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LINK BETWEEN FUNCTION-FLOW FAILURE RATES AND FAILURE MODES FOR EARLY DESIGN STAGE RELIABILITY ANALYSIS

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ABSTRACT

The scope of this paper is to provide an extension to the Function Failure Design Method (FFDM). We first implement a more robust knowledge base using Failure Mode/Mechanism Distributions 1997 (FMD-97). Then failure rates from Nonelectric Parts Reliability Data (NPRD-95) are added to more effectively determine the likelihood that a failure mode will occur. The proposed Functional Failure Rate Design Method (FFRDM) uses functional inputs to effectively offer recommendations to mitigate failure modes that have a high likelihood of occurrence. This work uses a past example where FFDM and Failure Modes and Effects Analysis (FMEA) were compared to show that improvements have been made. A four step process is presented to show how the FFRDM is used during conceptual design.

1. INTRODUCTION

In the process of design, functionality is where the voice of the customer is captured. For this reason, failure can be defined as the loss of functionality [1]. Meaning that if the design stops working in the way the customer prefers, it has failed. Since we design for functionality, data in this research has been tabulated to provide designers the capability to perform accurate reliability analyses directly after generating a functional model. Functional modeling is performed at the conceptual stage of design before any components have been determined [2]. This data has been carefully calculated using historical failure information and relationships between functions and components. Although, here the failure rates are linked to specific failure modes and offer the likelihood that the failure mode will occur given that a specific function-flow appears in the functional model.

Performing reliability analysis at the conceptual level of design offers the power of risk informed decision making to the designer. As the design process continues it becomes increasingly expensive to make design changes. Providing an analysis that can mitigate this problem at the conceptual level may significantly reduce the likelihood of costly failure events.

2. BACKGROUND

This section provides a survey of the relevant related research. These topics include Functional Modeling, FFDM, Risk in Early Design, and Failure Rates, Modes, and Mechanisms.

2.1. Functional Modeling

Functional modeling is a standard part of many engineering design methodologies and is used to describe a design at an abstract level. Generating a functional model is done early in the design process before components have been chosen in an original design problem or before reviewing existing component choices in a redesign problem. The design process, in a general sense, follows five steps; project definition and planning, specification definition, conceptual design, product development, and product support [3]. The functional design method is used in the first stage of conceptual design.

The format of functional models consists of functions connected by flows. The three types of flow include material, energy, and signal. Stone [4] standardized functional modeling by creating a common functional basis which provided a set number of functions and flows to describe the entire design space. The functional basis provides consistency across functional models of different designs. The functional basis is used as the starting point for this research. Failure rates of failure modes are found here for each term in the functional basis. Appendix A presents this data in a summarized version due to page limit restrictions. This includes each functional basis term.

Table 1 gives an example of how the functional basis is different from describing a design using general functionality.

TABLE 1: Example Using Functional Basis Terminology

General	Functional Basis
- Accept user's hand - Position user's hand - Move clipper to desired location - Apply force on lever to actuate clipper - Return clippers to storage - Release user's hand	- Import Human Energy - Import Human Material - Import Solid Material - Guide Solid Material - Position Solid Material - Actuate Solid Material - Guide Solid Material - Position Solid Material - Export Human Energy - Export Human Material - Export Solid Material

2.2. Function Failure Design Methodology

FFDM is a structured formulation of the function-failure analysis method introduced by Tumer and Stone [5], and is used to perform failure analysis in the conceptual design stage. This method also aids the designer by using a function-based concept generator approach which helps streamline the design process [6]. The proposed extension to FFDM, FFRDM, does not use this concept generation. Instead, FFRDM is used only to inform the designer at the functional level of design. FFDM utilizes knowledge bases which link product function to failure modes. The knowledge base data is archived in the form of a function-component matrix and a component-failure mode matrix. This reduces the need for a designer to have a large intellectual knowledge base.

FFDM has several advantages including reduced high user workload, using an archived failure knowledge base, being usable during functional design, using the functional basis, component taxonomy, and failure mode taxonomy as a formalized failure language, and is practical for electrical and mechanical systems [7].

Currently, FFDM lacks a strong component failure mode knowledge base. Only 63 failure mode occurrences have been observed in this framework previously [5]. Adding to the knowledge base provides confidence in the results. Using FMD-97 [8], this research has added approximately 36,700 failure mode occurrences to the component-failure mode matrix.

2.3. Risk in Early Design

Risk in Early Design (RED) is a conceptual design tool which uses functional inputs to assess risk. An algorithm along with historical failure data is combine to provide the designer failure modes, likelihood, and severity from the functional inputs.

The RED database is populated by three sources including functional models, bill of materials, and failure reports. Bill of materials and failure reports provide the component name and failure mode occurrence respectively. Data is converted using naming taxonomies for failure modes [9], components [10], and functions [4] to standardize the process. Each taxonomy is explicitly defined and defines the entire set of potential names. Figure 1 shows how each source correlates to matrices EC, CF, and EF. The matrix EF is produced by multiplying matrix EC by CF.

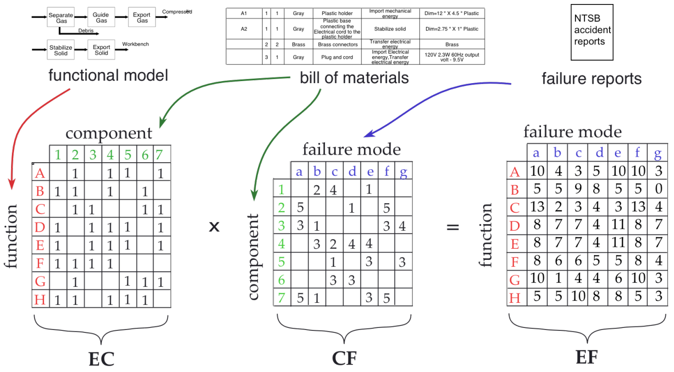


FIGURE 1: Red Database Population

This information can be used to determine the respective difference in occurrence between failure modes for a specific function. Similarly it can be determined which failure modes globally occurs with the greatest frequency. Although, this can not be used to predict likelihood of a failure mode. The current CF matrix has approximately 600 observed occurrences. The proposed method has observed over 36,700 occurrences to provide more robust results. Using sixty times the number of occurrences will give the designer confidence that the method is well backed by a large knowledge base.

In addition to this calculation, RED provides calculations for failure severity and likelihood. Failure severity was gathered through studying NASA, FMEA, and risk engineering sources. These sources provide the foundation to generate the CF' matrix using scores from 0 to 5, where 5 is the most severe. A similar matrix calculation was performed as in Figure 1. The result is the occurrence of functional failure severity. Failure likelihood was generated from a detailed list of component failure occurrences. The failures were sorted low to high based on their occurrences. These were also categorized in to a 0 to 5 scale and a matrix calculation was performed to determine the likelihood of the functional failures.

The likelihood data was tabulated solely using failure occurrence. Likelihood cannot be determined in the absence of time since failure is time dependent. While strictly using occurrence data, common components will observe increased likelihood because they are used more often. Less common components, which may have a higher failure rate, could receive a lower likelihood value because their failures are observed less often. The solution is to use failure rate information in the place of recorded failure occurrence. The FFRDM knowledge base proposed in this research provides failure rates of failure modes for specific functions. This is the necessary data to generate quantitative likelihood results at the conceptual stage of design.

2.4. Failure Rates, Modes, and Mechanisms

Failure rate (λ) is a commonly used and well accepted variable found during risk and reliability calculations. In general, (λ) is recorded in units of Failure/Million Hours or Failure/Million Miles. The depends on the source and how the data was collected.

A common problem in reliability engineering is how failure can be mitigated. The root of this problem can be better understood by the cause and result of a failure. Depending on the source, the terms failure mode and failure mechanism are defined differently. Often, they are used interchangeably as the end state of a failure. Collins uses the term failure mode as the physical process or processes that produce a failure [11]. Blischke and Murthy define this as the description of a fault. Although, neither provide a definition for failure mechanism. FMD-97 defines failure mode as the observable consequence of failure. Here, this definition is adopted and is extended to also include any change in behavior. FMD-97 defines failure mechanism as the physical process which causes the failure.This definition will also be adopted.

A common vocabulary of failure modes has been developed for mechanical systems by Collins [11]. Work done by Stone and Tumer [9] has provided a failure mode taxonomy for both electrical and mechanical systems. The latter will be used here to convert failure modes from those listed in FMD-97. Although, for mechanical failure modes that appeared in both taxonomies, definitions/descriptions were consulted from Collins text to gather more consensus.

2.5. Failure Modes and Effects Analysis

The goal of FMEA is to identify, evaluate, and prevent critical component or functional failures [12]. FMEA can be performed in exactly the same manner using either components or functions. Failure is commonly defined as a loss in functionality and therefore this research focuses on FMEA using functions. Critical functions receive a recommended schedule and action to reduce the failure mode risk. FMEA is a tool used to analyze systems to gather information that a decision can be made from.

High risk functions are determined by the risk priority number (RPN). The FMEA analysis starts by identifying a list of functions and their potential failure modes. A list of functions can be produced from the functional model while a list of components is produced from the detailed component design architecture. Failure modes are determined by expert knowledge or extensive research of similar designs. The RPN value is the product of three variables; occurrence, severity, and likelihood of detection. Occurrence refers to the likelihood that the failure will occur, severity is how bad the failure is, and likelihood of detection is how hard the failure is to detect. From the list of potential failures, the occurrence, severity, and likelihood of detection are scored on a scale of 1 to 10, resulting in an RPN value in the range of 0 to 1000. The usefulness of FMEA as a design tool is to look at the RPN values relative to each other and determine which functions need action taken and which do not. From this analysis, the designer can determine the critical functions of a system and make design changes accordingly.

Information for single failure mode input into the FMEA is not a long process. This simply involves entering the function, an associated failure mode, then listing the severity, detection, and occurrence values. These values are also subjective and can lead to a poor analysis of critical failures. Although, to perform a complete FMEA for the entire design can be very time consuming. This involves generating a list of potential failure modes for each function. At a functional level this is not intuitive and at a component level would require domain-specific expert knowledge. Some functions, or components, can have over 50 distinct failure modes that should be considered. Next, each failure mode must have the severity, detection, and occurrence determined and recorded. Once this is done, it must be determined which functions have too high of an RPN value, then recommended actions must be recorded. In all, this analysis becomes very time consuming.

FMEA also requires expert engineers to properly perform. Experts have acquired a knowledge base that only they have access to. Although, even the seasoned professional can miss failure modes with high occurrences. Using a computerized knowledge base solves this simple mistake. Experts have recorded data for years which has been grouped in to a single data source. The data found in this research was calculated using this historical failure rate data. Engineers with little experience in a specific field can use this data to produce expert level results.

The research described in this paper provides a solution to FMEA. This can reduce the time required by an expert, or in some cases, eliminate the need for an expert altogether. In FFRDM the functional model is used to generate the relevant failure modes for a design. Failure modes are provided with failure rates as a way to accurately determine the occurrence. Calculating the RPN value is not needed. Prior work has shown that final recommendations by FFDM can exceed those of FMEA [5]. This example is revisited to show that improvements have been made in the extension from FFDM by providing further useful recommendation and discussing recommendations given previously that had low occurrence values.

3. RESEARCH APPROACH

This section provides information and the steps followed to arrive at the knowledge base for FFRDM. Two data sources were used as a starting point, NPRD-95 and FMD-97. Failure modes in FMD-97 were converted to a failure mode taxonomy. A repository of product information was used to generate function to component relationships. These relationships in conjunction with NPRD-95 and FMD-97 were used to build the knowledge base for FFRDM.

3.1. Component Failure Rate Data Source [13]

NPRD-95 was used as the source of the component failure rate data. NPRD-95 was put together by Reliability Information Analysis Center. This reference is an ongoing effort to collect and provide high volumes of data from a variety of sources including both military and commercial. This specifically includes warranty manuals, government sponsored studies, published papers and reports, databases, and military maintenance systems. From the previous publication, NPRD-91, 56% more data has been acquired. A strong emphasis was put on data quality during the collection phase. This was done by ensuring completeness of data, consistency of data, equipment population tracking, failure verification, and characterization of operation histories. Often data is discarded if it does not meet quality standards. This document did not indicate failure modes or mechanisms. Failure, as observed in NPRD-95, is classified generically under solving the symptoms of the failure. A part failed if, when it was replaced, the failure symptoms were not present anymore.

Comprehensive indices are provided for background on the parts and sampling. These include the component manufacturer, model or part number, nominal performance specifications specific to each part, population tested, number of operation hours, and number failed. The operating hours and number of parts failed is used to generate failure rates for both specific components and component classes. For example, a failure rate is provided for a specific type of actuator, then a combined failure rate is given for the actuator class. The failure rate for each component class is the sum of the total components failed for that class divided by the sum of the operating hours for each component in that class. Calculating both types of data lets the user employ the data at a generic or specific level.

This data was employed in the Component-failure mode matrix. A component naming taxonomy was used to define the entire set of components that would be used in both the function-component and component-failure mode matrix. This taxonomy was also used to look up values in NPRD-95. For each component in the taxonomy that also appeared in NPRD-95, a failure rate was recorded. For components that did not match verbatim, definitions in the component naming taxonomy were used to determine whether or not a failure rate value should be recorded.

3.2. Failure Modes and Mechanism Data Source [8]

FMD-97 is a document constructed by the Reliability Information Analysis Center to provide high volumes of data on failure modes and mechanisms. This data is collected from a variety of sources and presented in a single document. Failure modes and mechanisms are given for electrical, electronic, mechanical, and electromechanical parts and assemblies.

FMD-97 is the second edition of this document replacing FMD-91. Important improvements have been made including a new algorithm used to combine data sources and additional raw data that has been collected since the first edition was published. These have significantly improved the quality of this document and the usability of the data.

The data in FMD-97 was used to populate the component-failure mode matrix. In the same manner as the component naming taxonomy, failure modes in this document were fit to a failure mode taxonomy [9]. Definitions provided in the taxonomy were used for justification when names were not verbatim. Also, the *data details* section of FMD-97 offered additional information for this justification.

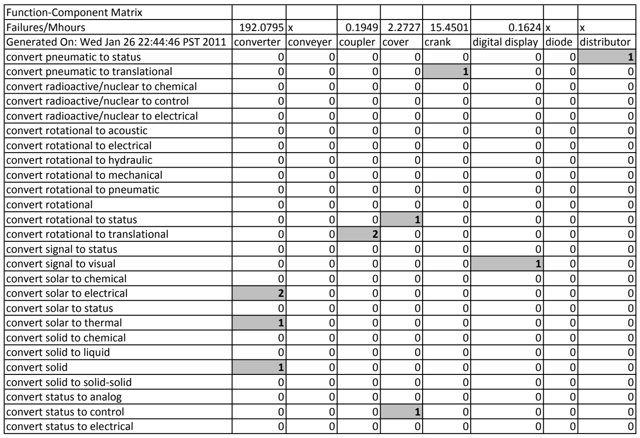
Four failure mode categories were created to accommodate those failure modes which did not adequately fit to the taxonomy. These include control issue, unknown, other, and failure mechanism. A *control issue* is the loss in control or communication of the design, but also includes signal losses. This does not indicate any sort of physical failure necessarily. This could in many cases, for example, be a software failure. In a sensor, this would be the inability to retrieve data stored on the sensor even though it exists. Intermittent operation is also included here. The *unknown* category was listed within FMD-97. Failures were recorded, but the cause and result was not. For obvious reasons, this data could not be converted to anything listed in the failure mode taxonomy and was therefore left as *unknown*. The *other* category was also a category listed in FMD-97 and was reserved for failure modes which are rarely observed for a component type. Although the occurrence of the *other* is high (see Appendix A for data), the occurrence within this category for any given failure mode is very low. For this reason the data within the *other* category in FMD-97 was added up and kept under the listing *other*.

As described previously, failure modes and failure mechanisms are defined differently in this research. FMD-97 provides both but does not distinguish between the two within the data, even though the cause and result of a failure are significantly different phenomenon in many cases. The category *failure mechanism* was created to parse out what were considered to be the cause of the failure. There does not currently exist a failure mechanism taxonomy used for design. Parsing these out was done by proving which were failure mechanisms. Any failure mode/mechanism listing in FMD-97 with an artifact in it was selected to be a failure mechanism. When FMD-97 lists these failure modes/mechanisms under a component, the assumption is that the listed artifact was the cause and not the result. For example, the component *connector* has failed 8 times by a *contact* failing and 4 by *wire* fracturing. Both *contact* and *wire* are artifacts of the component connector and were recorded as failure mechanisms. Both *design* and *workmanship* were also grouped with failure mechanism since their name describes them as predating the failure occurring. Listings with specific information such as *loss of capacitance* or *change in resistance* are included as failure modes because they imply a specific change in behavior. Those such as *electrical failure* and *excessive leakage* are more general and were also defined as failure modes. If it is unclear that the listed failure mode/mechanism was a mode or a mechanism, it was considered to be a mode.

3.3. Repository Data

The Design Engineering Lab Repository (http://designengineeringlab.org/delabsite/repository.html) at Oregon State University was used for function component mapping and data structuring. A function-component matrix was queried from the repository using terms from the functional basis and component naming taxonomy [9].

The function-component matrix is used to capture the relationship between the functions and component naming terms. The function-component matrix lists component naming terms across the first row as column headers and function-flow pairs down the first column. The matrix is then filled with the occurrences of the number of times a function is solved by a component. The matrix is populated in a column format where every occurrence is listed for a specific component before any are listed for the next component. This is because functions are related to components in the repository database and not the other way around. There are 164 components from the component naming terms listed and 731 function-flows. The total number of occurrences is 16,365.



Function-Component Matrix								
Failures/Mhours	192.0795	x	0.1949	2.2727	15.4501	0.1624	x	x
Generated On: Wed Jan 26 22:44:46 PST 2011	converter	conveyer	coupler	cover	crank	digital display	diode	distributor
convert pneumatic to status	0	0	0	0	0	0	0	**1**
convert pneumatic to translational	0	0	0	0	**1**	0	0	0
convert radioactive/nuclear to chemical	0	0	0	0	0	0	0	0
convert radioactive/nuclear to control	0	0	0	0	0	0	0	0
convert radioactive/nuclear to electrical	0	0	0	0	0	0	0	0
convert rotational to acoustic	0	0	0	0	0	0	0	0
convert rotational to electrical	0	0	0	0	0	0	0	0
convert rotational to hydraulic	0	0	0	0	0	0	0	0
convert rotational to mechanical	0	0	0	0	0	0	0	0
convert rotational to pneumatic	0	0	0	0	0	0	0	0
convert rotational	0	0	0	0	0	0	0	0
convert rotational to status	0	0	0	**1**	0	0	0	0
convert rotational to translational	0	0	**2**	0	0	0	0	0
convert signal to status	0	0	0	0	0	0	0	0
convert signal to visual	0	0	0	0	0	**1**	0	0
convert solar to chemical	0	0	0	0	0	0	0	0
convert solar to electrical	**2**	0	0	0	0	0	0	0
convert solar to status	0	0	0	0	0	0	0	0
convert solar to thermal	**1**	0	0	0	0	0	0	0
convert solid to chemical	0	0	0	0	0	0	0	0
convert solid to liquid	0	0	0	0	0	0	0	0
convert solid	**1**	0	0	0	0	0	0	0
convert solid to solid-solid	0	0	0	0	0	0	0	0
convert status to analog	0	0	0	0	0	0	0	0
convert status to control	0	0	0	**1**	0	0	0	0
convert status to electrical	0	0	0	0	0	0	0	0

FIGURE 2: Function-Component Matrix Snippet

The example function-component matrix snippet in Figure 2 shows *convert rotational to translational* being solved twice by the *coupler*. Zeros in the matrix indicate that there is no observed relationship in the repository of the particular function-flow and component. The component naming terms along the first row of the function-component matrix are specifically defined [14]. These terms line up with the component classes listed in NPRD-95.

3.4. Converging Data Using Matrix Multiplication

Two matrices, discussed in section 3.1 through 3.3, were generated to create the FFRDM knowledge base. Once the component-failure mode matrix was populated with occurrences of the failure modes, each row was normalized. The failure rates, recorded from NPRD-95 for each component, were listed adjacent to each component name. Each cell containing the normalized failure mode occurrence was multiplied by the component failure rate. This distributed the failure rate of a component between all of its observed failure modes. The result of this calculation is the failure rate of a failure mode for a specific component.

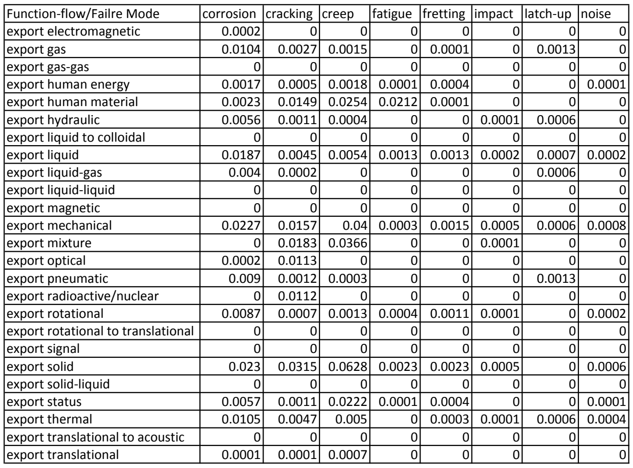
The next step was done by multiplying the function-component matrix by the component-failure mode matrix. The function-component matrix is 731 cells by 165 cells and the component-failure mode matrix is 165 cells by 39 cells. As a result of the large sized matrices, the matrix multiplication was carried out in Matlab. The results were then exported back in to excel. The result of this calculation is the failure rate of a failure mode for a specific function and therefore the knowledge base for FFRDM.

4. RESULTS

This section begins with a description of the FFRDM knowledge base. FFRDM during the design process is then described using four steps. An example is used to show how this process takes place. Recommendations are provided for this example based on a functional model and the likelihood of occurrence.

4.1. Failure Mode Data

In Appendix A, the FFRDM knowledge base is presented in a table format. Due to size restriction, data is presented for functions instead of function-flows. Figure 3 shows a snippet of the full data set. The top row are failure modes taken from the failure modes taxonomy and the first column are function-flows from the functional basis. The cells in the matrix are failure rates in failures per million hours. These values represent the number of times a function-flow will fail in a specific failure mode for every million hours of operation. Values of zero indicate that there does not exist a relationship between a failure mode and function flow. It should be noted that this work does not claim that functions have failure modes. Rather, this research has found that functions are linked to components which have failure modes. The function-component and component-failure mode relationships prove that a relationship does exist between functions and failure modes. Although, it does not make sense to say that the failure mode belongs to the function since it was observed from a component failing.



Function-flow/Failre Mode	corrosion	cracking	creep	fatigue	fretting	impact	latch-up	noise
export electromagnetic	0.0002	0	0	0	0	0	0	0
export gas	0.0104	0.0027	0.0015	0	0.0001	0	0.0013	0
export gas-gas	0	0	0	0	0	0	0	0
export human energy	0.0017	0.0005	0.0018	0.0001	0.0004	0	0	0.0001
export human material	0.0023	0.0149	0.0254	0.0212	0.0001	0	0	0
export hydraulic	0.0056	0.0011	0.0004	0	0	0.0001	0.0006	0
export liquid to colloidal	0	0	0	0	0	0	0	0
export liquid	0.0187	0.0045	0.0054	0.0013	0.0013	0.0002	0.0007	0.0002
export liquid-gas	0.004	0.0002	0	0	0	0	0.0006	0
export liquid-liquid	0	0	0	0	0	0	0	0
export magnetic	0	0	0	0	0	0	0	0
export mechanical	0.0227	0.0157	0.04	0.0003	0.0015	0.0005	0.0006	0.0008
export mixture	0	0.0183	0.0366	0	0	0.0001	0	0
export optical	0.0002	0.0113	0	0	0	0	0	0
export pneumatic	0.009	0.0012	0.0003	0	0	0	0.0013	0
export radioactive/nuclear	0	0.0112	0	0	0	0	0	0
export rotational	0.0087	0.0007	0.0013	0.0004	0.0011	0.0001	0	0.0002
export rotational to translational	0	0	0	0	0	0	0	0
export signal	0	0	0	0	0	0	0	0
export solid	0.023	0.0315	0.0628	0.0023	0.0023	0.0005	0	0.0006
export solid-liquid	0	0	0	0	0	0	0	0
export status	0.0057	0.0011	0.0222	0.0001	0.0004	0	0	0.0001
export thermal	0.0105	0.0047	0.005	0	0.0003	0.0001	0.0006	0.0004
export translational to acoustic	0	0	0	0	0	0	0	0
export translational	0.0001	0.0001	0.0007	0	0	0	0	0

FIGURE 3: Function-Failure Mode Matrix Snippet

In the component-failure mode matrix there were 41 components which had both failure mode and failure rate information. There also exist function-flows in the repository that have no observed occurrences. This results in some function-flows not having data. This can be seen in Figure 3 for *export translational to acoustic*. FFRDM can not provide data for these function-flows during the design process.

Since there are often many components that are a solution to a function-flow, there are often several failure modes fit to each function-flow. In some cases there an even distribution of failure modes for that particular function-flow. For example, in the function-failure mode matrix *convert electromagnetic to mechanical energy* has 11 failure mode occurrences. *Galling & Seizure* has the lowest failure rate with a value equal to 0.0001 failures per million hours while *wear* has the highest with a value equal to 0.0015 failures per million hours. In this case there is no particular failure mode that would stand out to the designer as needing to be mitigated. This case makes it hard to provide any useful recommendations because none of the failure modes stand out beyond any other. In other cases there is one or two distinct failure modes for a specific function-flow which stand out significantly. The failure mode *creep* for *regulate solid* has a value equal to 0.0219 failures per million hours. The next closest value is 0.0037 failures per million hours. Here the designer can see that the failure mode *creep* is the most likely to occur and would provide recommendations to mitigate this failure mode. In most cases there is a distribution of failure mode data. In this situation a few failure modes have either high or low likelihood values and several have moderate likelihood values. Figure 4 shows data for *secure solid* where 19 failure modes have been observed. Failure rate values range from 0.001 to 0.5901 failure per million hours. For this function-flow there is a single failure mode that stands out, *wear*, and several with moderate and low values. Recommendations would be provided to mitigate *wear*, cracking, and creep.

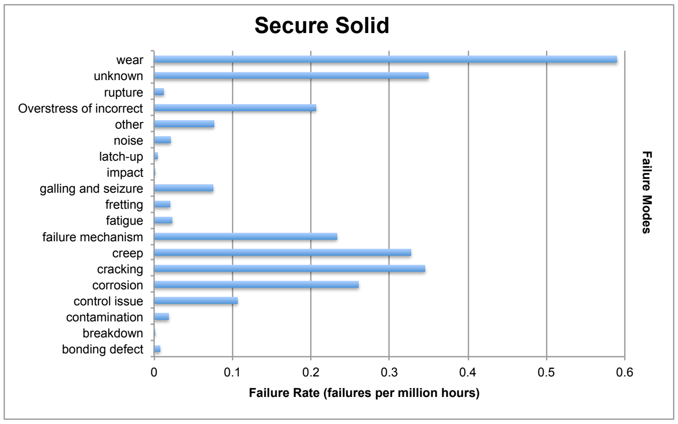


FIGURE 4: Failure Mode Data for *Secure Solid*

4.2. Functional Failure Rate Design Method

This method is used during the conceptual stage of design when the functional model is complete. The process to accomplish this is done in four steps. To validate the steps to use the FFRDM knowledge base, a past FFDM example has been revisited. In this example, FFDM was used during the design of a portable air compressor to provide recommendation that would mitigate potential failures. In this section it is used to outline the use of the four steps and the FFRDM knowledge base.

Step 1: Import function-flows from the functional model

Figure 5 shows the functional model for the portable air compressor.

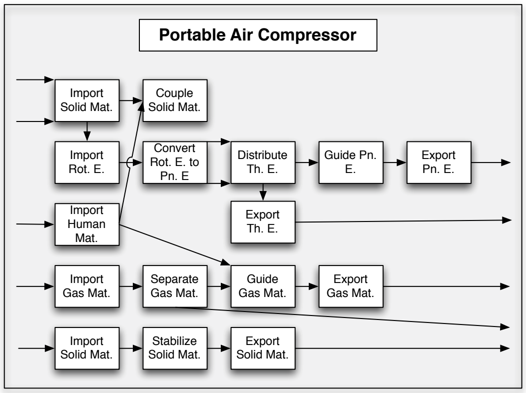
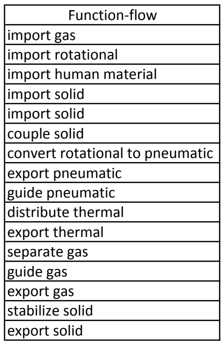


FIGURE 5: Functional Model for Portable Air Compressor

This information is formatted into a table format as shown in Figure 6. It is important to notice the *import solid* appears twice in the functional model and twice in Figure 6. This must be true in order for step 3 of the methodology to generate accurate results.

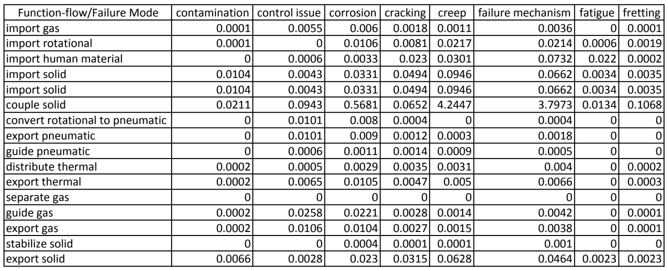


Function-flow
import gas
import rotational
import human material
import solid
import solid
couple solid
convert rotational to pneumatic
export pneumatic
guide pneumatic
distribute thermal
export thermal
separate gas
guide gas
export gas
stabilize solid
export solid

FIGURE 6: FFDM Step #1 Snippet

Step 2: Look up function-flows in the FFRDM knowledge base

There will be several failure modes for each functional input and all should be recorded for the most complete results. A snippet of the result of step #2 is shown in Figure 7.

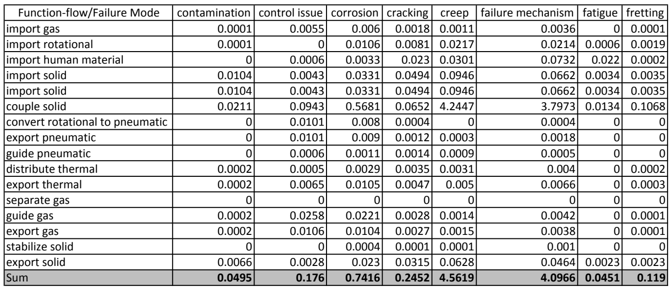


Function-flow/Failure Mode	contamination	control issue	corrosion	cracking	creep	failure mechanism	fatigue	fretting
import gas	0.0001	0.0055	0.006	0.0018	0.0011	0.0036	0	0.0001
import rotational	0.0001	0	0.0106	0.0081	0.0217	0.0214	0.0006	0.0019
import human material	0	0.0006	0.0033	0.023	0.0301	0.0732	0.022	0.0002
import solid	0.0104	0.0043	0.0331	0.0494	0.0946	0.0662	0.0034	0.0035
import solid	0.0104	0.0043	0.0331	0.0494	0.0946	0.0662	0.0034	0.0035
couple solid	0.0211	0.0943	0.5681	0.0652	4.2447	3.7973	0.0134	0.1068
convert rotational to pneumatic	0	0.0101	0.008	0.0004	0	0.0004	0	0
export pneumatic	0	0.0101	0.009	0.0012	0.0003	0.0018	0	0
guide pneumatic	0	0.0006	0.0011	0.0014	0.0009	0.0005	0	0
distribute thermal	0.0002	0.0005	0.0029	0.0035	0.0031	0.004	0	0.0002
export thermal	0.0002	0.0065	0.0105	0.0047	0.005	0.0066	0	0.0003
separate gas	0	0	0	0	0	0	0	0
guide gas	0.0002	0.0258	0.0221	0.0028	0.0014	0.0042	0	0.0001
export gas	0.0002	0.0106	0.0104	0.0027	0.0015	0.0038	0	0.0001
stabilize solid	0	0	0.0004	0.0001	0.0001	0.001	0	0
export solid	0.0066	0.0028	0.023	0.0315	0.0628	0.0464	0.0023	0.0023

FIGURE 7: FFDM Step #2 Snippet

Step 3: Sum failure rate data for each failure mode

The failure rates in each column should be summed to yield a total failure rate for each failure mode. This step sets the stage to determine which failure modes the designer should spend time to determine recommendations for. A snippet of this result can be seen in Figure 8.



Function-flow/Failure Mode	contamination	control issue	corrosion	cracking	creep	failure mechanism	fatigue	fretting
import gas	0.0001	0.0055	0.006	0.0018	0.0011	0.0036	0	0.0001
import rotational	0.0001	0	0.0106	0.0081	0.0217	0.0214	0.0006	0.0019
import human material	0	0.0006	0.0033	0.023	0.0301	0.0732	0.022	0.0002
import solid	0.0104	0.0043	0.0331	0.0494	0.0946	0.0662	0.0034	0.0035
import solid	0.0104	0.0043	0.0331	0.0494	0.0946	0.0662	0.0034	0.0035
couple solid	0.0211	0.0943	0.5681	0.0652	4.2447	3.7973	0.0134	0.1068
convert rotational to pneumatic	0	0.0101	0.008	0.0004	0	0.0004	0	0
export pneumatic	0	0.0101	0.009	0.0012	0.0003	0.0018	0	0
guide pneumatic	0	0.0006	0.0011	0.0014	0.0009	0.0005	0	0
distribute thermal	0.0002	0.0005	0.0029	0.0035	0.0031	0.004	0	0.0002
export thermal	0.0002	0.0065	0.0105	0.0047	0.005	0.0066	0	0.0003
separate gas	0	0	0	0	0	0	0	0
guide gas	0.0002	0.0258	0.0221	0.0028	0.0014	0.0042	0	0.0001
export gas	0.0002	0.0106	0.0104	0.0027	0.0015	0.0038	0	0.0001
stabilize solid	0	0	0.0004	0.0001	0.0001	0.001	0	0
export solid	0.0066	0.0028	0.023	0.0315	0.0628	0.0464	0.0023	0.0023
Sum	**0.0495**	**0.176**	**0.7416**	**0.2452**	**4.5619**	**4.0966**	**0.0451**	**0.119**

FIGURE 8: FFDM Step #3 Snippet

Step 4: Provide designer with recommendations based on summed failure rates

To provide useful recommendations from the failure modes with high likelihood, definitions provided in the failure mode taxonomy must be consulted and additional research should be performed. Definitions in the taxonomy offer details on the physical phenomena that occurs during failure. Additional research can help the designer to understand how the high likelihood failure modes occur in a general sense. These were used to determine the additional recommendations in Table 3.

4.3. Design Recommendations

To validate the FFRDM knowledge base, a past FFDM example was used. It should be noted that this was the design of a new product and was chosen to be compatible with information in the original FFDM knowledge base. The FFRDM knowledge base is not limited to failures from a specific domain and will offer information not seen by the previous knowledge base. FMEA was also performed in this example and compared with FFDM. It was determined that FFDM provides similar recommendations as FMEA as well as others which were not predicted by FMEA [5]. Here, the analysis has been done using the FFRDM knowledge base to show that, in general, the same recommendations can be made as well as additional recommendations. Also, in section 4.4 the likelihood of the failures is discussed as a way to offer the designer information on which recommendations require more attention than others.

This analysis shows that improvements in FFDM have been accomplished. This is done first by verifying the same recommendations can be obtained that were proposed by the original FFDM knowledge base. Table 2 shows the function-flows along with the original recommendations for the portable air compressor.

TABLE 2: FFDM Example for a Portable Air Compressor

Function-flow	Recommendation
Import Gas Import Rot.E. Import Hand Import solid Couple solid Convert Rot.E. to Pn.E. Export Pn.E. Guide Pn.E. Distribute Th.E. Export Th.E. Separate Gas Guide Gas Export Gas Stabilize Solid Export Solid	- 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

The recommendations provided in Table 2 were derived directly from the failure modes returned by the function-flows. These same function-flows were queried for the FFRDM knowledge base and returned all but one of the failure modes. The missing failure mode was *yielding* which correlated to the *perform extensive stress analysis on support feet* recommendation.

Along with these, other failure modes were discovered for which recommendation should be provided. These include *failure mechanism*, *creep*, and *unknown*. *Unknown* is listed as a failure mode with a high likelihood but recommendations will not be provided since none can be derived. Recommendations that summarize these added failure modes can be found in Table 3.

TABLE 3: Additional Recommendations for the Portable Air Compressor

Failure Mode	Recommendation
Failure Mechanism	- Research air intake and shaft support selection to mitigate artifact failure - Simulate design/build prototype to verify design - Inspect and evaluate periodically during manufacturing to mitigate error
Creep	- Perform Finite Element Analysis to locate stress concentrations

Failure mechanism, as described previously, is caused by either an artifact failing, a poor design, or poor workmanship during the building process. This information about *failure mechanism* was used to reason about what recommendations should be offered to the designer. The first three recommendations address this.

Creep can be described as the tendency of a solid material to undergo plastic deformation over time due to high material stress. Finite Element Analysis (FEA) can be used to identify these stresses bases on force inputs. It is recommended that once the design has geometry, FEA be performed. This can be done for a rough sketch or the final design. A variety of software packages can be used in conjunction with a solid modeling program to reduce high user workload during this process. For example, Patran is capable of importing Solidworks drawings, but can also be used to reproduce physical geometries for FEA.

Although this recommendation does not mitigate a failure during functional design, it offers information during functional design that will be used to mitigate failure.

4.4. Failure Mode Likelihood

Recommendations have been provided based on the FFRDM knowledge base by using the four step process. In this knowledge base a likelihood in the form of a failure rate is provided for each failure mode. This is used to determine which failure modes should receive the most attention during design based on the likelihood of failure. The additional failure modes presented in section 4.3 were those with a high likelihood. *Wear* is the only original failure mode that was considered to have a high failure rate. The failure rates associated with the additional three failure modes along with four of the five in the original example are summarized in Table 4. The top four failure modes are significant because their failure rates are noticeably higher than the others.

TABLE 4: Failure Rates of Failure Modes for Portable Air Compressor

Failure Mode	Failure Rate (Failure per Million Hours)
Unknown	5.2435
Creep	4.5619
Failure Mechanism	4.0966
Wear	3.3714
Corrosion	0.7416
Fretting	0.1190
Fatigue	0.0451

The predominate failures associated with air compressors include not building a sufficient amount of discharge air at the specified pressure, not being able to achieve the specified pressure, and bearing failures [15]. The first two are a direct result of wear in the valves. The failure mode *wear* was initially given by FFDM and was also given by FFRDM as one with a high likelihood. Also, bearing failure corresponds directly to *failure mechanism*. The first recommendation in Table 3 provides mitigation for this failure event.

Of the original failure modes proposed by FFDM, *corrosion*, *fretting,* and *fatigue* had a low likelihood of occurring. There are not related to predominate failure which leads to the conclusion that the recommendations associated with these failure modes are not likely to occur and can be discarded. Implementing likelihood to the failure modes reduces unnecessary work during the design process and steers designers to critical failure modes.

5. CONCLUSION

The Functional Failure Rate Design Method was generated and presented to provide critical failure information in the conceptual design stage to reduce the likelihood of failure. The data in this knowledge base shows the likelihood that a function-flow fails in a specific failure mode and motivates reliability analysis at the early stage of design. The FFRDM knowledge base is an extension of FFDM. Failure rates of components have been added to make decisions for which failure modes should be prioritized. A significant increase in data has also been used to expand the knowledge base to provide robust results. To validate this addition, the FFRDM knowledge base was used on a past FFDM example of a portable air compressor. This analysis shows that improvements in FFDM have been accomplished by determining additional failure modes which were originally overlooked. Recommendations were provided for these failure modes.

6. FUTURE WORK

The data presented in FMD-97 lists failure mode occurrences for specific components. In this research this data was converted from the listed failure modes in FMD-97 to a failure mode taxonomy. These taxonomies, Collin's on mechanical failures and Stone and Tumer's on both mechanical and electrical, list failure modes in a single level. Formatting the taxonomy in this manner assumes that all failure modes can be described at a single level. Although, if there is a lack of information at the time the failure is observed, the definitions provided in the current taxonomy would likely be too descriptive to adequately fit the failure. The failure mode taxonomy should be restructured to assume a hierarchal format. This provided two distinct advantages. First, when the failure is being inspected and recorded in to data records for use later, it will not be necessary to fit a failure to a failure modes that is more detailed than the inspection can offer. If only general information can be gathered about the failure, it should only be recorded in such a manner. The Reliability Information Analysis Center has also recognized this issue. Data that is not acquired to their standards must be discarded. A hierarchal structure for failure modes will result in data being recorded more accurately, providing more data useable during the design process. The second advantage for a new format is that the designer can perform reliability analyses at different levels of abstraction. Failure modes can be viewed at the highest level as a material, energy, or signal failure. This structure will follow the functional basis. This offers designers direction and information for later reliability analyses.

In addition, the FFRDM knowledge base should be entered in the repository in the Design Lab at OSU. This would take the next step to automate this process, reducing user workload to mitigate failure.

7. ACKNOWLEDGMENTS

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APPENDIX A: Fails/Mhours

	bonding defect	breakdown	contamination	control issue	corrosion	cracking	creep	failure mechanism	fatigue	fretting
actuate	1.0E-4	0	1.1E-3	3.2E-2	1.7E-2	2.4E-3	5.4E-3	5.7E-2	9.0E-4	4.0E-4
allow	0	0	0	9.0E-4	4.5E-3	0	6.0E-4	4.0E-4	0	0
change	1.4E-2	0	3.2E-3	7.6E-3	1.1E-1	4.9E-2	1.2E-1	8.1E-2	1.9E-2	4.7E-2
channel	0	0	0	0	0	0	1.0E-4	1.0E-4	0	0
collect	0	0	0	2.0E-4	0	7.2E-3	2.4E-3	5.0E-4	0	0
condition	0	0	0	0	4.0E-4	8.0E-4	3.0E-3	5.6E-3	0	1.2E-3
connect	0	0	0	0	1.2E-3	3.0E-4	1.0E-4	7.0E-4	0	0
contain	0	0	0	0	2.0E-4	0	0	4.0E-4	0	0
convert	9.0E-4	1.0E-4	9.5E-3	2.8E-1	3.6E-1	5.4E-2	1.4E-1	1.6E-1	1.2E-2	4.1E-3
decrease	0	0	0	0	0	0	0	0	0	0
decrement	0	0	0	0	0	0	0	0	0	0
detect	0	0	0	2.0E-4	0	0	0	5.0E-4	0	0
display	0	0	0	5.8E-3	1.0E-2	2.6E-3	6.6E-2	1.9E-3	0	0
distribute	7.0E-4	0	1.0E-3	1.3E-2	3.1E-2	2.3E-2	2.0E-2	1.7E-2	1.0E-3	3.0E-3
export	1.4E-3	2.0E-4	1.7E-2	8.3E-2	1.3E-1	1.2E-1	2.1E-1	2.2E-1	2.6E-2	7.5E-3
extract	0	0	0	0	4.0E-4	7.0E-4	3.0E-4	0	0	0
guide	3.4E-2	2.0E-4	1.2E-2	1.2E-1	4.4E-1	2.2E-1	4.3E-1	4.4E-1	7.2E-2	1.1E-1
import	1.5E-3	9.0E-4	2.2E-2	3.3E-2	1.0E-1	1.7E-1	2.8E-1	3.2E-1	4.5E-2	9.1E-3
increase	0	0	0	0	0	0	0	0	0	0
increment	0	0	1.0E-3	1.0E-4	0	0	0	7.0E-4	0	0
indicate	0	0	0	8.1E-3	1.5E-2	1.0E-2	9.3E-2	1.3E-2	1.7E-3	1.0E-4
inhibit	0	0	0	0	2.2E-3	4.0E-4	1.1E-3	4.4E-3	0	0
join	3.0E-4	0	1.0E-4	1.1E-3	1.1E-2	9.2E-3	2.6E-2	3.3E-2	4.0E-4	1.6E-3
link	0	0	0	0	4.5E-3	7.2E-3	2.5E-3	1.0E-4	0	0
measure	0	0	0	0	0	0	0	0	0	0
mix	1.0E-4	0	0	6.0E-4	7.0E-4	2.0E-4	6.0E-4	5.0E-4	1.0E-4	4.0E-4
position	5.8E-3	2.2E-3	2.1E-2	4.5E-2	2.2E-1	2.2E-1	3.2E-1	4.1E-1	4.5E-2	2.8E-2
prevent	0	0	0	6.0E-4	1.6E-3	3.0E-4	3.0E-4	3.5E-3	0	0
process	0	0	1.0E-3	3.0E-4	0	5.6E-3	0	1.2E-3	0	0
provision	0	0	0	0	0	0	0	0	0	0
regulate	2.3E-3	0	1.6E-2	1.7E-2	4.1E-2	1.0E-2	6.5E-2	6.2E-2	4.1E-3	8.5E-3
remove	0	0	0	0	7.0E-4	0	7.5E-3	6.6E-3	0	2.0E-4
rotate	0	0	0	1.0E-2	8.0E-3	4.0E-4	0	4.0E-4	0	0
secure	7.7E-3	1.0E-3	2.4E-2	1.1E-1	2.6E-1	3.8E-1	3.6E-1	2.4E-1	2.4E-2	2.1E-2
sense	0	0	7.6E-3	4.9E-3	7.2E-3	3.0E-3	4.6E-2	1.7E-2	1.7E-3	0
separate	0	0	3.5E-3	6.0E-4	7.0E-4	7.7E-3	1.9E-2	6.5E-3	8.0E-4	1.0E-4
shape	0	0	0	3.8E-3	6.8E-3	1.8E-3	4.4E-2	1.2E-3	0	0
signal	0	0	0	0	2.0E-4	0	0	4.0E-4	0	0
stabilize	0	0	0	2.0E-4	4.0E-4	1.0E-4	1.0E-4	1.5E-3	0	0
stop	3.0E-4	0	3.0E-4	9.1E-3	6.6E-2	8.6E-2	1.0E-1	7.8E-2	1.6E-3	1.0E-3
store	0	2.3E-3	6.8E-3	1.2E-2	1.2E-2	1.6E-2	3.2E-2	3.1E-2	0	6.0E-4
supply	2.0E-4	2.3E-3	4.5E-3	6.0E-3	8.4E-3	1.3E-3	2.7E-2	2.8E-2	3.0E-4	1.3E-3
support	0	0	1.0E-4	0	4.7E-3	7.0E-4	1.5E-3	3.2E-3	8.0E-4	1.0E-4
transfer	1.3E-2	1.0E-3	1.3E-2	1.1E-1	2.5E-1	5.5E-2	1.4E-1	1.8E-1	2.7E-2	4.2E-2
translate	0	0	0	0	0	0	0	0	0	0
transmit	5.0E-4	0	1.0E-4	7.4E-3	2.1E-2	7.4E-3	7.4E-2	1.6E-2	7.0E-4	2.5E-3
transport	0	0	0	5.0E-3	4.0E-3	2.0E-4	0	2.0E-4	0	0

APPENDIX A (continued): Fails/Mhours

	galling and seizure	impact	latch-up	noise	other	Overstress of incorrect current magnitude	rupture	unknown	voiding	wear
actuate	7.7E-3	0	0	5.0E-4	2.3E-2	1.2E-1	6.0E-4	4.5E-2	0	5.8E-2
allow	8.0E-4	0	0	4.0E-4	7.0E-4	8.0E-4	1.0E-4	1.9E-3	0	8.0E-4
change	1.4E-2	0	0	8.6E-3	1.5E-2	1.5E-2	1.7E-2	1.3E-1	1.0E-4	3.3E-1
channel	0	0	0	0	0	0	0	1.0E-4	0	2.0E-4
collect	1.0E-4	0	0	0	0	1.9E-3	0	9.0E-4	0	0
condition	0	0	0	0	0	8.0E-4	0	2.6E-3	0	1.6E-3
connect	0	0	0	0	2.0E-4	0	1.0E-4	4.0E-4	0	2.5E-3
contain	0	0	0	0	0	0	0	1.0E-3	0	5.0E-4
convert	9.0E-2	4.0E-4	2.0E-2	3.1E-2	1.1E-1	1.9E-1	7.8E-3	2.7E-1	0	4.2E-1
decrease	0	0	0	0	0	0	0	0	0	0
decrement	0	0	0	0	0	0	0	0	0	0
detect	1.0E-4	0	0	0	0	1.9E-3	0	9.0E-4	0	0
display	2.0E-4	0	0	0	2.0E-3	1.0E-4	0	6.7E-2	0	7.1E-3
distribute	1.3E-2	3.0E-4	1.3E-3	1.1E-3	8.5E-3	1.1E-2	1.2E-3	3.0E-2	0	9.9E-2
export	7.0E-2	1.7E-3	5.7E-3	3.1E-3	5.0E-2	8.0E-2	5.3E-3	2.3E-1	0	7.0E-1
extract	0	0	0	0	4.0E-4	0	0	1.1E-3	0	4.9E-3
guide	9.1E-2	1.1E-3	7.0E-3	3.1E-2	9.1E-2	1.6E-1	3.9E-2	5.1E-1	0	1.5E+0
import	7.9E-2	1.7E-3	1.2E-3	2.5E-3	4.2E-2	1.7E-1	6.2E-3	2.7E-1	0	9.4E-1
increase	0	0	0	0	0	0	0	0	0	0
increment	3.0E-4	0	0	0	3.0E-4	1.7E-3	0	1.0E-4	0	4.0E-4
indicate	4.0E-4	0	0	0	3.0E-3	5.5E-3	2.0E-4	9.8E-2	0	3.1E-2
inhibit	1.1E-3	0	0	0	3.0E-4	3.0E-4	1.0E-4	6.4E-3	0	6.4E-3
join	2.3E-2	4.0E-4	0	2.0E-4	4.7E-3	6.6E-3	1.3E-3	3.7E-2	0	5.1E-2
link	0	0	0	0	1.0E-4	0	0	4.0E-4	0	5.0E-4
measure	0	0	0	0	0	0	0	0	0	0
mix	5.0E-4	0	0	1.0E-4	3.0E-4	2.0E-4	2.0E-4	2.2E-3	0	4.1E-3
position	6.2E-2	1.3E-3	1.3E-3	1.2E-2	6.5E-2	2.2E-1	1.4E-2	4.0E-1	0	9.0E-1
prevent	4.0E-4	0	0	0	2.0E-4	1.3E-3	0	1.0E-2	0	6.4E-3
process	4.0E-4	0	0	0	3.0E-4	4.4E-3	0	1.0E-3	0	6.0E-3
provision	0	0	0	0	0	0	0	0	0	0
regulate	3.3E-2	0	0	1.5E-3	1.9E-2	5.5E-2	4.0E-3	9.4E-2	1.0E-4	1.1E-1
remove	0	1.0E-4	0	0	6.0E-4	2.0E-4	4.0E-4	8.5E-3	0	3.6E-3
rotate	0	0	1.2E-3	0	1.2E-3	1.6E-3	0	0	0	8.0E-4
secure	7.5E-2	1.1E-3	4.5E-3	2.1E-2	7.6E-2	2.1E-1	1.2E-2	3.5E-1	0	6.6E-1
sense	1.0E-3	0	0	0	1.7E-3	1.7E-2	0	5.1E-2	0	1.9E-2
separate	4.0E-4	0	0	0	5.0E-4	9.0E-4	2.0E-4	1.2E-2	0	2.9E-2
shape	2.0E-4	0	0	0	1.4E-3	0	0	4.4E-2	0	4.8E-3
signal	0	0	0	0	0	8.0E-4	0	1.0E-3	0	5.0E-4
stabilize	1.0E-4	0	0	0	0	2.0E-3	0	3.0E-3	0	1.2E-3
stop	2.9E-2	4.0E-4	0	0	1.7E-2	1.7E-2	3.1E-3	1.4E-1	0	1.6E-1
store	1.0E-2	3.0E-4	1.2E-3	0	1.8E-2	1.5E-1	8.0E-4	3.5E-2	1.0E-4	5.5E-2
supply	8.5E-3	3.0E-4	6.0E-4	1.0E-4	1.7E-2	1.4E-1	1.0E-3	3.0E-2	0	3.1E-2
support	1.0E-4	0	0	0	1.0E-4	3.0E-4	0	1.6E-3	0	7.8E-3
transfer	5.4E-2	5.0E-4	7.5E-3	2.2E-2	5.7E-2	1.7E-1	1.8E-2	2.0E-1	0	6.7E-1
translate	0	0	0	0	0	0	0	0	0	0
transmit	1.7E-2	2.0E-4	0	3.0E-4	7.3E-3	7.5E-3	6.0E-4	8.7E-2	0	1.0E-1
transport	0	0	6.0E-4	0	6.0E-4	8.0E-4	0	2.1E-3	0	2.8E-2