

Chapter 1

A METHOD TO COMPUTE EARLY DESIGN RISK USING CUSTOMER IMPORTANCE AND FUNCTION-FLOW FAILURE RATES

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Abstract The general method for using customer importance to validate a design misses the important opportunity to influence how that design is created. The intent of this research is to capture risk during the conceptual design stage. Risk is calculated using function-flow failure rates and customer importance. This allows the designer to effectively identify what functionality should be given additional importance during the generation and selection of design concepts. Functional risk using customer importance has not yet been investigated. In general, risk is implemented later in the design process. A generic process to calculate the risk is presented, then applied to an example where a subset of function-flows have been identified as generating 75% of the risk.

1.1 Introduction

In general, customer importance gives designers evaluation criteria and metrics for use later in design. Using this information in this form offers designers a basic *design validation* scheme. However, this information becomes more useful when it is used during the design process to create the final solution. In a similar respect, reliability is often used during the design process to make design changes. Mitigating unreliable components to improve the health of a design is good practice. Strictly using reliability will miss fixing the problems that are most important to the customer. Merging customer importance with reliability allows the designer to effectively identify what should be mitigated in the design. This need is addressed here by transitioning customer importance to consequence and reliability to the probability of failure. These values are used to calculate the risk of losing functionality in the design.

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1.2 Background

1.2.1 Methods for Early Design Risk and Reliability

Research in reliability engineering has focused on moving analyses earlier in the design process. The Function Failure Design Method (FFDM) is used in the early stage of design and provides the relationship between functions and failure modes. FFDM is a structured formulation of the function-failure analysis method introduced by Tumer and Stone (1). FFDM has several advantages including reduced user workload, using an archived failure knowledge base, being usable during early design, using the Functional Basis, component taxonomy, and failure mode taxonomy as a formalized failure language, and being practical for electrical and mechanical systems (1). This method also aids the designer by using a function-based concept generator approach helping to streamline the design process (2). FFDM utilizes knowledge bases that link product function to failure modes. Data in the knowledge base is archived in a function-component matrix and a component-failure mode matrix, which reduces the need for a designer to have a large intellectual knowledge base. The function-failure mode matrix is produced by multiplying the function-component and component-failure mode matrices together.

Two independent advances have been made to improve FFDM. The Risk in Early Design (RED) method has prioritized failures using severity and occurrence (3, 4). An interactive tool has been developed to aid designers in creating reliable designs (<http://idecms.srv.mst.edu/ide/>). The Function Failure Rate Design Method (FFRDM) has prioritized failures using only occurrence (5). This method was constructed by applying failure rates of components to the knowledge base. The designer can use a functional model to determine which failure modes are the most probable to occur.

System Failure Modes and Effects Analysis (System FMEA) is a bottom up approach to risk analysis used to provide design recommendations to reduce the risk of failure, or risk of losing functionality (6-8). The Risk Priority Number (RPN), used to determine which functions to provide recommendation for, is determined by the designer and does not use any information from the customer. The designer makes an assumption that each function holds an equal importance to the customer, and in the event of a failure, the function that fails is irrelevant. These analyses provide the designer information before components have been selected to facilitate making customer-oriented design decisions.

Quantitative Risk Assessment (QRA), also referred to as Probabilistic Risk Assessment (PRA) in the nuclear power industry and Performance Assessment within waste repositories, is a top-down design risk methodology. Fundamentally, this method answers three questions; what can go wrong?, how likely is this to occur?, and what are the consequences (9)? A typical QRA relies on executing five independent steps. The first step is to list all undesirable events. Next

the initiating events (IE) are found, accounting for disturbances to normal operation. The first two steps allow for specific analyses to be conducted such as Fault Tree and Event Tree, answering the first question. Step four uses all evidence to evaluate probabilities for each scenario, answering question two. Finally, the list of scenarios is rank ordered by risk value. The benefits of QRA include improved exploration over other commonly used methods of potential risks, improved likelihood of finding risk associated with complex interactions within the system, and it focuses on uncertainty quantification to facilitate decision making (10). QRA is a comprehensive failure analysis and requires a large workload to perform. The method provided in this research is simple to perform and produces high-level results specifically tied to the customer requirements.

Previous research has determined a method to calculate system reliability during functional design (11). This work presents a process to compute constant function-flow failure rates using component failure rates and historical data relating components to functions. The historical data from the Design Repository (<http://designengineeringlab.org/delabsite/repository.html>) leverages information from existing designs to more accurately model the function-flow failure rates. A five-step process is used to calculate the reliability. Examples show the usefulness of the methodology and compare the results to the traditional reliability block diagram. This research uses the function-flow failure rates to generate a probability of failure for the element risk calculations.

1.2.2 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 general, follows five steps; *project definition and planning*, *specification definition*, *conceptual design*, *product development*, and *product support* (12). 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 (13) 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. This research uses failure rates for the terms in the functional basis. The functional basis is also used as the functional language to generate the functional model in Figure 1.

1.3 Research Approach

This section presents a process to calculate function-flow risk. The intent is to provide a step-by-step process that the designer can reproduce on other designs. The requirements to complete this process include customer requirements for the intended design and a functional model.

Step 1: Gather Failure Rate and Customer Importance Data

First, failure rate data is needed to calculate the probability of failure. To gather function-flow failure rate data, tables in (11) can be used. These tables provide minimum, maximum, and weighted average failure rates for each function-flow in the functional basis. Prior work presented a method to calculate these failure rates for other functional taxonomies or function-to-component relationships. The *weighted average* failure rates are recorded for each function-flow in the functional model. The weighted average is used since this value observes all occurrences where a component has solved a function, then methodically uses these relationships with component failure rates to calculate the average failure rate.

Second, customer importance is required to determine consequence data. Consequence data is typically set on a scale from 1 to 10 where 1 is the least important and 10 is the most important. There are a variety of ways to obtain customer importance data. It is encouraged in this step to use an ethnographic survey where the customer is presented with a list of requirements to provide feedback. In general, ethnographic surveys use a 1 to 5 scale. This can be transitioned to a 1 to 10 scale by multiplying by 2. When multiple customers are involved, an average value for each customer requirement should be calculated. An example of the result to step 1 is shown in Table 1 and Table 2.

Step 2: Generate Consequence Data

Transitioning from customer importance data to function-flow importance depends on the mapping between customer needs and flows in the functional model. During the generation of the functional model, customer requirements are correlated to flows. The importance value for each customer requirement is directly translated across this mapping to arrive at an importance for a flow. In many cases, this will result in a flow listed several times with varying importance values. These values should be averaged to determine a final flow importance value. Any function that exists along a flow naturally receives the importance rating of that flow (i.e., all functions along a flow have the same importance value).

Risk calculations use the term consequence, not importance. This research transitions the terminology of customer importance to consequence by noting that the two are equal. The higher importance a specific function has, the higher the consequence is to the customer for losing that functionality. Similarly, lower importance results in a lower consequence of loss. An example of this step can be seen in Table 4.

Step 3: Element Risk Calculations

Risk is defined using the following equation:

$$K(t) = P_{fail}(t) * C \quad (1.1)$$

where $K(t)$ is the risk as a function of time, $P_{fail}(t)$ is the probability of failure as a function of time, and C is the consequence. The probability of failure is defined using the following equation:

$$P_{fail}(t) = 1 - R(t) \quad (1.2)$$

where $R(t)$ is the reliability as a function of time. Function-flow failure rates are used to calculate the probability of failure and ultimately the risk associated to each function-flow.

The function-flow consequence is used as an indicator to the designer to show where the customer places the most importance in the design. Combining this with the probability of failure presents a true risk value to the designer. The risk values for each function-flow quantitatively represent the impact of failure. For example, function-flows with a low probability of failure and a relatively high consequence only raise a moderate to low risk level to the customer. The customer has identified not wanting to lose the functionality, although the low probability of failure assures the customer that the likelihood this loss will occur is low. On the other hand, the risk level is raised when the probability of failure and the consequence are both high values. The product of two high values generates a high risk for lost functionality. An example of this step is summed up in Figure 2.

1.4 Example

An example showing how to calculate function-flow risk is presented here. This example uses the design of a letter folder, which is currently employed at a rehabilitation facility. The intent of this letter folder is to be used by low-functioning individuals to tri-fold a standard 8.5x11 inch piece of paper. Further details about the design are shown throughout this section as needed.

The functional model in Figure 1 was constructed using the functional basis and according to the procedures outlined by Stone (13). The high-level, or black-box, function of the letter folder is to fold paper. Using language from the functional basis, this functionality is described by the verb-noun pair *change solid material*. This functional language was chosen specifically to match with the failure rates used in step 1 to gather the failure rate data. In order to achieve the customer requirements, additional functionality has been included in the model.

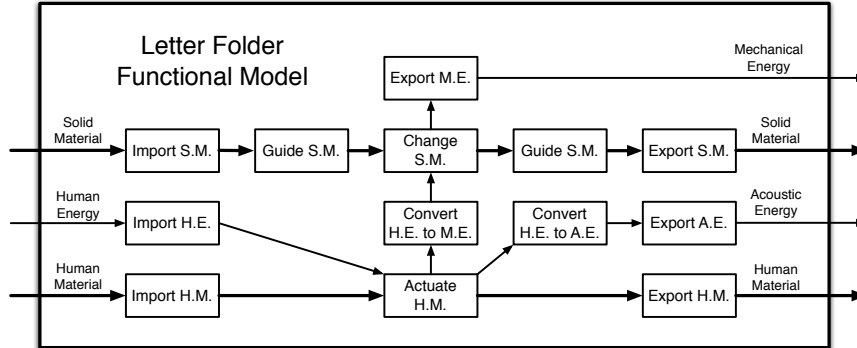


Figure 1: Functional Model for the Letter Folder Design

Step 1: Gather Failure Rate and Customer Importance Data

Using the tables generated in prior work (11), failure rates are recorded for each function-flow in the functional model. The function *convert human energy to acoustic* did not have any values so a risk calculation cannot be performed. This information is shown in Table 1.

TABLE 1: Functional-flow Failure Rate Data for the Letter Folder Design (11)

Function-flow	Failure Rate
import solid	7.57
guide solid	17.01
change solid	113.18
guide solid	17.01
export solid	9.69
import human energy	3.12
import human material	3.14
actuate human energy	0.18
actuate human material	0.18
export human energy	1.39
export human material	3.65
convert human energy to acoustic	x
export acoustic	9.26
convert human energy to mechanical	5.31
export mechanical	4.89

An ethnographic survey, seen in Table 2, was used to generate how important each requirement was for each customer. The values under each customer, on a scale with increasing importance from 1 to 5, indicate how important each requirement is to a specific customer. Actual customer names were not included for confidentiality. The final column was added after the survey was finished to display the average customer importance for each customer requirement.

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TABLE 2: Ethnographic Survey for Importance of Requirements based on individual Customers

Evaluation (1-5)	Customer Requirements	Customer 1	Customer 2	Customer 3	Avg Customer
OPERATION	Quiet operation	3	2	3	2.67
	Simple to use	5	5	5	5.00
	Lowest functioning individuals can operate	5	5	5	5.00
	Requires minimal dexterity	5	4	4	4.33
	Involves user into the process	3	2	3	2.67
	Ergonomic	5	5	5	5.00
CAPABILITIES	Bi-folds paper	3	3	3	3.00
	Tri-folds paper	5	5	5	5.00
	Folds different paper sizes	5	5	5	5.00
	Different patterns or styles	3	2	3	2.67
GENERAL	Portable	3	1	2	2.00

Step 2: Generate Consequence Data

Each customer requirement was then correlated to a flow in the functional model (e.g., Correlate CR's to FLOW). These values are multiplied by 2 to convert to a 1 - 10 scale. Table 3 displays the average customer importance for each flow(s).

TABLE 3: Average Customer Importance for Each Flow

Customer Requirements	Correlate CR's to FLOW	Avg Customer Importance (X2)
Quiet operation	Acoustic energy	5.33
Simple to use	Human material and energy	10
Lowest functioning individuals can operate	Human material and energy	10
Requires minimal dexterity	Human material and energy	8.67
Involves user into the process	Human material and energy	5.33
Ergonomic	Human material and energy	10
Bi-folds paper	Mechanical energy and solid material	6
Tri-folds paper	Mechanical energy and solid material	10
Folds different paper sizes	Solid material	10
Different patterns or styles	Solid material	5.33
Portable	Human material and energy	4

Table 3 shows the same flow listed several times in the second column. These flows evolved from different customer requirements, but each only exists once in the functional model. This means that each flow enters and exits the functional model only one time each. During this final step, each value in the *Avg customer importance (X2)* column of Table 3 is averaged for a specific flow. For example, the values 10.00, 10.00, 8.67, 5.33, 10.00, and 4.00 average to a value of 8.00, which becomes the final customer importance value for Human Material and Human Energy. The term customer importance was employed in the original ethnographic study. A natural change in terminology takes place where customer importance is called consequence. Table 4 lists the final consequence values for each flow in the functional model.

TABLE 4: Final Consequence Value for Each Flow in the Functional Model

Flow	Consequence
Acoustic energy	5.33
Human material and energy	8.00
Mechanical energy	8.00
Solid material	7.83

A final transition must be made from flow consequence to function-flow consequence. Each function along a flow naturally inherits the consequence value of that flow. For example, *import, guide, change, guide, and export solid material* all individually have a consequence of 7.83. Functions cannot be distinguished specifically from flow to determine consequence values using the method described in this research. However, the probability of failure is specific to each function-flow, which presents unique risk values.

Step 3: Element Risk Calculations

Equations 1 and 2 were used to arrive at the results in Figure 2. The Pareto chart displays the risk value using the bar graph and the cumulative risk function using the line graph. The Pareto principal states that approximately 80% of the effects come from 20% of the causes. It was identified that 75% of the risk is a result of 21% of the functionality; *guide-*, *change-*, and *guide-solid material*. This result shows that three of the functions along *solid material* flow can be grouped together and identified as the risk indicators for the letter folder design. Specific risk values include *guide solid* (9%), *change solid* (57%), and *guide solid* (9%). These three function-flows should be carefully solved and evaluated later in the design process.

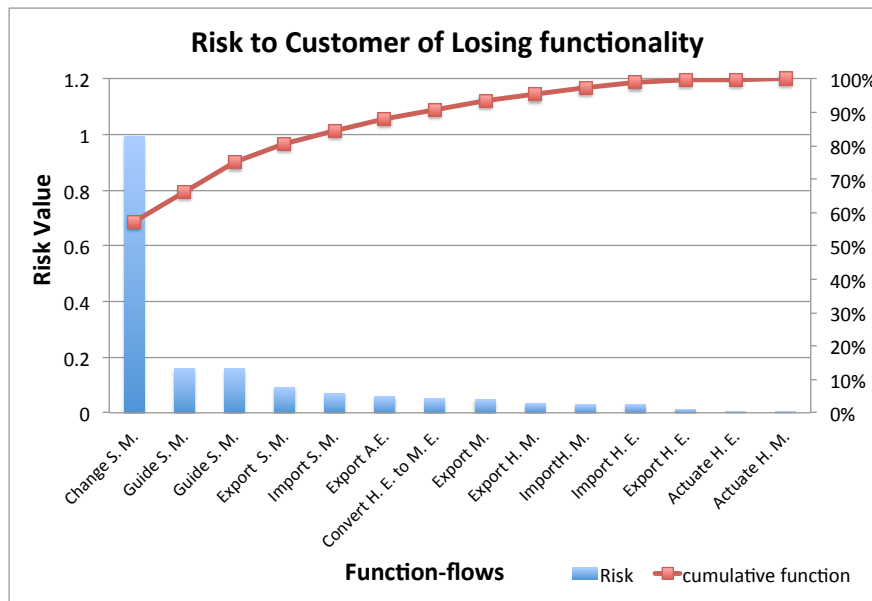


Figure 2: Risk Indicators for Losing Functionality

1.5 Discussion

It is difficult to justify changing a functional model, because doing so tells the customer they are getting something different than what they originally requested. Computing risk values of function-flows does *not* constitute reasoning to change the functional model even though risk is calculated during functional design. Instead, these values are used to indicate the risk to the designer of losing functionality based on what the customer has identified as important. The designer should use the risk values to identify which components can carefully solve the function-flows to achieve maximum reliability and reduce the likelihood of lost functionality. Consequence values, used in the risk calculation, are set values that come straight from the customer. Reducing *component reliability* is an optimal mitigation strategy for high-risk function-flows. Efforts to select highly reliable components should be made during concept generation and detailed design based on functions with high consequence.

The highest risk function-flow for the letter folder, used as an example in this paper, is *change solid* with approximately 57% of the total risk. In this design, *change solid* is the least desirable function-flow to have a high-risk value since this is also the black-box function. However, this is critical information for the designer to have during the early stage of design. When design concepts are created and evaluated, solutions to *change solid* should hold more weight than solutions to other function-flows in the design.

1.6 Conclusion

In this research, risk combines the consequence of losing functionality with the probability that functionality will be lost. The general method of using customer importance to validate a design misses the important opportunity to influence how that design will be solved. The intent of this research is to capture risk during the conceptual stage of design. This information is used to indicate to the designer which function-flows require more effort during the generation and selection of design concepts. A generic process to arrive at the functional risk is shown in detail and includes an example. This process can be employed using different techniques to generate customer importance and function-flow failure rates.

1.7 Future Work

The future goal of this research is to provide an integrated risk and reliability methodology to be used in early design. Reliability will be used to meet design requirements while risk will inform the designer of important areas of the design that require specific attention for generating design concepts.

1.8 Acknowledgements

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