designers to develop a list of failure modes that could or might occur for a given component. This necessitates that members of the FMEA team have a vast knowledge of potential failures in order to enumerate possible failures. Within an FMEA approach these potential failures are then subjectively ranked for severity, occurrence and detectability based upon the users' judgment. The rankings generated by this subjective system can greatly fluctuate when assigned by different engineers. Nevertheless, this analysis at least yields some information about these metrics while the FFDM method only returns output for the failure mode.

Attempts have been made to modify FMEA for use in conceptual design. Hari and Weiss [10] have developed a failure analysis method known as CFMA that uses an FMEA-style analysis on the functional representation of a design. CFMA is a step toward bringing failure analysis to the front end of design, but continues to use the natural language for describing functions and subsequent subjectivity of traditional FMEA methods. While the failure modes for CFMA are described in terms of form rather than function, the CFMA process is driven by consideration of concept functionality. Similarly, the Advanced FMEA (AFMEA) method of Kmenta et al. [13] is a system design failure analysis method that is based on a behavior model that includes both the functionality and physical entities of a design solution. This functional dependence allows AFMEA to be performed in the early stages of system design yet AFMEA is operationally similar to FMEA and the method relies on a design personnel rather than a type of expert system for identifying failures.

In electrical design, there have been attempts to undertake FMEA-like failure analysis at the conceptual design stage. The FLAME System [14, 15] links its failure analysis to a functional model derived during conceptual design. In FLAME, the functional models are embodied by components from an extensive library. The embodied representations are then subjected to a computer simulation in order to see the effect of a list of possible failures within the new design. This list of possible failure modes exists for all components within the library, and has been assigned based on historical failure occurrences. This type of system can be adopted in electrical design since the systems, and their possible failures, can be easily simulated by computer analyses. However, for mechanical design, subjecting all components of a design to an entire list of possible failure modes, even within a computer simulation, would prove extremely time-consuming and impractical.

WIFA (the German acronym for "knowledge-based FMEA") [12] is a failure analysis tool that seeks to populate knowledge bases with information from past FMEAs and use them when conducting current FMEAs. This methodology strives to use historical information from past failure analyses to guide new designs by storing the past FMEA results in a knowledge base. But, by archiving past FMEAs, WIFA is not populating its knowledge bases with actual occurrence data. It is relying on the analysis of past FMEA teams to be widely applicable to new designs. Regardless of this particular data, clearly the development of such a knowledge base requires considerable effort.

Knowledge base-driven failure analysis tools, like some of those reviewed above, can trace their roots to the efforts of Collins et al. [16] and Barbour [17] to introduce matrix techniques into FMEA logistical archiving. The failure-experience matrix of Collins et al. shows a great advance in archiving historical failure information for use in future designs. Coincidentally, related work of Collins [18] formed the basis for the failure mode vocabulary used in this article. The Advanced Matrix FMEA Technique of Goddard and Dussault [19] added to the work of Barbour. This was an early drive for standardizing the format for FMEAs into matrices to allow for ease of information storage and reuse. More currently, Henning and Paasch [20] reuse past FMEA data to develop matrices that aid in investigating the diagnosability of failure occurrence. Their method seeks to evaluate designs based on life-cycle costs of fault (failure) isolation. All of these researchers have lessened the logistical problems of reusing past FMEAs and archiving actual failure data.

With respect to the uncertainty inherent in FMEA analysis, some past work by Thornton [21] may lead to an approach for handling the uncertainty of failure and risk data. Thornton has developed a model of decision making under uncertainty to account for characteristics of the manufacturing organization, market, and product. Beyond FMEA, recent efforts have attempted to improve reliability-based design optimization (RBDO) by developing a hybrid approach that involves the selective use of two techniques depending on the concave or convex nature of the performance function being optimized [22].

2.2 Related Research: The Function-Failure Analysis and Knowledge Base

A critical part of the FFDM method is a required knowledge base of previous products. The approach in this research is to utilize a matrix based approach that derives potential failures through a series of matrix multiplications that relate functions to failures through an association of i) functions to components and subsequently ii) components to failures. In particular, the designer simply needs a function-component (**EC**) and a component-failure (**CF**) matrix. The end goal of a function-failure knowledge base, designated as the function-failure (**EF**) matrix, exists as a computed result of these first two matrices and is developed through the process detailed by Roberts et al. [4]. For purposes of the current work, this **EF** matrix is the format for the knowledge base that explicitly contains failure information related to functions. Within **EF**, the i rows are representative of function and flow pairings (i.e., a functional description) and the j columns represent failure modes. Individual matrix entries, ef_{ij}, indicate the number of distinct components solving function i that have failed by failure mode j. Thus, an entry of 4 in **EF** indicates that four distinct instances exist in the knowledge base where the function and flow pairing (row) of the given entry correlates to the same entry's failure mode (column). The process of populating a function-failure knowledge base begins by obtaining failure information from an engineered product. The failure information is scrutinized to determine the failed component and the failure mode. A functional model for the failed component is then developed [23, 24] at a detailed level. The sub-functions from the detailed functional model are then entered into the **EC** matrix and through the above calculation are correlated to their respective failure mode and added to the function-failure knowledge base. As more failed components are added to the knowledge base, the distribution of failure mode occurrences across functions can be used to determine which failure modes will occur more often than others for each function. A suitable knowledge base for the FFDM should contain failure information for many sub-functions so that it can be used for new designs that span a wide range of functionality.

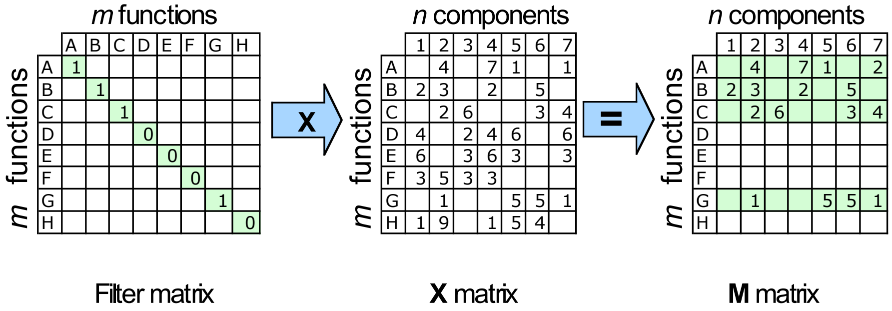
In order to support a suitable knowledge base that can be applied across a wide range of product designs, the notion of a basis set of functionality that spans the functionality of a set of products is adopted for this research in the form of the functional basis formalized by Hirtz et al [24]. This language is standardized in the sense that particular verbs used to describe some functionality are explicitly defined, thus allowing the designer to use a 'standard' verb for a given functional meaning rather than perhaps using multiple synonyms which ultimately give rise to variability in functional descriptions especially if more than one designer is involved in specifying and interpreting a functional model. Standardization in this regard brings a degree of clarity to the current work that reduces the ambiguity of describing product functionality. The vocabulary of Arunajadai et al [3] is also used to specifically address the description of failure modes.

In previous work by Roberts et al. [4], National Transportation Safety Board (NTSB) accident reports concerning Bell 206 rotorcraft accidents were reviewed to allow for an initial test of the function-failure theory of Tumer an Stone [2]. The NTSB reports offered the first opportunity to populate a knowledge base with an abundance of actual component failures. The work of Roberts et al. sought to investigate the failures in four systems of the Bell 206 rotorcraft. They examined 33 components from the compressor, engine, powertrain, and turbine systems. Of these 33 components, 18 of them exhibited 10 unique failure modes. In their research, functional descriptions of these components were only examined at the highest (most vague) level of description, resulting in one to five function and flow terms for each component. Roberts et al. [4] did succeed in using a common functional vocabulary to populate a knowledge base, but their natural language descriptions of failure modes leads to problems when trying to relate this knowledge base across a wide range of products. We have extended this work and derived an improved function-failure knowledge base by using a more standardized vocabulary to describe the failure modes and by examining the components' functional models at a more detailed level. This enhanced knowledge base is used in this paper for the case studies.

2.3 Related Research: The Concept Generator Method

The research of Strawbridge et al. [6] is also prominently used in this research. Their concept generator allows functional models to be embodied into a physical form by applying historical physical solutions to new design problems. The concept generator draws these solutions from a repository of information on a wide range of engineered products. This information is archived in matrix form, designated as the chi matrix (**X**). It contains *n* columns for all enumerated physical concepts in the repository and *m* rows for each function and flow pairing. Entries in **X** indicate the number of instances that exist in the repository for the function-component combination of the given row and column. To use the concept generator, an *m* x *m filter* matrix is formulated from a detailed functional model of the design. Each non-zero element on the diagonal of this filter matrix indicates that the corresponding function is present in the functional model. This filter matrix allows the user to "weed out" all physical solutions that hold no meaning within their new design. The filter matrix is then multiplied by

X, with the resulting matrix listing the possible physical solutions for the functional model. The resulting matrix is designated as the morphological matrix (**M**) for the new design where the entries in this matrix reflect the number of instances in the repository that share the same function-component combination. Regardless of the product architecture, whether modular or integral, **M** simply indicates candidate physical solutions for a set of functions. Selecting, configuring, and embodying these candidate solutions is left to the designer. Figure 1 illustrates the matrix multiplication process. In this paper, we integrate the concept generator into the FFDM to aid the designer in deriving physical solutions.



	A	B	C	D	E	F	G	H
A	1							
B		1						
C			1					
D				0				
E					0			
F						0		
G							1	
H								0

Filter matrix

	1	2	3	4	5	6	7
A		4		7	1		1
B	2	3		2		5	
C		2	6			3	4
D	4		2	4	6		6
E	6		3	6	3		3
F	3	5	3	3			
G		1			5	5	1
H	1	9		1	5	4	

X matrix

	1	2	3	4	5	6	7
A		4		7	1		2
B	2	3		2		5	
C		2	6			3	4
D							
E							
F							
G		1			5	5	1
H							

M matrix

Figure 1. The Concept Generator Method.

3. POPULATING THE FUNCTION-FAILURE KNOWLEDGE BASE

In this research, we use failure information for the Bell 206 rotorcraft to populate an initial knowledge base. Previous work has utilized the same failure data [4]. However, in this research we have reevaluated the failure data in greater detail to derive a more robust knowledge base for use in the FFDM. In particular, the component space has been increased to include the airframe, fuel system and rotor systems, in addition to the four systems investigated by Roberts et al [4]. NTSB accident reports were again used to allow for actual failure occurrence data to populate the component-failure matrix. Various rotorcraft maintenance manuals and engineering judgment were used to derive detailed functional models of each component, therefore attaining the overall rotorcraft function-component (**EC**) matrix. Within these 7 systems, 41 components have been enumerated, with 25 of these components exhibiting a definable failure mode. A total of 63 failures were extracted from the NTSB reports to have occurred in these 25 components. Of these 63 failures, there were 15 unique failure modes within the vocabulary of Arunajadai et al. [3]. These unique failure modes are shown as grey entries in the complete listing of possible failure modes seen in Table 2. The initial high-level exploration of the function space by Roberts et al. [4] resulted in only 24 unique function-flow representations. By further investigating the function space to a more detailed level, 55 unique function-flow representations are identified and listed in Table 3. Populating the function-failure knowledge base at this added level of detail captures a larger set of failure information for use in the FFDM. The steps taken to yield the final function-failure include determining the **EC** from multiplying the Filter matrix by aggregate **X** associated with the rotorcraft subsystems. The final **EF** (function-failure) result is then obtained by multiplying **EC** by **CF** for the rotorcraft. Table 4 illustrates the **EF** for the rotorcraft where the matrix entries indicate the number of instances in the rotorcraft system where a given function is related to the corresponding failure. This particular **EF** forms the basis for the function-failure knowledge base we use in determining the potential failure modes with the FFDM in the design examples presented in following sections.

Table 2. Failure Modes from NTSB Rotorcraft Accident Study.

Abrasive Wear	Direct Chemical Attack	Intergranular Corrosion
Adhesive Wear	Ductile Rupture	Low Cycle Fatigue
Biological Corrosion	Force/Temperature Induced Deformation	Pitting Corrosion

- Brinnelling
- Brittle Fracture
- Buckling
- Cavitation Erosion
- Corrosion Fatigue
- Corrosive Wear
- Creep Buckling
- Creep Stress Rupture
- Crevice Corrosion
- Deformation Wear
- Fretting Fatigue
- Fretting Wear
- Galling and Seizure
- Galvanic Corrosion
- High Cycle Fatigue
- Hydrogen Damage
- Impact Deformation
- Impact Fatigue Wear
- Impact Fracture
- Impact Fretting
- Radiation Damage
- Selective Leaching
- Spalling
- Stress Corrosion
- Surface Fatigue Wear
- Thermal Fatigue
- Thermal Relaxation
- Thermal Stress
- Yielding

Table 3. Functions from the NTSB Rotorcraft Accident Study.

Change Gas	Export HyE	Import Gas	Regulate HyE
Change Liquid	Export Liquid	Import HE	Regulate Liquid
Change PnE	Export ME	Import HyE	Regulate ME
Change RotE	Export PnE	Import Liquid	Secure Solid
Convert HE to RotE	Export RotE	Import ME	Stabilize Solid
Convert PnE to ME	Export Solid	Import PnE	Stop Gas
Convert RotE to ME	Export ThE	Import RotE	Stop HyE
Convert RotE to PnE	Guide Gas	Import Solid	Stop Liquid
Couple Solid	Guide HyE	Import ThE	Stop PnE
Distribute Liquid	Guide Liquid	Inhibit Liquid	Stop Solid
Distribute ME	Guide PnE	Join Solid	Store ME
Distribute ThE	Guide RotE	Link Solid	Supply ME
Export Gas	Guide Solid	Position Solid	Transmit ME
Transmit PnE	Transmit RotE	Transmit ThE	

Table 4. Function-Failure Knowledge Base from NTSB Rotorcraft Accident Study.

Function/Failure	Abrasive Wear	Adhesive Wear	Buckling	Corrosion Fatigue	Deformation Wear	Direct Chemical Attack	Force Induced Deformation	Fretting Fatigue	Galling and Seizure	High Cycle Fatigue	Low Cycle Fatigue	Stress Corrosion	Thermal Fatigue	Thermal Shock	Yielding
Change Gas	0	0	1	1	0	0	0	1	0	2	0	0	1	1	1
Change Liquid	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0
Change PnE	0	0	0	0	0	0	0	0	0	2	0	0	1	1	1
Change RotE	0	0	0	0	1	0	0	1	2	3	0	0	0	2	0
Convert HE to RotE	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2
Convert PnE to ME	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Convert RotE to ME	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Convert RotE to PnE	0	0	1	1	0	0	0	1	0	2	0	0	1	1	1
Couple Solid	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
Distribute Liquid	0	0	0	0	1	0	0	1	2	3	0	0	0	2	0
Distribute ME	0	2	1	1	1	3	0	2	0	7	1	0	0	1	3
Distribute ThE	2	0	0	0	1	1	0	0	0	4	0	1	2	1	2
Export Gas	2	0	1	2	0	0	0	2	0	4	1	1	2	1	2
Export HyE	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
Export Liquid	0	1	1	2	2	3	1	2	2	6	0	0	0	3	3
Export ME	0	0	0	0	0	2	1	0	0	2	0	0	0	0	2
Export PnE	0	0	1	2	0	0	0	2	0	4	1	0	1	1	2
Export RotE	1	0	0	0	0	0	0	0	2	3	0	1	1	1	0
Export Solid	2	2	1	2	2	4	1	3	2	12	1	1	2	4	8
Export ThE	1	0	0	0	1	1	0	0	0	2	0	1	1	0	1
Guide Gas	1	0	1	2	0	0	0	2	0	4	1	1	2	1	2
Guide HyE	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
Guide Liquid	0	1	1	2	1	3	1	1	0	3	0	0	0	1	3
Guide PnE	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Guide RotE	0	0	0	0	1	0	0	1	2	4	0	0	0	2	0
Guide Solid	2	0	1	2	0	0	0	1	0	3	0	1	2	2	1
Import Gas	2	0	1	2	0	0	0	2	0	4	1	1	2	1	2
Import HE	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2
Import HyE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Import Liquid	0	1	1	2	2	3	1	2	2	6	0	0	0	3	3
Import ME	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0
Import PnE	0	0	0	1	0	0	0	1	0	4	1	0	1	1	2
Import RotE	1	0	1	1	0	0	0	1	2	5	0	1	2	2	1
Import Solid	2	2	1	2	2	4	1	3	2	12	1	1	2	4	8
Import ThE	1	0	0	0	1	1	0	0	0	2	0	1	1	0	1
Inhibit Liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Join Solid	0	2	1	1	2	3	1	3	2	9	1	0	0	3	7
Link Solid	2	1	0	1	1	1	0	1	2	6	0	1	2	3	1
Position Solid	1	2	1	2	2	3	1	2	2	9	0	1	2	4	6
Regulate HyE	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
Regulate Liquid	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
Regulate ME	0	1	0	0	0	2	0	0	0	2	0	0	0	1	1
Secure Solid	2	2	1	2	2	4	1	3	2	12	1	1	2	4	7
Stabilize Solid	0	1	0	0	0	2	0	0	0	1	0	0	0	0	1
Stop Gas	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stop HyE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Stop Liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Stop PnE	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stop Solid	0	0	0	0	0	0	0	0	2	2	0	0	0	1	0
Store ME	0	0	0	0	0	0	1	0	0	0	0	0	0	0	3
Supply ME	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2
Transmit ME	0	1	0	1	1	2	1	1	0	5	1	0	0	1	6
Transmit PnE	0	0	0	0	0	0	0	1	0	2	1	0	0	0	1
Transmit RotE	1	1	0	0	1	1	0	1	0	2	0	1	1	1	0
Transmit ThE	2	0	0	0	2	1	0	1	2	7	0	1	2	3	2

4. A METHODOLOGY FOR FAILURE ANALYSIS IN CONCEPTUAL DESIGN

Pahl and Beitz [25] state that the quality of a product has to be built-in from the beginning of the design process and maintained throughout the production process. They go on to state that up to 80% of all faults can be traced back to insufficient planning and design work. Knowing this, it is hypothesized here that beginning failure analysis during conceptual design will have a positive impact on the quality of the product being designed. The major problem with this desire is the difficulty in performing failure analysis on a product that has yet to be designed and only exists as a functional representation. The development of the FFDM addresses this problem so that failure analysis can be performed at a truly conceptual stage.

The goal of the FFDM is to improve on previous failure analysis tools so that it can be applicable even in conceptual design. The FFDM is structured as a systematic technique that is easy to use. The FFDM also offers the benefit of requiring few people to perform the analysis since the method is based on archived failure occurrence information rather than human recollection. The FFDM's utilization of functional models of a design allow it to be used in conceptual design since functional models are independent of the physical form of the product being analyzed.

In addition to its failure analysis capabilities, the FFDM offers the ability to be used as a "start-to-finish" design method in conjunction with the concept generator approach or be used with more traditional concept generation approaches as a stand-alone failure analysis tool. In either case, the main purpose of FFDM is to identify failures. Naturally, the designer must balance the use of this or other failure analysis tool with the need to satisfy functional requirements and adhere to design constraints. During redesign, the FFDM can be applied when exploring the existing product at the component level. Each of these applications of the FFDM requires the use of a function-failure knowledge base to convey the relationship between past failures and functionality.

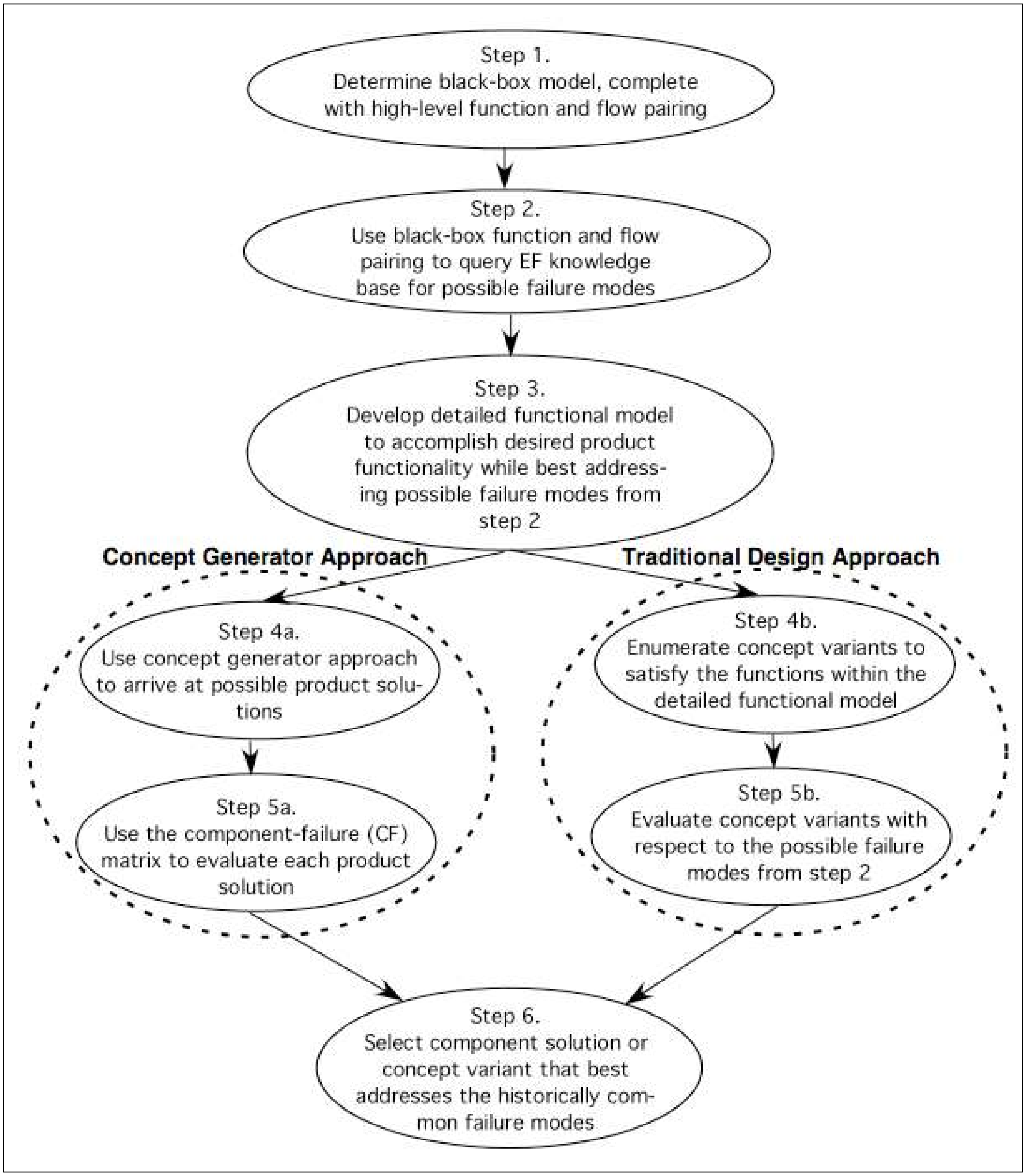


Figure 2. FFDM and Concept Generator Procedure.

4.1 Using FFDM for Design

The FFDM procedure is shown in Figure 2. Specifically, the steps of the method are described below.

1. Develop a black-box model for the new design or the component being redesigned that best describes its overall functionality. The function and flow pairing should use the secondary level of functions and flows from the functional basis as defined in Hirtz et al [24]. This level refers to the level of abstraction in the language. The function 'store electrical energy' is at this level for example.
2. Use the function-flow representation from the black-box model to query the function-failure knowledge base to determine the most common failure modes exhibited by that function. By definition, a black box addresses one singular overall function, so this query examines only the failures associated with this function. Performing such a query for a set of functions within a functional model is simply an aggregate examination of several black box functions, each with their own associated set of failure modes. In this manner, failures occurring as a result of interactions are not taken into account insofar as the **EF** knowledge base does not address the complex coupled effects of interactions among components. Note that other work addresses the issue of interactions among failures [2, 7].
3. Derive a detailed functional model for the design. This detailed functional model should show the complete desired functionality of the design and should also address the failure modes enumerated in step 2.

   Accounting for these initially identified failure modes generally involves adding functions to those that describe the desired functionality of the design. For the case of a black box function 'guide rotational energy' as shown in Figure 3, the three most common failure modes have historically been high-cycle fatigue, galling and seizure and thermal shock. This is indicated by the entries in the function-failure matrix that are relatively high for these particular failure modes. To address thermal shock, the designer might add functionality to the detailed functional model in order to shield the component from external heat and dissipate the heat generated by the component. By this action, the designer arrives at a more accurate functional model earlier in the design stage. Nevertheless, this added functionality itself is a point of failure and is evaluated in the following steps.

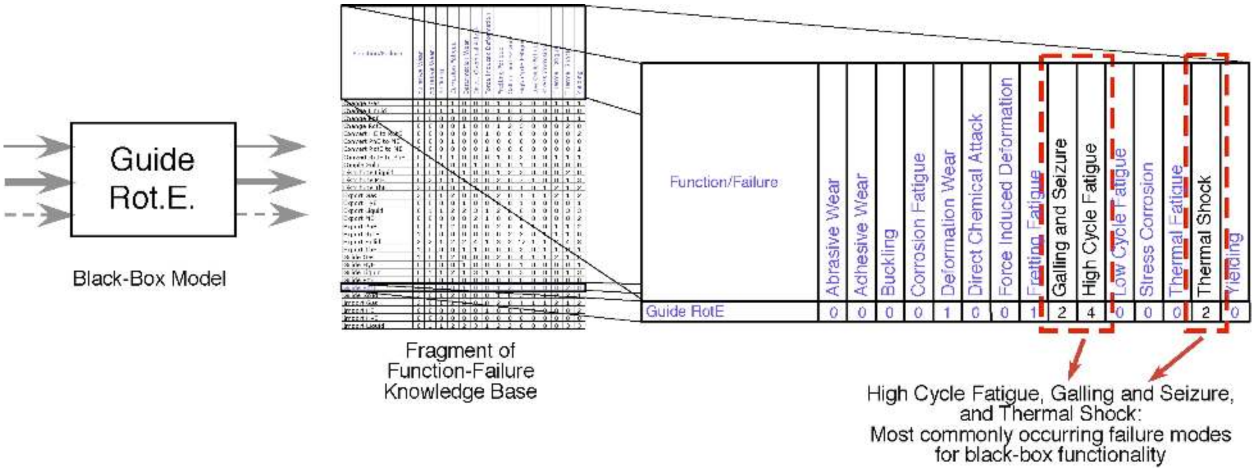


Figure 3. Using the FFDM to Enumerate Failure Modes for a Given Function.

It is at this point that the designer can choose from two paths to follow in their design. One path is the concept generator approach and the other is a conventional process. Selection of this choice is simply an issue of designer preference although the concept generator approach does offer the advantage of a greater degree of assisted concept generation. Steps 4a and 5a show the necessary steps within the concept generator approach, while steps 4b and 5b show the necessary tasks for a design without the use of the concept generator.

4a. Use the detailed functional model from step 3 with the concept generator to arrive at possible product solutions. To do this, multiply the filter matrix (created based on the detailed functional model) by the function-component (**X**) matrix to generate candidate physical solutions.

5a. Evaluate these product solutions with the component-failure matrix. This involves querying the component-failure matrix for each possible physical solution. By doing so, the designer gets a list of failure modes that have historically occurred for each solution.

For a design approach that utilizes more traditional concept generation, use steps 4b through 6.

4b. Use conventional design methods (brainstorming, etc.) to enumerate concept variants that satisfy the functionality in the detailed functional model derived in Step 3. Recall that these concept variants account for any added functionality that has not yet been analyzed in terms of failures. Hence, the following step addresses this issue despite some degree of redundant failure checking that overlaps the initial check in step 2.

5b. Evaluate this list of concept variants with respect to the failure modes from step 2. This involves suggesting suitable analyses for each potential failure mode. For example, if high cycle fatigue is a potential failure mode, then each concept variant should be analyzed for resistance to fatigue. This analysis can also involve exploring materials selection and manufacturing possibilities for each concept variant.

6. Select component physical solution or concept variant with the fewest historically troublesome failure modes or that performed the best during the failure analysis in the previous step. It could be necessary to perform further appropriate analyses to arrive at a final component design that avoids the common historical failure modes. Engineering judgment is required here to ensure that the identified failure modes are viable for the current application and excess analyses are not being performed.

At any point during these design steps, the designer can query the function-failure knowledge base with functions from the detailed functional model in order to better understand failures that are likely to occur in the new design. Similarly, assessments can be performed as a concept evolves so that potential failure issues can be addressed.

5. METHOD EVALUATION

Two components comprise the evaluation of the FFDM. First, the method is evaluated in broad terms in order to provide a cursory overview of method capability. This amounts to assessing the method by direct observation and contemplation of the method in terms of method features and benefits. Second, a more thorough assessment is performed by applying the Validation Square approach developed by Penderson et al [26].

5.1 Direct Assessment of FFDM and Case Studies

In conjunction with the overview presented in Table 1, the main key features and highlights of the method are clarified here by direct evaluation. The foremost attribute of the FFDM approach is the use of a knowledge base that acts as a surrogate for the experience of the designer. Clearly, this knowledge base does not remove the responsibility of the engineer to check and confirm the design but the knowledge base does provide a source of relevant failure information that simply does not exist in FMEA outside the designer's personal experience. This knowledge does come with fundamental limitations. First, the recommended failure modes are treated as independent events since the knowledge base does not account for the coupling effects between failures of multiple components and functions. Interaction effects are addressed in other work where similarity matrices are used to deal with failure interactions by allowing the FFDM to identify failures that tend to occur together [2, 7]. Second, the designer must still judge the indicated failure modes in order to recommend some action.

The second main feature of FFDM is the ability to use the approach during the functional stage of conceptual design because failures are linked to functions via matrix manipulation. The language of the functional basis and the failure mode vocabulary both contribute to this capability by providing a well-defined set of nomenclature used in the method. Due to the nature of the particular functional language used, a broad set of products can be modeled [24]. Beyond this, the failure mode vocabulary also has applications in FMEA and other techniques where such a vocabulary is appropriate. A more extensive failure mode vocabulary (including polymers, electrical applications, etc.) will allow the FFDM to be applied to a wider range of components and systems, with particular application to spacecraft anomalies, and is currently under development [5, 27].

Next, two comparative case studies between the FFDM and FMEA are presented to illustrate the FFDM procedure. The first example is conducted using both failure analysis methods on a new design. Similarly, the second comparison conducts both analyses on an existing product and compares the output from each. For these comparisons, test participants who are all graduate students at the University of Missouri-Rolla are given the same initial problem statement to conduct each analysis. One student performs the FDMA and three students perform FMEA on an individual basis – not as a team. Results for the FMEA case are shown as the aggregate results of these three students. Both the control and experimental groups are given the same input specification for the design problems. A time of one hour is allotted for the exercise.

5.1.1 Failure Analysis Comparison for a New Design

For the new design case, a design problem is formulated that is compatible with the information in the knowledge base of rotorcraft data. Specifically, this comparison is based on the design of a highly portable, small-scale air compressor that can be attached to a hand-held power drill. The design challenge is that this compressor should work with all hand-held power drills and be capable of blowing small debris away in order to clean an area such as a workbench. Two test groups are formed where the FMEA set is comprised of multiple but individually acting design engineers while a single design engineer, independent of the FMEA team, performs the FFDM analysis. Each is given the same basic statement for the design problem noted above as well as an initial design representation described below. The intent of this approach is to yield a first order estimate of the differences between the two different failure approaches. Further rigor would necessitate a greater sample set of designers and an experimental approach that accounts for designer expertise, collaborative efforts, and a large number of other complicating factors. These sources of error are taken into account in the validation discussion that follows the case studies.

Since traditional FMEA methods are not easily applicable to transforming functional representations into physical designs, an initial design representation must be established before an FMEA can be performed. The initial physical design of the air compressor, seen in Figure 4 was created using the concept generator approach of the FFDM.[1] The reader must note that this initial physical design is, for purposes of the *failure analysis*, independent of the FFDM. That is to say, the concept generator is simply one source for deriving an initial physical solution. For this example, the initial physical representation developed by the concept generator does not include any additional functionality identified by assessing the failure modes of the black-box function (as prescribed in Steps 2 and 3 from above). The functional model used as input to the concept generator is based solely on identifying the chains of sub-functions that satisfy the customer needs. The air compressor physical design shown in Figure 4 is subjected to an FMEA and failure analysis within the FFDM. Output from the analyses is ultimately a set of recommended actions for completing the design of the air compressor where these recommended actions from both methods are compared in Table 5.

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[1] Note- This step would normally not occur when performing the FFDM, it is included here to offer a design on which the FMEA can be performed. In the actual FFDM, the first physical model would already exhibit functionality and/or componentry to address possible failure modes. In this case, the initial physical design does not address any possible failure modes.

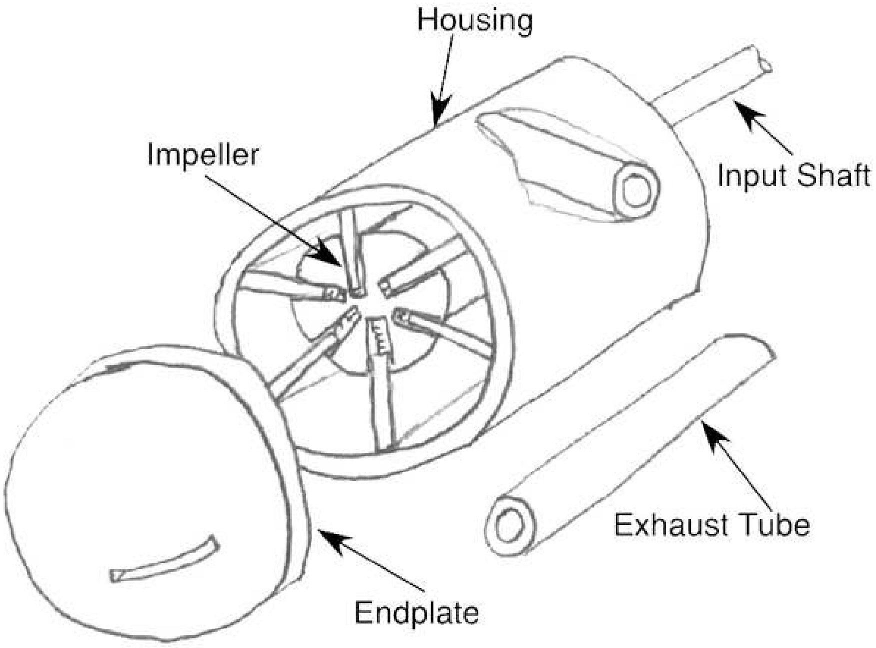

Figure 4. Initial Compressor Physical Design.

Table 5. Recommended Actions from Failure Analyses of Compressor.

FFDM			FMEA
Function	**Historical Failures**	**Recommended Actions**	**Recommended Actions**
Stabilize Solid Import Rot.E. Convert Rot.E. to Pn.E. Guide Pn.E. Import Pn.E. Export Pn.E.	Direct Chemical Attack High Cycle Fatigue Abrasive Wear Fretting Fatigue Thermal Shock Thermal Fatigue Yielding	-Choose materials that can properly interact with air and water -Perform fatigue analysis on rotating components and housing -Include a filter screen on air inlet -Include bearings to support shaft -Choose a flexible material for the exhaust tube -Fin the endplate for better heat transfer -Choose a hardened material with clamping flats for input shaft -Perform extensive stress analysis on support feet	-Use hardened and grooved material for input shaft -Add self-aligning bearing to support input shaft -Perform fatigue analysis on housing -Include a cleanable screen for air inlet -Include a precise sealing surface between housing and endplate -Use flexible material for exhaust tube

Figure 5 schematically shows how the FFDM is applied to the compressor design. First, a black-box model is developed to show the overall functionality and input and output flows of the new design. The black-box function and flow pairing of "convert rotational energy to pneumatic energy" is then used to query the function-failure knowledge base to compute a list of failure modes likely to occur. This list, also shown in Figure 5, is scrutinized during the derivation of the detailed functional model for the compressor. The inclusion of thermal fatigue and thermal shock in the list of possible failure modes leads the designer to add the functionalities of distribute thermal energy and export thermal energy to the detailed functional model. Similar analysis leads to the inclusion of a "separate gas" function on the incoming airflow to avoid the failure mode of abrasive wear for the "import gas" function.

At this point, functional embodiment with the concept generator leads to concept variants, which are then scrutinized against the list of possible failure modes that occur for their individual functionality. Recommended actions are then generated based on these failure modes. The FFDM analysis directly leads to the inclusion of the incoming air filter, shaft support bearings, finned end cap and flats on the shaft to facilitate coupling with the drill in the final design. The FFDM also leads the designer towards various fatigue and stress analyses and aids in material selections throughout the design.

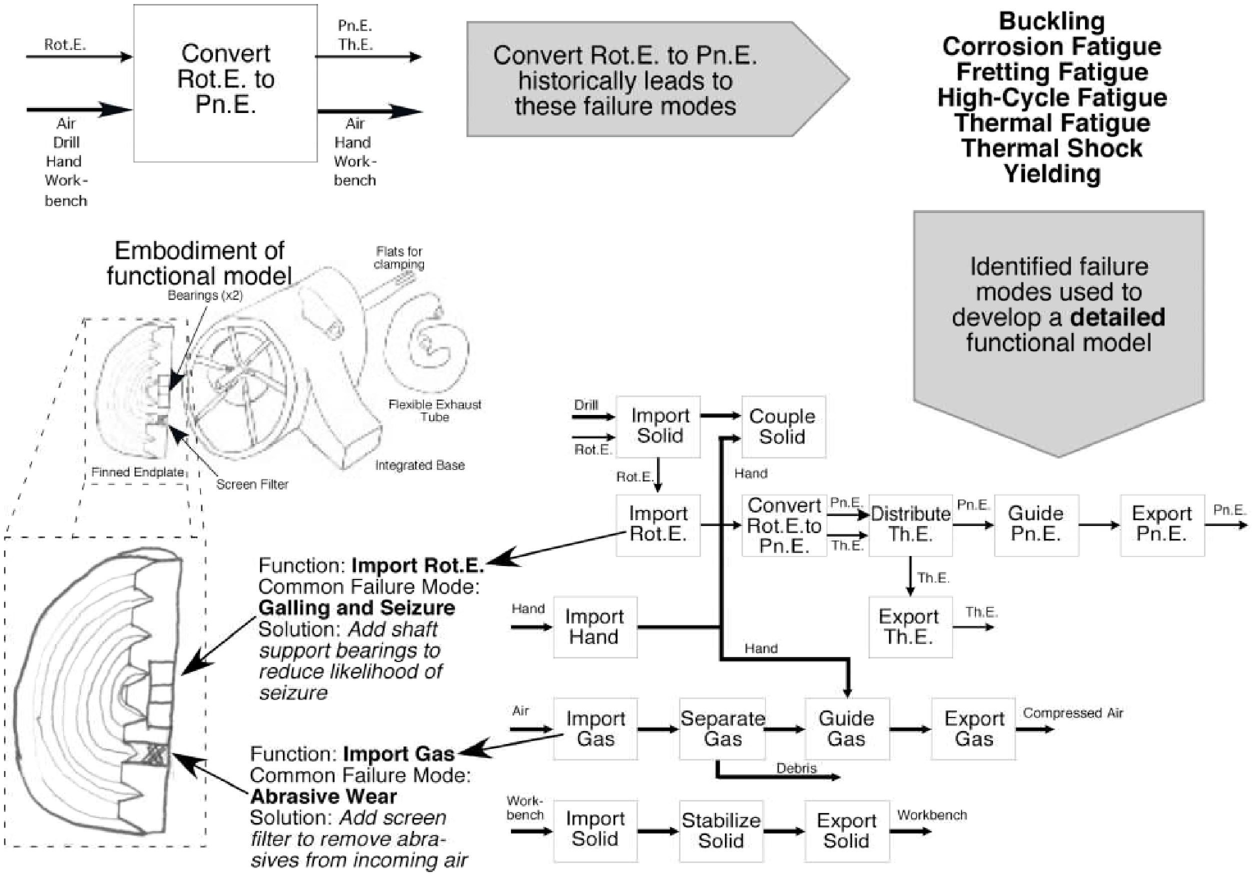

Figure 5. The FFDM Approach for the Compressor Design.

Comparing Results for the Compressor Design

It should be noted that the recommended actions for this new design example from both the FMEA and the FFDM provided insightful directions for component design. The FFDM recommendations are greater in number which might be explained by the FMEA group recognizing only more realistic failures while the FFDM approach yielded a greater and perhaps excessively large set. As an alternative interpretation, the FFDM has a knowledge base with a more complete set of potential failures than the expertise afforded by the FMEA group. In particular, the thermal consequences of this design were overlooked or at least not acknowledged by the FMEA test subjects, but investigated by the FFDM. It is possible that at the time of the analysis, the FMEA test subjects each made a deliberate choice to ignore these issues since limited time dictates that not all failure modes be addressed. By comparison, the recommendations from the FFDM approach show considerable overlap with the FMEA results.

5.1.2 Failure Analysis Comparison for an Existing Product

For this comparison, three components from a Campbell Hausfeld 1/2" air impact wrench are analyzed using both FMEA and the FFDM. An exploded view of the impact wrench is shown in Figure 6. The components used within this comparison of the failure analysis methods are the anvil, inlet bushing and housing back plate. Recommended actions from each methodology to best eliminate the failure mode occurrence are compared on a component-by-component basis. As in the first case study, three design engineers individually conducted the FMEA test while a single design engineer, independent of the FMEA group, performs the FFDM analysis.

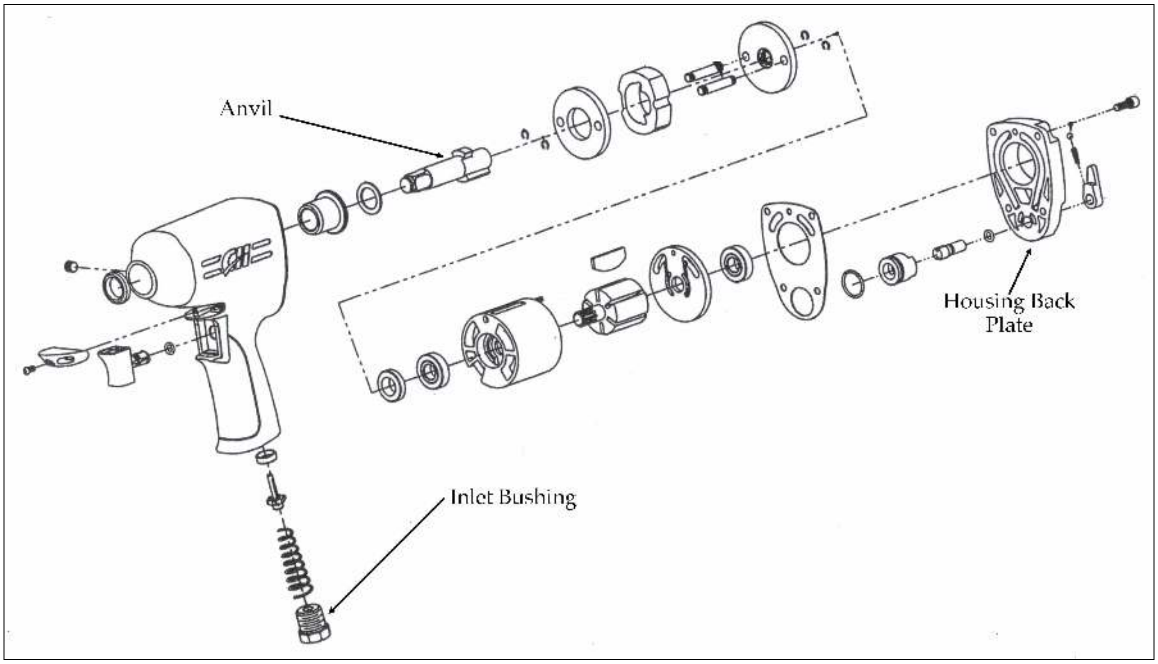

Figure 6. Exploded View of Campbell Hausfeld 1/2" Air Impact Wrench.

Results for the Anvil

The anvil's main functionality is to export both rotational and impact energy from the wrench. Within the casing, the anvil interacts with the hammer, and externally, the anvil attaches to a socket. The socket would then link the impact wrench to the nut or bolt that is being turned. The comparison in Table 6 shows that the recommended actions resulting from both failure analysis methods are quite similar. The FFDM did however identify a somewhat larger list of recommended actions. Recommendations for stress and fatigue analysis were recommended by FFDM but not by FMEA and in general, the FMEA recommendations seem to be aimed more at manufacturing and maintenance than up-front design.

Table 6. Recommended Actions from Failure Analyses of Impact Wrench Anvil.

FFDM			FMEA
Function	**Historical Failures**	**Recommended Actions**	**Recommended Actions**
Transmit Rotational Energy Transmit Impact Energy Export Rotational Energy	Abrasive Wear Deformation Wear Direct Chemical Attack Yielding Galling and Seizure	-Increase surface hardness -Test completed parts for sufficient surface hardness -Explore surface plating -Perform rotational fatigue analysis -Perform fatigue testing on a sample of completed parts -Perform stress analysis to determine suitable materials and heat treatments -Investigate added lubrication at bushing	-Test completed parts for sufficient surface hardness -Non-destructively test completed parts to assure strength -Lubricate anvil-to-bushing interface

Results for Inlet Bushing

The inlet bushing's main functionality is to import compressed air into the impact wrench from an external source. The bushing threads into the wrench housing and is held in place with a thread-locking compound. Either a compressed air hose or "quick-connect" fitting is threaded into the internal diameter of the bushing. A wire screen filter is present within the bushing to filter any solid debris out of the incoming air. The comparison in Table 7 shows the recommended actions from both methods to be similar. The FFDM does not account for "clogging" of the screen filter. Currently, the failure mode vocabulary does not describe "clogging" accurately since a "clog" usually indicates the failure of some other component. For example a part might clog because it fills substantially with metal chips dislodged from a bearing that is according to some established definition, clearly galling. The vocabulary used for the failure modes defines the term for a given failure mode so that ambiguity for failure terms is minimized. This applies to both FFDM and FMEA since test subjects used the same vocabulary for both approaches. In the case of the bearing, it would be said to fail via galling and seizure and this would be entered into the knowledge base as such. The cumulative set of multiple failures leading to this seizure are not captured however.

Table 7. Recommended Actions from Failure Analyses of Impact Wrench Inlet Bushing.

FFDM			FMEA
Function	**Historical Failures**	**Recommended Actions**	**Recommended Actions**
Import Pn.E. Transmit Pn.E.	Fretting Fatigue Yielding	- Explore thread-locking solutions -Investigate component hardness to ensure that threads will not yield -Perform hardness testing on completed parts	-Explore thread-locking solutions -Investigate the use of a self-cleaning filter

Results for Housing Back Plate

The housing back plate is bolted to the rear of the impact wrench and supports the internal rotating components while also acting as a manifold to distribute the compressed air. Table 8 shows some overlap with the thread-locking solution recommended in both analyses. The suggestion for a self-cleaning filter seems to be an innovative solution not accounted for in the FFDM. For both types of analysis, the emphasis of recommended actions seems to be on manufacturing quality assurance rather than pre-production design effort.

Table 8. Recommended Actions from Failure Analyses of Impact Wrench Housing Back Plate.

FFDM			FMEA
Function	**Historical Failures**	**Recommended Actions**	**Recommended Actions**
Transmit Pn.E. Guide Pn.E. Stabilize Solid	Yielding Fretting Fatigue Direct Chemical Attack	-Perform x-ray testing on a sample of parts to check for material impurities -Perform testing on a sample of completed parts to check for ability to withstand impact -Choose material with resistance to water, oil, etc. -Ensure good gasket fit with additional sealant -Pressure test assembled wrench to ensure good seal -Explore the implementation of an improved upstream filter	-Non-destructive testing of component under common loading conditions -Explore self cleaning filter for the incoming compressed air -Perform testing to ensure a quality seal between the back plate and the housing

Comparing Results for the Impact Wrench Redesign

For these three components of the impact wrench, the results from the FFDM again suggest performing more analyses than the FMEA approach. With respect to the clogged filter issue, it should be noted that clogging is not a recognized failure mode within the vocabulary that has been used for this research. The same argument applies to the FMEA method since the students using the FMEA technique in these experiments used the same knowledge base which therefore has the same vocabulary. Expansion of the failure mode vocabulary is a key area for concentrating further research in order to more precisely capture a broader set of failures. This improvement could impact both FFDM and FMEA approaches.

5.2 VALIDATION SQUARE ASSESSMENT

The Validation Square [26] is used as a six step framework here for progressively evaluating the FFDM. The first step involves addressing the validity of the individual constructs that form the FFDM. In this case, the major constitutive items include the terms for specifying functions, components, and failure modes as well as the structures in which these terms are manipulated. The functional language used is valid based on its well-defined nature [24]. The terms used for components and failure modes are valid based on the clarity observed in the initial knowledge base established above. The structures for these terms are simply matrices that explicitly relate these terms together so their validity is not a concern.

The second step is to validate method consistency in order to ensure that the method process is workable by having adequate information throughout its process. This step also determines if the information generated is excessive, unnecessary, invalid, or insufficient. The limitation of the FFDM in this regard is the knowledge base. The FFDM is only as adequate as the set of failures archived in the **CF** matrix which means that potentially, the method will not be indicate all relevant failures. As the size of the knowledge base grows, this limitation is reduced. Conversely, this larger size may produce a greater number of false positives in the sense that more potential failures may be indicated than are really necessary. Pruning this oversized failure set then becomes an issue. These difficulties notwithstanding, the method is workable and assuming the knowledge base is developed without error, the method is a feasible process. As a third step, the Validation Square addresses example problems used to test the method. Validation at this stage is simply the acceptance of the examples as appropriate for verifying method performance. The above case studies both use reasonable products that are representative of the type of devices for which failure analysis techniques are intended. Based on this consideration, the examples support acceptance of the third validation step.

The fourth step is intended to verify the utility of the method for the example problems. Here the issue is whether or not users of the method showed benefit relative to some reference. From this perspective, the results are encouraging. In both case studies, the FFDM resulted in a greater number of recommended actions. Anecdotally, this seems positive although some of the recommendations are admittedly low probability events. Nevertheless, the greater coverage of potential failures is taken as a positive result. Figure 7 gives an overview of the recommended actions from both case studies in terms of the number of overlapped recommendations as well as the recommendations unique to the FFDM and the FMEA methods. The case study involving the compressor resulted in much greater overlap than the recommendations for the impact wrench. Reasons for this effect are unclear although one partial explanation is that the FMEA test subjects scaled the number of their recommended actions to be proportionate to the scale of the design problem under investigation. Here the compressor is clearly more complex than the individual problems of the anvil, inlet bushing, and back plate. Again, this explanation is speculative but supported by the results. Figure 7 also shows that while the FFDM presents a greater number of recommended actions, the FMEA approach consistently produces one unique recommendation.

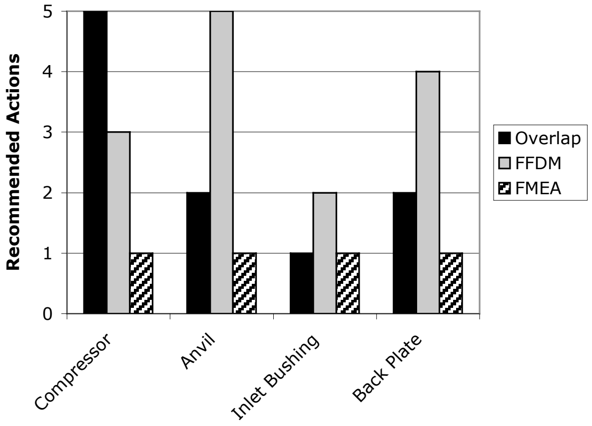

Figure 7. Overview of Experimental Results.

The fact that this greater coverage was obtained using one designer compared to the three engineers performing FMEA is particularly encouraging and suggests that the results can be attributed to the usefulness of the results to the method. These combined results support the validation of the FFDM for both the fourth and fifth steps. While multiple case studies across several designers would improve the confidence of the results, the results although limited do support the conclusion that FFDM is relatively effective at recommending a set of failure modes compared to the FMEA approach. Extrapolating this inference beyond the two case studies to other products is the test for the sixth and final validation step. Given the nature of the products in the above examples in that they are in the mainstream of mechanical products for which FFDM is intended, it is reasonable to conclude that the FFDM approach would be effective as well for other products at a similar level of complexity and scale.

6. DISCUSSION AND FURTHER WORK

Revisiting the case of the failed electric transformers from the introduction, the cracks found at the base of the cooling fins originated because of high cycle fatigue. Since transformers operate under static conditions, fatigue had not been considered in the original design selection. But, during their shipment on rail cars, vibrations caused a situation of fatigue to develop at the locations where the fins were welded to the transformer case. As reported, these cracks caused the failure of the transformer coils [1].

While this incident is not directly related to the operational aspects of the product, the FFDM does have the potential for capturing such problems. The cooling fins in this situation perform the function of “transmit thermal energy.” When querying the rotorcraft function-failure knowledge base with this function, the most commonly occurring failure mode is high cycle fatigue. This would have brought the possibility of this failure into the sight of the designer and suggested a thorough fatigue analysis or some corrective measures to avoid this failure when considering the mode of shipment. Additionally, it may prove useful in conceptual design to augment operational failures with other categories such as manufacturing, assembly, transport, maintenance, etc.

Further research is underway to improve upon the failure mode vocabulary of Arunajadai et al. [3] to include electrical failures and improve the failure definitions concerning composite materials and polymers [27]. These additions to the failure mode vocabulary will allow the knowledge base to be expanded to include components that exhibit these failures.

At this point, the rotorcraft function-failure knowledge base is the only one that has been developed and tested in a limited manner. It will be necessary to develop other function-failure knowledge bases or add to the existing one in order archive historical failure occurrence knowledge from other areas such as consumer products and the automotive industry. JPL's space missions are currently under study to derive component functionality and extract failure mode information from the existing Problem and Failure Reporting database [5]. The expansion of the function-failure knowledge bases will logically occur after the failure mode vocabulary has been increased.

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