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EARLY DESIGN STAGE RELIABILITY ANALYSIS USING FUNCTION-FLOW FAILURE RATES

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ABSTRACT

In this paper, failure rates for function-flow pairs are presented. This data creates an opportunity for the designer to move reliability analysis earlier in the design process. The function-flow failure rates can be used to make design decisions before components are selected giving the designer increased knowledge to explore alternative options. A reliability block diagram approach has been adopted to evaluate the reliability of three designs at both the functional and component level. The results show that the bounds from the functional reliability overlap those of the component reliability.

1. INTRODUCTION

Traditional reliability engineering techniques have been used to increase safety and reduce the likelihood of failures for many years. As the field of reliability engineering grows, so do the efforts to increase its presence in early design. The early design phase has the distinct advantage of offering the designer cost-effective choices as opposed to later in the design process. The premise of this research is to provide the designer with more knowledge to which these important decisions can be made. Data, which can be used in a variety of ways, is presented here in the form of function-flow failure rates. Similar to component failure rates, this data can be used to select reliable function-flows, or can be employed in traditional reliability engineering analyses such as Functional Reliability Block Diagram (FRBD). Specifically, a methodology was proposed to calculate the system level reliability using FRBD and function swapping to show the usefulness of the data.

The scope of this research is to first present minimum, maximum, and weighted average function-flow failure rates. This information is based on collected data and is not intended to discuss failure modes or mechanisms. Second, a design methodology is introduced to calculate system level reliability at the functional level.

2. BACKGROUND

This section provides a survey of related research including several traditional and non-traditional reliability engineering techniques, the Function Failure Design Method (FFDM), and the use of a normalization method to account for variations in archived data sets.

Traditional risk and reliability analysis techniques exist primarily to move failure assessments into the earlier stages of design. These efforts look at system components, critical events, and system characteristics to assess risk and reliability during the design phase. Reliability engineering techniques can help engineers better meet the needs of customers. In general, customers want two things out of a product. First they want the product to function properly according to their needs, and second they want it to function reliably. Assessing reliability during the design stage helps drive designs to function reliably. In reliability engineering failure is defined as a design not functioning as originally intended for a given life in specific operating conditions [1]. There are several methods used to increase the reliability of the design including Failure Modes Effects and Criticality Analysis (FMECA), Event Tree Analysis (ETA), Fault Tree Analysis (FTA), and Reliability Block Diagrams (RBD). Each of these analyses accomplishes a different goal and are each used during the design process.

The goal of FMECA is to identify, evaluate, and prevent critical component failures [2]. Critical components are determined by the risk priority number (RPN). Components with high RPN values receive a recommended action and schedule to resolve their being critical. The FMECA analysis starts by identifying a list of components and their potential failure modes. 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 it will be 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 of 0 to 1000. The usefulness of FMECA as a design tool is to look at the RPN values relative to each other and determine which components needs action taken and which do not. From this analysis, the designer can determine the critical components of a system and make design changes accordingly.

A variety of software tools and methodologies exist to improve and automate FMEA including FMEA streamlining [3], WIFA [4], FLAME [5, 6], CFMA [7], and Advanced FMEA (AFMEA) [8, 9]. Although, these automated tools are not capable of predicting failures.

ETA is a bottom-up approach to system reliability analysis and is used to determine the likelihood of an outcome based on an accidental event [10]. This shows the designer end failure states that have a high probability of occurring. ETA uses the probability of different failures occurring in the system combined with the probability of safety barriers to determine the final state probabilities. A safety barrier is anything in the design used to resolve a failure in the chance that is occurs. This would, for example, be a ceiling sprinkler system in the event of a building fire. ETA is computationally simple to perform, although depending on the number of accidents analyzed and the level of detail explored, it can be lengthy. The usefulness of this method is in the ability to determine accurate probabilities for events and barriers, then make design decisions to increase the system reliability. It can be difficult to accurately define the probabilities of events and barriers [11]. Design decisions cannot be made with confidence unless these probabilities are well accepted. A fuzzy logic has been developed to account for this. Specifically it determines the uncertainty in the probability of failures and defines a qualitative impact of certain outcomes. This also can be a useful tool for decision making.

FTA is a top-down approach to reliability analysis which begins with an undesirable state and determines the initial cause [12]. Events that could cause the undesirable event are listed in the row below it. Beneath each of the row 1 events are row 2 events. This continues until a basic event is reached where there does not exist a further occurrence to cause it. Between each row are the connections and logic gates that define each of the relationships. In general, two types of logic gates are used; “AND” and “OR”. AND gates require that each of the events in the next row must occur for the event to occur. OR gates only require a single event in the next row to occur for the higher level event to occur. Probabilities are assigned to each event so the probability of the top failure event can be determined. The top event probability is simple to calculate. In order to perform FTA, the system must be well understood so everything is captured.

RBD are another method used to determine system level reliability of a design during the design stage [13]. This is useful when requirements dictate the level of reliability a design can have. For complex systems, these diagrams are useful as a visual tool to see where failures will occur. They also make computation simple to perform. Although, the diagram itself is not used to show the architecture of the system, but instead only to provide graphical information on how it fails. Meaning that if components are connected in the RBD, this does not necessarily mean they are in the physical design. In general, there are two structure types; series and parallel. These refer to the a theoretical path of working components that a design can take to accomplish its overall function. If the structure is series, there is only a single path and all components along that path must function properly or the design fails.

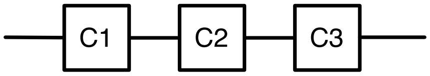


FIGURE 1: Series Structure of a Reliability Block Diagram

If the path splits into a parallel structure, any path is sufficient to accomplish the function. In other words, there must always exist a path from start to finish of properly functioning components in order for the design to be functioning. For example, two motors running in parallel to drive the same component where either motor meets the power requirement for the overall system. The system can still function if one of the motors fails.

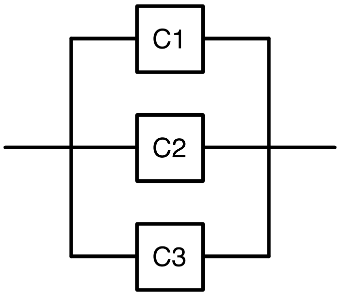


FIGURE 2: Parallel Structure of a Reliability Block Diagram

Failure rate data for each component, given by the variable (λ), is needed to calculate the reliability. Also, a time value (t) is needed since reliability is time dependent. For electromechanical designs it can be assumed that the reliability behaves according to an exponential distribution. It is standard to use an exponential distribution for electromechanical components. Equations to calculate the system level reliability using an exponential distribution:

$$R_{series} = \prod_{i=1}^{n} R_i \qquad (1)$$

$$R_{parallel} = 1 - \left(\prod_{i=1}^{n}(1 - R_i)\right) \qquad (2)$$

$$R_i = e^{-\lambda_i * t} \qquad (3)$$

These are useful to determine the system level reliability to meet design criteria. The designer can also use the RBD to add redundancies that increase reliability. Problematic areas become easy to identify in a large design using this technique.

A disadvantage to generating RBD is the high user workload. A variety of software tools have automated this process including Reliasoft BlockSim – Version 6.5.2, ARINC Raptor – Version 7.0.07, and Relex Software Reliability Block Diagram [14].

Less common methods such as Synergetic Reliability Prediction (SYRP) are also used during the design process to predict later life failure [15]. This method has been shown to be accurate but requires an in-depth and lengthy analysis and expert knowledge to perform. Work has been done to estimate the probabilities of failures using the mean time between failure, but is a lengthy process and requires a significant amount of work to understand [16].

2.1. Function Failure Design Methodology

FFDM is a structured formulation of the function-failure analysis method introduced by Tumer and Stone, and is used to perform failure analysis in the conceptual design stage [17]. This method also aids the designer by using a function-based concept generator approach which helps streamline the design process. FFDM is a start-to-finish design method which utilizes knowledge bases that link product function to failure modes and product function to design concepts. The knowledge base data is archived in the form of a function component matrix and reduces the need for the designer to have a large intellectual knowledge base.

FFDM has several advantages over other reliability engineering methods including reduced high user workload, using archived failure knowledge base, being usable during functional design, using a formalized failure language, and is practical for electrical and mechanical systems [18].

2.2. Normalization Method for Achieved Data Sets Using the Heaviside Function

An archived set of product data inevitably contains a certain amounts of variations. This would, for example, include data completeness and correctness. Normalization methods provide a systematic way to lessen the impact of data variations.

McAdams and Wood used a norming method to develop a quantitative design-by-analogy metric based on the functional similarity of products [19]. This norming method uses a pair of rules to account for differing product customer needs importance and complexity. Data was represented using a product function matrix for easy manipulation and data structuring. Each matrix element is the product of 2 ratios; the number of functions in a particular product over the average number of functions in a product and the average customer needs rating over the customer needs for a particular product. Norming this data gives the designer a way to calculate the similarity metric of a design. This value is then used to select analogous designs.

The Heaviside function is used as a conditional binary multiplication. In the case that a specific cell value is equal, or not equal, to zero the value of the Heaviside becomes one, or zero. To determine the average number of functions for a product the Heaviside function was summed across each row and column.

3. RESEARCH APPROACH

This section presents the method for determining the function-flow failure rates. The steps include finding component failure rates, mapping functions to components, validating the data, and calculating the minimum, maximum, and weighted average function-flow failure rates.

3.1. Component Failure Rate Data Source

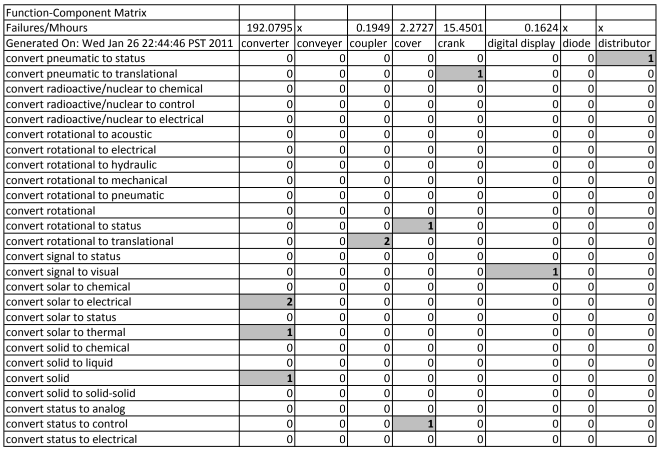
Nonelectric Parts Reliability Data (NPRD-95) [20] was used as the source of the component failure rate data. This reference is an ongoing effort to collect and provide high volumes of data from a variety of sources including both military and commercial. This specifically includes warranty manuals, government 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. Also, 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.

3.2. 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 tool within the repository has the capability to generate Microsoft Excel spreadsheets based on the designer's intent. For the purpose of this research, a function-component matrix (FCM) was created with function-flows and using the component naming.

The FCM is used to capture the relationship between the functions and component naming terms. Structurally, the FCM 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. Initially there are 164 components 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 3: Function-Component Matrix

The example FCM snippet in Figure 3 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 FCM are specifically defined [21]. These terms line up with the component classes listed in NPRD-95. The data was translated over from NPRD-95 and entered into the Excel spreadsheet. For names that did not match identically, the component naming definitions were used to justify that the data was correctly being transferred. For components without data, an X was entered for the component failure rate.

3.3. Applying Rules Using the Heaviside Function

As a means to take the failure rate listed for a specific component to individual function-flows, it is important to avoid letting particular components dominate the data. For example, a *nozzle* has solved *couple solid* three times out of 2045. Since the *nozzle* has a high failure rate of (718 failure per million hours), *couple solid* will also have a high failure rate. Although the *nozzle* solves the function *couple solid* in this particular case, it is an exception rarely observed. The Heaviside function has been used as a way to assign an importance rating. The occurrence data must meet the requirements of the Heaviside function according to the following rules.

Rule 1: A function-flow must be solved at least 3 times.

This requires that any function will either see a variety of failure data because it is solved by different components, or has been solved by the same component at least three times.

Rule 2: A cell must contain greater than 1% of the total occurrences for the entire component.

For a component that has 100 occurrences, a function-flow must be solved more than once by this component or the failure rate is not inherited. This rule will eliminate function-flows from inheriting failure rates when their solution is an exception to how the component is generally solved.

3.4. Function-flow Failure Rates

The process to use the data to determine the functional failure rates after applying the rules is described here. The process to determine the weighted average differs from that of the minimum and maximum and is described in the following paragraph.

The matrix resulting from the Heaviside calculation was used as a starting point to determine the weighted average failure rate. Another matrix was formulated which used a logic test to determine if a cell has an occurrence greater than zero, then if that particular component had failure rate data. If these conditions were met, then the two were multiplied and placed in the cell. These values across a row for a specific function-flow were summed and divided by the total number of occurrence for the same function-flow. The total occurrences were those that occurred when the component also had failure data. This way, components that were not counted in the summation were also not counted in the total number of occurrences. This calculation determined the weighted average function-flow failure rates.

To determine the minimum and maximum failure rates, the matrix remaining from the Heaviside calculation was converted into a binary matrix containing values of only 1 and 0. A binary matrix is used only to show that there exists a relationship between a function-flow and a component. This eliminates the occurrence information since it does not capture the one to many relationship between function-flow and component. This is due to how the FCM is constructed. A component is listed, then the occurrences for it solving each function-flow are listed in the same column. This data represents only when one or more functions are solved by the same component. It does not reflect the occurrences when a single function is solved by multiple components. In this instance, each component that solves a part of this function-flow would list a value of 1 for that function-flow in its own column. This results in the solution for that function-flow adding up to greater than one.

4. RESULTS

This section presents the results of the function-flow failure rates. This data is presented in a complete table in Appendix A. An RBD style failure analysis has been adopted for validation. Both RBD's and the proposed methodology are used to calculate system level reliability of each design to evaluate the usefulness of the calculated data. This comparison is done using three different designs.

4.1. Proposed Methodology for Calculating System Reliability

This process involves five steps. Figure 4 provides an overview and flowchart for the proposed methodology.

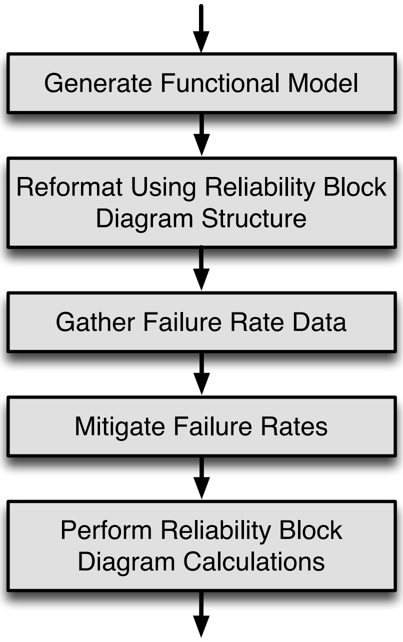


FIGURE 4: Methodology to Calculate System Reliability

This analysis begins by generating a complete functional model. All functions and flows necessary to satisfy the customer needs must be present. Function-flows are then restructured to reflect the FRBD instead of the functional model. Each function-flow is placed in a box, then the designer must reason about its role in the overall system failure. If the function-flow fails, will the entire design fail, or is there an additional functionality that would keep this from occurring? In the case where there is not, this function-flow is in series in the FRBD. If there is additional functionality, these two function-flows are in parallel. Next, data is pulled out of Appendix A for each function-flow. All values including minimum, weighted average, and maximum should be recorded. Functionality can be added or functions can be swapped to reduce the combined failure rate. This is explained in section 4.2. Equations (1-3) are then used to calculate the reliability in the same manner as a traditional RBD. This should be individually calculated for the minimum, weighted average, and maximum failure rate.

4.2. Exploring New Functions in the Functional Model

Exploring functions to reduce the combined failure rate using this framework is done one of two ways. First, functions can be swapped out for new functions which have lower failure rates and second functions can be added using a parallel structure in the RBD.

This data can be used to let the designer know when to explore different functions in the functional model. Certain function-flows with high failure rates can be exchanged with others to generate alternate final designs. This leads to a component with a low failure rate solving the function-flow. Since functional modeling is performed at an abstract level and problem statements are often not well defined, new functions can be explored in place of others to solve the same blackbox function. Another option when the basic functionality is strictly required by the product is to add mitigating functions for the high failure rate functions. For example, if the function *convert pneumatic energy to mechanical energy* has an unacceptable failure rate and is known to historically fail from overheating, additional functionality to mitigate this failure can be used. This could be *distribute thermal energy* or *export thermal energy*. In the RBD this would reduce the final failure rate because the new functionality would be in parallel with *convert pneumatic energy to mechanical energy*. In reality, this would be adding a heat sink which is commonly done to relieve heat from a system and reduce the likelihood of failure.

4.3. Methodology Example Using Real Products

As a way to validate the proposed methodology using the function-flow failure rates, examples have been provided. Three products each with functional models (FM) and configuration flow graphs (CFG) were found [19, 22]. An RBD approach has been adopted to measure the reliability of each CFG. These traditional RBD were constructed with component failure rates from NPRD-95. In the reliability calculation an exponential distribution of failure rates was assumed. Since products have relatively few components and no redundancies, it was determined that the RBD structure was entirely in series. That is, if any component fails, the overall function is no longer accomplished.

In order to use the functional failure rates, the proposed methodology is used. Again, the three products are relatively simple and do not contain any parallel structures or redundancies. For more complex systems, redundancies would be present in the RBD structure resulting in a combination of parallel and series structures.

The three products evaluated were an electric toothbrush, an electric bread slicer, and an automated bottle capping machine. Each product had an overall reliability calculated from the traditional RBD, and for comparison purposes a minimum, maximum, and weighted average reliability using the proposed methodology. Time values were selected to reflect a reasonable operation for each.

The first product explored was an electric toothbrush. The blackbox function of this product is to *separate solids*. The results in Figure 5 show that the average reliability at 1,000 hours is 95%. The proposed methodology results were compared relative to the traditional RBD. The maximum is less than 1% higher while the minimum is significantly lower, only 7% reliable at 1,000 hours. The weighted average is 4% lower. This result is expected based on the components and function-flow pairs present in the design. The largest component failure rate seen in the product was the *link* with a value of 10.97 failures per million hours and the lowest was the *housing* at 0.013 failures per million hours. The function with the greatest failure rate was *export solid* with a value of 717 failures per million hours. The minimum was found in the function-flow *import solid* at 0.0018 failures per million hours.

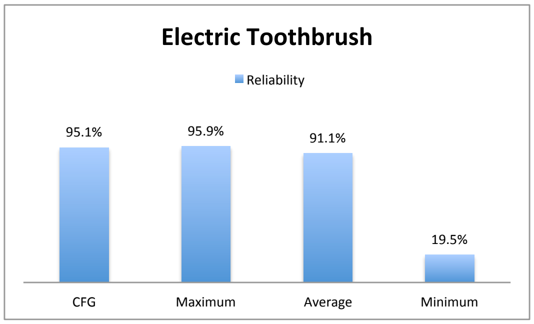


FIGURE 5: Reliability Results for the Electric Toothbrush

Four function-flows and two components were not included in the reliability calculations. These components included *electric wire* and *guiders*. *Electric wire* does not have failure rate data in NPRD-95. The rate for *guiders* was excluded because the function-flows that it maps to does not have data. These function-flows include *convert rotational to translational mechanical energy* and *transfer translational mechanical energy*. Similarly, *transfer electrical energy* was excluded as a result of the missing *electrical wire* data. *Mix solid to mixture* did not receive failure rate data as a result of not passing the rules discussed previously. This is one of many functions accomplished by the *brush* component on the toothbrush. The *brush* was left in the calculation as were the other function-flows that is solves.

The next product tested was an electric bread slicer. This product also *separates solids*, but uses a different variety of components to accomplish its blackbox function. The reliability found from the RBD at 1,000 hours was 96%. The results from the proposed methodology show the minimum, maximum, and weighted average were found to be 85%, 99%, and 96% respectively. The results for this product show a strong correlation between the traditional RBD and the weighted average from the proposed methodology. Components in the electric bread slicer with the highest and lowest failure rates were the *handle* (11.01 failures per million hours) and an *electric switch* (0.82 failures per million hours). For the function-flows these were both *import human energy* and *actuate electrical energy* (25.81 failures per million hours) and *import electrical energy* (0.0021 failures per million hours).

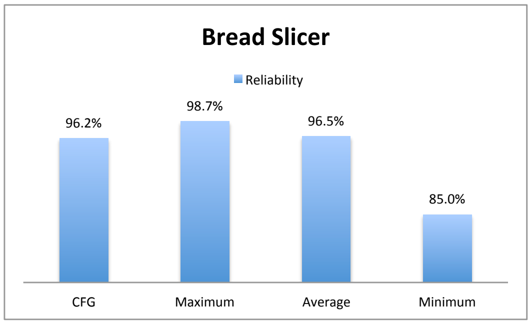


FIGURE 6: Reliability Results for the Electric Bread Slicer

Two components and five function-flows were not included in the reliability calculations. Both *blade* and *electric wire* are without failure rate data in NPRD-95 and therefore their corresponding function-flows were not included in the calculation. These function-flows include *transfer electrical energy*, *import solid*, *secure solid*, *separate solid*, and *export solid*.

The third product tested was an automated bottle capping machine. This product imports a bottle on a belt, grabs it with a clamp, caps it, then exports the capped bottle. The blackbox function of this product is to *couple solids*. The reliability of the bottle capping machine at 10,000 hours was 61%. The results from the proposed methodology for the minimum, maximum, and weighted average were found to be 7%, 76%, and 49% respectively. The components with the highest and lower failure rates were a *handle* (11.01 failures per million hours) and an *electric conductor* (0.019 failures per million hours). Function-flows with the highest and lowest failure rates were both *actuate electrical energy* and *import human energy* (25.81 failures per million hours) and *import electrical energy* (0.0021 failures per million hours).

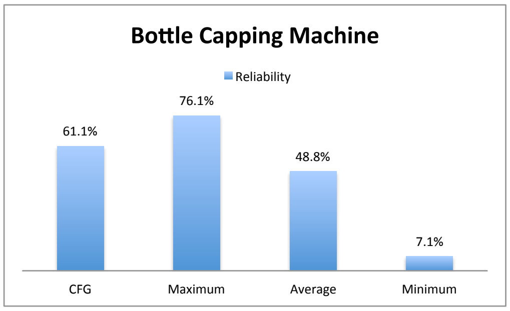


FIGURE 7: Reliability Results for the Bottle Capping Machine

Eleven components and twelve functions were excluded from the reliability calculations. This was due to either the function-flow or component not having failure rate data. In either case, the components and function-flows were mapped to each other and both were excluded.

Without being able to account for the data in a design, uncertainty is introduced to the calculation. This is a limitation to the choice of using the function-flow failure rates in the proposed methodology. The three products evaluated were not chosen because they had failure rate data, as this would not be the case in a design project. They were chosen because they had complete CFG and FM which were already generated.

In the three designs evaluated, two function-flows resulted in two components that ultimately lowered the system level reliability. These functions include *export solid*, and *converts electrical energy to rotational mechanical energy*, and their corresponding components were *brush*, and *electric motor*.

In the toothbrush, the two brush components had a combined series failure rate of 18.30 failures per million hours while their corresponding function-flows had a combined failure rate of 56.92 failures per million hours. The *brushes* individually had the second highest failure rate in the product and account for approximately half of the failures that would occur in the toothbrush. Similarly, their corresponding function-flows make up for half of the failures in the weighted average.

For the automated bottle capping machine, the component with the highest failure rate, an *electric motor*, was present twice in the design. The combined series failure rate of these motors is 18.48 failures per million hours. In this design, the *electric motor converts electric energy to rotational mechanical energy*. This function occurs twice in the functional model and has a combined failure rate of 18.77 failures per million hours. The two *electric motors* account for approximately 40% of the overall failure rate while the conversion from electrical to rotational energy accounts for approximately 25% of the combined failure rate using the proposed methodology.

This information shows that critical components can be identified using the proposed methodology. The comparison between these shows a positive result for the use of the proposed data. Understanding the range for the reliability before any components have been selected is a useful tool in the early design stage.

5. CONCLUSION

The effort to move reliability engineering into the early stage of design is an increasing area of interest. This research aims to increase knowledge of the system at the functional level.

Currently, failure rate data is available for components. Here similar data has been generated for function-flows to give designers the same advantage at the functional level of design. This was done using a FCM and the Heaviside function. The Heaviside function required that function-flows were solved with enough occurrences to be counted which protects them from inheriting failure rate data from components that are rarely their solution.

The new failure rate data has been used to make decisions at the design phase and determine system reliability with a weighted average and an upper and lower bound. This was done using the proposed methodology.

6. FUTURE WORK

The component failure rate data used from NPRD-95 does not give any indication of how a component failed. As discussed previously, a failure observed in this document was described as solving the symptoms of failure. Research has been done to break function failures into failure modes based on a set number of failures. This method will be examined to find a way to get a failure rate of a failure mode for a specific function-flow. This data provides the designer more information in the early design stage and will help guide important design decisions.

7. ACKNOWLEDGMENTS

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Appendix A: Function-flow Failure Rates

Function-flow	Wtd Avg	Min	Max	Function-flow	Wtd Avg	Min	Max
	Fails/Mhours	Fails/Mhours	Fails/Mhours		Fails/Mhours	Fails/Mhours	Fails/Mhours
actuate control	1.97E+0	8.20E-1	2.58E+1	display status	5.40E+1	5.40E+1	5.40E+1
actuate control to electrical	8.20E-1	8.20E-1	8.20E-1	distribute electrical	4.30E+0	5.28E-1	8.08E+0
actuate electrical	1.25E+0	1.79E-1	2.58E+1	distribute liquid	2.41E+2	2.92E+0	7.18E+2
actuate human energy	1.79E-1	1.79E-1	1.79E-1	distribute material	3.64E+2	9.15E+0	7.18E+2
actuate human material	1.79E-1	1.79E-1	1.79E-1	distribute mechanical	8.89E+0	1.95E-1	2.08E+1
actuate mechanical	7.25E+0	1.79E-1	2.58E+1	distribute optical	5.73E-1	5.73E-1	5.73E-1
actuate solid-liquid	5.84E+0	5.47E+0	6.20E+0	distribute solid	7.18E+2	7.18E+2	7.18E+2
change control	4.59E+0	4.59E+0	4.59E+0	distribute thermal	6.43E+0	6.12E-2	1.97E+1
change electrical	2.01E+0	9.00E-2	4.59E+0	export acoustic	6.63E+0	6.63E+0	6.63E+0
change electromagnetic	7.48E+0	2.21E-2	1.12E+1	export control	2.10E-3	2.10E-3	2.10E-3
change hydraulic	3.93E-1	3.93E-1	3.93E-1	export electrical	1.84E+0	1.90E-2	3.61E+0
change liquid	7.18E+2	7.18E+2	7.18E+2	export electromagnetic	2.27E+1	5.73E-1	4.48E+1
change material	1.23E+2	5.40E+1	1.92E+2	export gas	1.17E+2	2.25E+0	7.18E+2
change mechanical	5.11E+0	9.30E-1	1.97E+1	export human energy	1.79E-1	1.79E-1	1.79E-1
change rotational	4.56E+0	2.92E+0	4.69E+0	export human material	3.12E+0	1.31E-2	1.97E+1
change signal	1.92E+2	1.92E+2	1.92E+2	export hydraulic	6.84E+0	1.95E-1	1.34E+1
change solid	1.45E+2	2.00E-2	7.18E+2	export liquid	2.67E+1	9.00E-2	7.18E+2
change solid-liquid	2.00E-2	2.00E-2	2.00E-2	export liquid to colloidal	2.25E+0	2.25E+0	2.25E+0
change translational	6.20E+0	6.20E+0	6.20E+0	export mechanical	5.29E+0	2.10E-3	2.58E+1
collect gas-gas	3.61E+0	3.61E+0	3.61E+0	export mixture	6.44E+0	5.28E-1	9.15E+0
condition control	1.83E+0	1.83E+0	1.83E+0	export optical	6.31E+0	3.04E+0	1.12E+1
condition electrical	1.83E+0	1.83E+0	1.83E+0	export pneumatic	1.54E+2	8.08E+0	7.18E+2
convert chemical to mechanical	6.63E+0	6.63E+0	6.63E+0	export rotational	3.71E+0	1.95E-1	9.63E+0
convert chemical to thermal	3.99E+2	6.63E+0	5.30E+2	export rotational to translational	2.25E+0	2.25E+0	2.25E+0
convert control to status	1.57E+1	5.73E-1	3.60E+1	export signal	3.61E+0	3.61E+0	3.61E+0
convert electrical	2.34E+0	9.00E-2	4.59E+0	export solid	1.21E+1	2.00E-2	7.18E+2
convert electrical to electromagnetic	6.72E+0	1.62E-1	4.48E+1	export solid-liquid	7.18E+2	7.18E+2	7.18E+2
convert electrical to mechanical	9.24E+0	5.00E-1	2.58E+1	export status	3.14E+1	5.73E-1	5.40E+1
convert electrical to optical	1.81E+0	5.73E-1	3.04E+0	export thermal	4.49E+0	2.00E-2	1.97E+1
convert electrical to rotational	9.39E+0	9.24E+0	1.20E+1	export translational	1.97E+1	1.97E+1	1.97E+1
convert electrical to status	5.73E-1	5.73E-1	5.73E-1	guide electrical	2.38E+0	2.33E+0	2.50E+0
convert electrical to thermal	4.04E-1	2.00E-2	8.08E+0	guide gas	1.34E+2	2.27E+0	7.18E+2
convert electromagnetic to electrical	7.41E+0	3.61E+0	1.12E+1	guide human energy	1.10E+1	1.10E+1	1.10E+1
convert electromagnetic to mechanical	2.21E-2	2.21E-2	2.21E-2	guide human material	3.45E+0	1.31E-2	1.10E+1
convert gas to liquid	2.53E+1	8.08E+0	3.39E+1	guide hydraulic	6.07E+0	1.95E-1	1.34E+1
convert human energy to control	2.01E+0	1.79E-1	1.34E+1	guide liquid	7.95E+0	9.00E-2	3.60E+1
convert human energy to mechanical	5.26E+0	1.79E-1	2.58E+1	guide mechanical	5.84E+0	5.28E-1	1.97E+1
convert human energy to rotational	3.81E+0	3.81E+0	3.81E+0	guide mixture	2.43E+2	5.28E-1	7.18E+2
convert human material to control	8.20E-1	8.20E-1	8.20E-1	guide pneumatic	7.45E+0	6.20E+0	8.08E+0
convert human material to mechanical	2.21E-2	2.21E-2	2.21E-2	guide radioactive/nuclear	1.12E+1	1.12E+1	1.12E+1
convert liquid to colloidal	1.20E+1	1.20E+1	1.20E+1	guide rotational	5.73E+0	1.95E-1	1.97E+1
convert liquid to gas	4.06E+0	2.00E-2	8.08E+0	guide signal	2.08E+1	2.08E+1	2.08E+1
convert magnetic to control	3.61E+0	3.61E+0	3.61E+0	guide solid	6.17E+0	1.80E-3	7.18E+2
convert magnetic to mechanical	2.21E-2	2.21E-2	2.21E-2	guide solid-gas	7.18E+2	7.18E+2	7.18E+2
convert mechanical	9.26E+0	3.72E+0	1.55E+1	guide solid-liquid	5.47E+0	5.47E+0	5.47E+0
convert mechanical to acoustic	8.31E+0	6.63E+0	9.15E+0	guide thermal	1.82E+2	8.08E+0	5.30E+2
convert mechanical to electrical	2.02E+2	3.61E+0	5.30E+2	guide translational	9.95E+0	1.95E-1	1.97E+1
convert mechanical to hydraulic	2.88E+1	1.20E+1	4.57E+1	import chemical	3.62E+2	6.63E+0	7.18E+2
convert mechanical to pneumatic	1.14E+1	2.00E-1	3.60E+1	import control	1.84E+0	1.79E-1	1.12E+1
convert mechanical to rotational	2.92E+0	2.92E+0	2.92E+0	import electrical	2.98E+0	2.10E-3	1.10E+1
convert mechanical to status	5.28E-1	5.28E-1	5.28E-1	import gas	2.22E+2	2.00E-1	7.18E+2
convert mechanical to thermal	2.68E+2	6.63E+0	5.30E+2	import human energy	2.70E+0	1.31E-2	2.58E+1
convert pneumatic to mechanical	2.00E-1	2.00E-1	2.00E-1	import human material	2.63E+0	1.31E-2	1.97E+1
convert pneumatic to rotational	2.00E-1	2.00E-1	2.00E-1	import hydraulic	2.93E+0	1.95E-1	8.08E+0
convert pneumatic to translational	7.83E+0	2.00E-1	1.55E+1	import liquid	2.38E+1	2.00E-2	7.18E+2
convert rotational to pneumatic	1.20E+1	1.20E+1	1.20E+1	import mechanical	3.96E+0	2.10E-3	1.97E+1
convert rotational to translational	9.05E+0	1.95E-1	1.97E+1	import mixture	9.15E+0	9.15E+0	9.15E+0
convert solid to liquid	1.20E+1	1.20E+1	1.20E+1	import optical	1.12E+1	1.12E+1	1.12E+1
convert translational to rotational	1.11E+1	3.88E+0	1.97E+1	import pneumatic	1.88E+2	6.20E+0	7.18E+2
couple electrical	4.59E+0	4.59E+0	4.59E+0	import rotational	4.01E+0	1.95E-1	1.97E+1
couple solid	9.71E+0	1.80E-3	7.18E+2	import solid	7.93E+0	1.80E-3	7.18E+2

Appendix A (continued): Function-flow Failure Rates

Function-flow	**Wtd Avg**	**Min**	**Max**	**Function-flow**	**Wtd Avg**	**Min**	**Max**
	Fails/Mhours	**Fails/Mhours**	**Fails/Mhours**		**Fails/Mhours**	**Fails/Mhours**	**Fails/Mhours**
import solid-liquid	2.94E+1	2.27E+0	1.92E+2	stop liquid to colloidal	2.25E+0	2.25E+0	2.25E+0
import thermal	5.31E+0	6.12E-2	1.97E+1	stop material	5.40E+1	5.40E+1	5.40E+1
import translational	9.63E+0	9.63E+0	9.63E+0	stop mixture	5.47E+0	5.47E+0	5.47E+0
indicate control	5.73E-1	5.73E-1	5.73E-1	stop pneumatic	5.47E+0	5.47E+0	5.47E+0
indicate electromagnetic	1.89E+1	5.73E-1	4.48E+1	stop rotational to translational	2.25E+0	2.25E+0	2.25E+0
indicate signal	1.02E+0	1.62E-1	3.61E+0	stop solid	4.60E+0	1.95E-1	5.40E+1
indicate status	1.34E+1	1.79E-1	5.40E+1	stop thermal	2.05E+0	6.12E-2	2.25E+0
indicate visual	5.40E+1	5.40E+1	5.40E+1	store chemical	4.08E+0	4.08E+0	4.08E+0
join solid	4.92E+0	1.95E-1	2.08E+1	store control	4.59E+0	4.59E+0	4.59E+0
link solid	2.92E+0	2.92E+0	2.92E+0	store electrical	4.10E+0	4.08E+0	4.59E+0
position human material	1.25E+1	1.10E+1	1.97E+1	store gas	1.92E+2	1.92E+2	1.92E+2
position liquid	1.15E+1	9.63E+0	1.34E+1	store hydraulic	2.00E-1	2.00E-1	2.00E-1
position mechanical	3.61E+0	3.61E+0	3.61E+0	store liquid	3.13E+0	2.25E+0	1.20E+1
position solid	3.81E+0	1.80E-3	7.18E+2	store mechanical	1.52E+0	1.95E-1	1.97E+1
process control	4.59E+0	4.59E+0	4.59E+0	store mixture	2.25E+0	2.25E+0	2.25E+0
process electrical	3.61E+0	3.61E+0	3.61E+0	store pneumatic	6.20E+0	6.20E+0	6.20E+0
process status	5.73E-1	5.73E-1	5.73E-1	store solid	3.87E+0	2.25E+0	1.20E+1
regulate control	2.36E+0	8.20E-1	6.20E+0	store solid-liquid	2.25E+0	2.25E+0	2.25E+0
regulate electrical	3.13E+0	9.00E-2	2.58E+1	supply electrical	3.94E+0	2.33E+0	4.59E+0
regulate gas	9.55E+1	5.47E+0	5.30E+2	supply gas	1.92E+2	1.92E+2	1.92E+2
regulate hydraulic	4.18E+0	4.23E-1	1.34E+1	supply hydraulic	2.00E-1	2.00E-1	2.00E-1
regulate liquid	5.73E+0	4.23E-1	1.34E+1	supply liquid	3.33E+0	2.25E+0	1.20E+1
regulate material	3.01E+1	6.20E+0	5.40E+1	supply mechanical	1.16E+0	1.95E-1	3.81E+0
regulate mechanical	4.00E+0	1.80E-3	4.69E+0	support solid	1.46E+0	1.80E-3	2.92E+0
regulate pneumatic	5.47E+0	5.47E+0	5.47E+0	transfer chemical	7.18E+2	7.18E+2	7.18E+2
regulate solid	9.73E+1	4.57E+1	1.92E+2	transfer control	4.19E+0	1.80E-3	1.33E+1
regulate thermal	1.33E+1	1.33E+1	1.33E+1	transfer electrical	3.42E+0	2.10E-3	9.24E+0
secure human material	1.97E+1	1.97E+1	1.97E+1	transfer gas	1.56E+1	1.20E+1	3.39E+1
secure mixture	9.15E+0	9.15E+0	9.15E+0	transfer human energy	9.87E+0	1.83E+0	1.10E+1
secure solid	5.52E+0	1.80E-3	7.18E+2	transfer hydraulic	6.08E+0	2.00E-1	1.20E+1
secure solid-liquid	1.92E+2	1.92E+2	1.92E+2	transfer liquid	2.66E+2	3.39E+1	7.18E+2
sense control	4.10E+0	3.61E+0	4.59E+0	transfer mechanical	6.93E+0	1.80E-3	7.18E+2
sense electrical	1.32E+1	1.32E+1	1.32E+1	transfer rotational	3.97E+0	9.30E-1	1.97E+1
sense solid	4.98E+1	4.57E+1	5.40E+1	transfer signal	1.79E-1	1.79E-1	1.79E-1
sense status	2.04E+1	3.61E+0	5.40E+1	transfer solid-liquid	2.49E+2	1.95E-1	7.18E+2
sense thermal	8.45E+0	3.61E+0	1.33E+1	transfer status	3.61E+0	3.61E+0	3.61E+0
separate gas	1.92E+2	1.92E+2	1.92E+2	transfer thermal	4.15E+0	1.90E-2	1.97E+1
separate material	9.63E+1	5.00E-1	1.92E+2	transmit control	5.40E+1	5.40E+1	5.40E+1
separate mixture	6.20E+0	6.20E+0	6.20E+0	transmit electrical	1.41E+1	1.90E-2	5.40E+1
separate solid	6.65E+0	4.23E-1	9.15E+0	transmit human energy	1.02E+1	1.83E+0	1.97E+1
shape solid	5.40E+1	5.40E+1	5.40E+1	transmit mechanical	7.86E+0	3.81E+0	2.08E+1
stabilize mechanical	3.61E+0	3.61E+0	3.61E+0	transmit pneumatic	2.08E+1	2.08E+1	2.08E+1
stop electrical	1.28E+0	6.12E-2	2.50E+0	transmit rotational	4.91E+0	1.95E-1	9.63E+0
stop gas	4.45E+1	5.47E+0	1.92E+2	transmit thermal	6.63E+0	2.00E-2	1.97E+1
stop hydraulic	5.47E+0	5.47E+0	5.47E+0	transport solid	1.47E+1	9.63E+0	1.97E+1
stop liquid	5.39E+0	2.00E-2	1.34E+1				