RISK DUE TO FUNCTION FAILURE PROPAGATION

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ABSTRACT
In design, the earlier potential problems are found and addressed in products, the less costly these problems will be. As a design matures, it is costly to make changes. Therefore, it is preferred to identify potential failures during the conceptual design phase. Several existing methods for this such as the Function Failure Design Method (FFDM) or Risk in Early Design (RED) provide potential failure information based on product functions during conceptual design. However, these methods of analysis are not complete, as these methods treat each function as an isolated event, not affected by any of the other functions in the design. In this paper, the function-based failure propagation method is presented to address this issue. A thermal control subsystem is used as an example to demonstrate the technique. Using this new method, a more complete picture of risk is formulated during the early stages of a design.

Keywords: conceptual design, function based design, probabilistic risk analysis

1 INTRODUCTION
Probabilistic Risk Assessment (PRA) techniques such as Failure Modes and Effects Analysis (FMEA) [1], Event Tree Analysis [2], and Fault Tree Analysis [3] are useful tools to analyze risks of mature systems. These techniques not only identify areas of potential failures (FMEA), but how those failures affect the rest of the system (ETA, FTA). This allows the design to be altered to account for these failures, either controlling or eliminating their danger to the system. Unfortunately, these techniques are not as successful at failure analysis during the conceptual design phase when the physical form of the system has yet to be determined.

Recent research efforts have been directed toward risk analysis in the conceptual design stage. The Risk in Early Design (RED) [4] method identifies potential failure in a system based on its functions. Therefore, this method can be used as a risk assessment tool on systems whose physical form hasn't been decided. While this method is a great step forward in risk assessment during conceptual design, it does not consider how failures affect the rest of the system. This paper describes a risk assessment method that describes how failures propagate through and affect functions in a system.

2 BACKROUND

2.1 Functional Modeling
Functional modeling is a design tool that describes a product or system in terms of the functions it performs [5]. Since this model is based on the function of a product rather than its components, this model can be generated before a physical artifact exists or components have been selected. The materials, signals, and energy are diagramed as they flow from outside the system, through functions that act on those flows, and exit the system. These flows are determined from the high-level customer needs, and diagrammed as a black box model. This general function that makes up the black box is then further defined into the functions that act on those flows, generating chains that show the process of one flow throughout the entire system. These chains are then combined to form the complete functional model of the system [5-7].

To allow for better communication in the use of these models, a functional basis has been developed as a language for functions and flows in the model [8]. By using this functional basis, historical product design data can be quantified in a uniform manner, which promotes the use of conceptual design tools such as the Concept Generator [9], Function Failure Design Method [10], and Risk in Early Design method (RED).

2.2 Risk in Early Design

Risk in Early Design [4] combines historical failure data with functional models to perform risk analysis as early as the conceptual design phase. RED results include a listing of functions and their associated failure modes, likelihoods, and consequences. These results can then be plotted on a fever chart to better illustrate the risk level of the system. RED allows even a novice engineer or one unfamiliar with a system to perform failure analysis on that system, because it identifies historically significant risks automatically. RED is useful to identify specific function-failure mode combinations early in the design process; however, RED treats each failure as a separate entity, not linked to any other failure [11]. Therefore, it does not consider failure combinations or their sequence.

In Figures 1, a sample RED output is shown. The fever chart is broken up into three colored sections. In this chart, green represents low risk elements, yellow represents moderate risk elements, and red represents the high risk elements. The numbers inside each grid represent the number of function-failure combinations have that particular likelihood and consequence. In this particular example, there are fifty-five low risk elements (green), ten moderate risk elements (yellow), and four high risk elements (red). Below the fever chart are eight of the sixty-nine returned results from the RED analysis. The two highest risk elements have both a consequence and likelihood of five, which would put them in the top right grid. These two elements would represent the greatest risk to the system, and should be the systems focused on most during the rest of design. For example, in a car, import gas might apply to the air intake of the engine, and export gas represents the exhaust. This RED analysis would point to these systems as the ones most likely to fail, and fail due to many repeated uses. To counter these failures, the components corresponding to these functions should be made to withstand many repeated cycles of use.
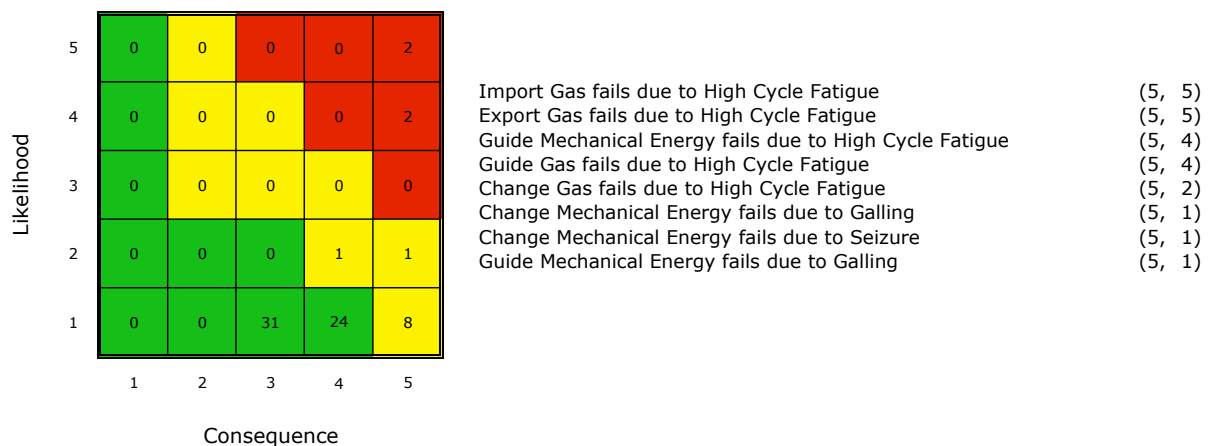

Figure 1. Example RED Fever Chart and Function-Failure Mode Output

2.3 Event Trees Analysis

ETA is a risk analysis technique that uses forward logic to analyze possible outcomes for an initiating event [2]. Starting with the initiating event, paths are created along events that can occur after the initiating event, in roughly chronological order. The outcome of each of these events is limited to success or failure, and each accident sequence is a different possible outcome for the system from that single starting event [12]. Event trees focus on chains of events; however, they do not handle parallel events in a system well, requiring events to be close to chronological. Furthermore, they are not well-

suited to events that have more than two possible outcomes, and can become very large as the number of events increases [13]. While this analysis does examine combinations of failures and the sequence of those same failures, it is focused more on the events that occur to a mature system; therefore, it is not well suited for risk analysis during the conceptual phase of design.

Shown in Figure 2 is an example event tree. At the left is the initiating event, followed by a sequence of events in roughly chronological order. Each event other than the initiating event, which is assumed to have happened, has the potential to end in success or failure. Using the tire of a car as an example, an initiating event could be the car driving in inclement weather. Following this event, there could be several different events, depending on the scope of the system. These events, such as the car moving too fast, the brakes functioning, the tire being fully inflated, and the tire bursting in this case, are treated as binary events that either occur or do not. Further, as some events will not matter if other succeed or fail, the tree can be pruned, simplifying it and removing outcomes that are redundant or have no meaning [13]. If the brakes fail, or the tires burst, the car will slide out of control, regardless of the events that happen after them.
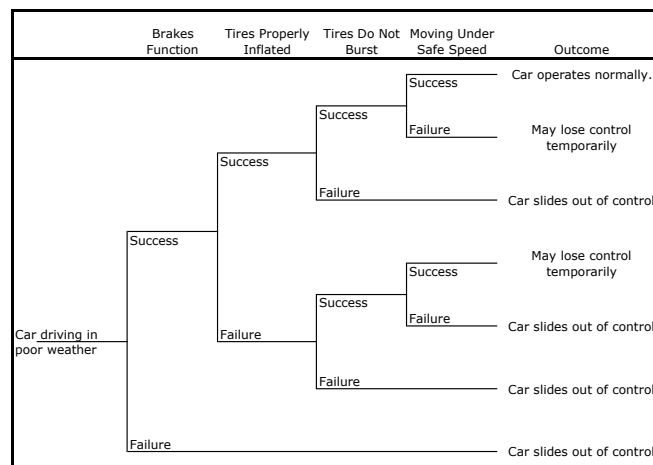

Figure 2. Example Event Tree

2.4 Fault Tree Analysis
FTA, unlike event tree analysis, use backward logic to identify possible causes of a top event or failure [3, 11]. Beginning with the top fault, possible faults that could cause it to occur are identified. This process is then repeated for each new fault generated until all possible root faults are found. Next, the probability of each chain of events occurring is determined. Fault trees also focus on chains of faults, and unlike event trees, fault trees can handle parallel chains of faults well. In addition, each fault tree is specifically tailored to its particular top failure, rather than the entire system [3]. However, they tend to be very complex and often difficult to understand, and like event trees, they can grow very large as the number of faults grows [14]. In addition, fault trees are acyclic and cannot model systems that can be kept running with repairs [15]. Like ETA, FTA focuses on combinations of failures; however, it too is not well suited for risk analysis during conceptual design because it works best on mature systems.

Shown in Figure 3 is a sample Fault Tree. Revising the previous example, the top fault would be one of the end results of the ETA, such as the car slides out of control. The events used in the previous example can again be used here as the individual faults that lead to this top fault. In this example, the top fault has two faults as its direct cause. Since these two faults are linked by the "And" operator, both must occur in order for the top fault to occur. Continuing with the car tire example, these two events could be the car moving to fast and the tire not being properly inflated, and both having to occur to cause the car to slide out of control. Similarly, Fault 2 has two additional faults that lead to it, Faults 3 and 4. These two faults are connected with the "Or" operator, and either one can cause Fault 2 to occur. Continuing with the tire, if the tire is not properly inflated, it could be overfilled or under filled, both causing the tire to be improperly inflated. There are additional operators that are used to

simplify a fault tree such as the "inhibit" gate, but they are simplified and special conditions of combinations of "And" and "Or" operators [16].
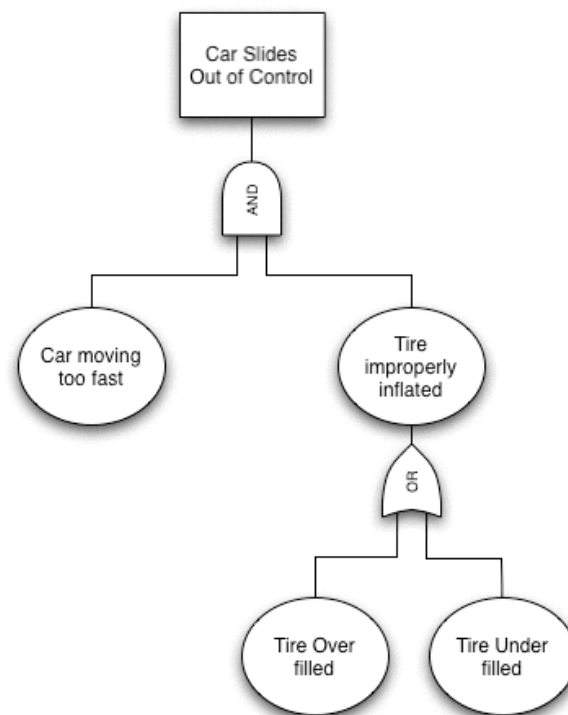

Figure 3. Example Fault Tree

2.5 Change Prediction
Another method of risk analysis during design focuses on the effects of changing components in a currently existing design [17]. The underlying theory of this works that changing one component in a design effects other components as well. By using the opinions of a team of experts, data was collected on which components are dependent on each other, and with what likelihood a change in one component propagates to another. This data was used to create a model of the changes in the system. In addition, each component also has a consequence of change, showing how much its change will affect the components dependent on it. Using the direct likelihoods, trees are created showing all possible paths to connect one component to another. These trees were used to calculate the combined likelihoods and consequences of a change propagating from one component to another [18]. This method provides a list of the components most likely to require changing if a single component is changed in a design. The change prediction method provides a means to predict chains of changes through a design, but focuses on components rather than functions. In addition, the model and data used are based solely on the opinions of engineers, rather than on collected historical data [19].

3 METHOD
While all of the above methods provide a means to analyze the risk to a system, they all lack a means to analyze chains of failures during the conceptual stage of product design. The function-based failure propagation method is presented as a means to analyze chains of failures through the functions present in a system, making it applicable to during early design stages before a product has assumed a physical form. In this section, the function-based failure propagation method is presented. First, the concept of function-based failure propagation is discussed. Next, the procedure to perform function-based failure propagation analysis is given. Third, the method of data collection is discussed. Finally, a case study on the model of a thermal control subsystem is performed.

3.1 Function-Based Failure Propagation
In the conceptual design phase, no specified components have been identified for a system. Instead, functions representing the basic operations a system performs are modeled. In order to analyze how

failures propagate through such a system model, a "common interface" between the functions must be identified. The concept of a "common interface" between components in a design can be carried over to a functional model of a system. In such a system, the common interfaces between two functions are the flows that travel between them. A failure in one function then has a likelihood of propagating to another function downstream along the flows connecting them.

These propagations form chains that can be illustrated as a series of trees similar in structure to a fault tree. Therefore, with the prescribed "common interface," given a particular function, possible root functional failures are found using backwards logic and the functional dependencies. Then, using data collected from past failures, the likelihoods of propagation are calculated and used to determine the likelihood that the function can fail due to failure propagation in the system.

3.2 Procedure

To perform the function-based failure propagation, a functional dependency matrix is generated from the functional model of the system using the flows as the common interface. Functions are directly dependant on the functions that are connected to them by one or more flows. For example, in Figure 4, Function D is dependent on Function C, and Function C is dependent on Functions A and B. Note that a function's dependency is independent of the type of flow and the number of flows from the previous functions. The functional dependency matrix is then populated with the likelihoods of a failure propagating to a particular function from one it is dependent on. The initiating functions are the functions that fail initially, and the dependent functions are those that the failure propagate to. In this example, the likelihood of propagation from C to D is $l_{C,D}$. For this method, the likelihood values are decimal values between zero and one, with zero denoting no likelihood of propagation, and one representing certain propagation of the failure. This is done to allow use of Boolean operators in the calculation of the total likelihood of propagation later on in the procedure. Likewise, each of the other functions' dependencies is used to populate the matrix. In places where there is no dependency, there is no likelihood of propagation, and thus the place filled in with a zero, (left black for figure clarity).
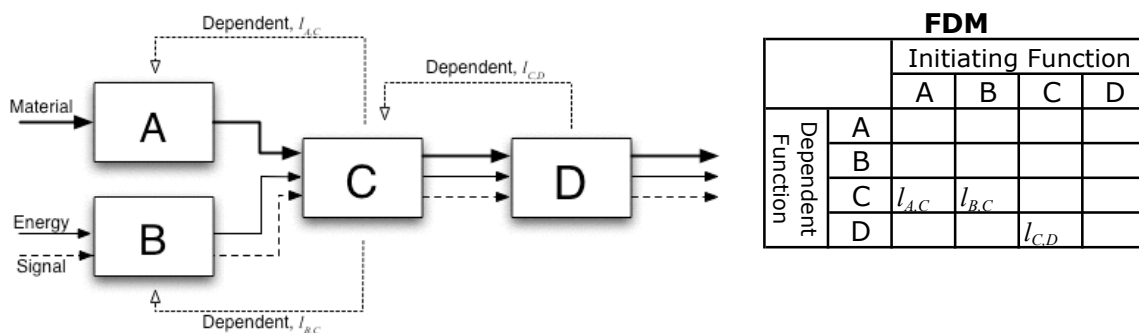

FDM

		Initiating Function			
		A	B	C	D
Dependent Function	A				
	B				
	C	$l_{A,C}$	$l_{B,C}$		
	D			$l_{C,D}$	

Figure 4. Example Functional Model and Corresponding Functional Dependency Matrix

Next, using the functional dependency matrix, propagation trees are built for each function in the model. These trees trace the path of a potential failure to each possible function that can propagate its failure to the end function. Each branch represents a different starting function, traveling to the same "root." In this example, functions A, B, and C can all propagate their failures to D. Function C propagates directly, and functions A and B propagate indirectly through C as seen in Figure 5. As shown in the figure, [A and C] or [B and C] or [C] can lead to failure of function D.
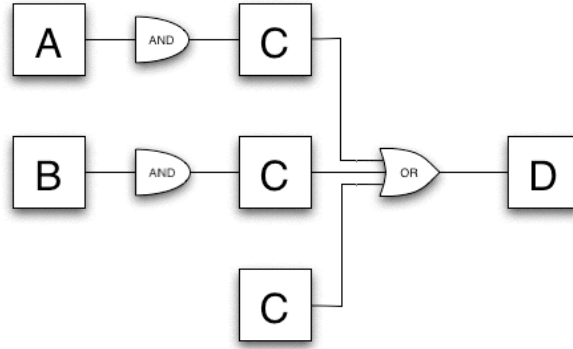
Figure 5. Example of a Propagation Tree for Function D

Finally, the total likelihood of propagation is calculated. Using the direct likelihoods from the functional dependency matrix and the trees generated, the total propagation likelihood is calculated using the Boolean operators "And" and "Or." Wherever there are multiple functions that failures can propagate from, the "Or" calculation is used. If a branch can only propagate a failure to a single function, the "And" calculation is used. The equations for both calculations are shown in Equations (1) and (2) [13].

$$\text{``And'' Calculation: } l_{b,u} \bigcup l_{b,v} = l_{b,u} \times l_{b,v} \tag{1}$$

$$\text{``Or'' Calculation: } l_{b,u} \bigcap l_{b,v} = l_{b,u} + l_{b,v} - (l_{b,u} \times l_{b,v}) = 1 - ((1 - l_{b,u}) \times (1 - l_{b,v})) \tag{2}$$

In these equations, l is the likelihood of propagation, b is the function being propagated to, and u and v are the functions being propagated from. For the example in Figures 4 and 5, there are three branches leading to function D. Two of the branches have two likelihoods each, and would be combined with the "and" operator. Then, each of the three branches would be combined using the "Or" operator to give the total likelihood of propagation as shown in Equations (3-5). Repeating this process for each function in the functional model yields the likelihoods of failure propagation through function in the model.

$$L_D = \left(l_{A,C} \bigcup l_{C,D} \right) \bigcap \left(l_{B,C} \bigcup l_{C,D} \right) \bigcap l_{C,D} \tag{3}$$

$$L_D = \left(l_{A,C} \times l_{C,D} \right) \bigcap \left(l_{A,C} \times l_{C,D} \right) \bigcap l_{C,D} \tag{4}$$

$$L_D = 1 - \left(\left(1 - \left[1 - \left((1 - l_{A,C} l_{C,D}) \times (1 - l_{A,C} l_{C,D}) \right) \right] \right) \times (1 - l_{c,D}) \right) \tag{5}$$

3.3 Data Collection

In order to properly use this method, historical data pertaining to failure propagation must exist. To this end, NTSB accident reports on Bell helicopters were used to provide a database of failure propagation data. Using the accident reports and a functional model of the helicopter's main systems, failures were plotted on the functional model. Following the functional model, the path that the failures propagated along were found, and chains of failure created. Finally, these failures were then tabulated into a matrix showing the number of times that each function pair had appeared. These numbers were then normalized, using the most frequently occurring failure propagation pair as the normalizing factor. In this way, each value collected becomes a decimal value between zero and one.

It is unlikely each possible failure mode that a function might fail by has the same likelihood of propagation. Some failure modes might have higher or lower likelihoods of propagation than others. However, for ease of calculation of those likelihoods, each failure mode for a function is assumed to have the same likelihood.

Using a modified form of the likelihood mapping from [20], the likelihood of each function pair was calculated. Some of the values from this data collection are shown in Figure 6. Along the left side are

the functions that failures are propagating from and along the top are the functions that failures are propagating to. At the intersection is the calculated likelihood value for that pair of functions.

	Import Mixture	Store Mixture	Guide Mixture	Separate mixture	Stop Solid	Export Solid	Change Gas	Mix Liquid & Gas	Convert Mixture to Chemical Energy
Import Mixture	0	0	0	0	0	0	0	0	0
Store Mixture	0	0	0.03	0	0	0	0	0	0
Guide Mixture	0	0	0	0.17	0	0	0	0	0
Separate mixture	0	0	0	0	0	0	0	0.23	0
Stop Solid	0	0	0	0.03	0	0	0	0	0
Export Solid	0	0	0	0	0	0	0	0	0
Change Gas	0	0	0	0	0	0	0	0	0
Mix Liquid & Gas	0	0	0	0	0	0	0	0	0.3

Figure 6. Partial Table of Collected Failure Propagation Data

As this is not a complete database, there are pairs of functions that do not exist or have no data yet. In the case study that follows, the above data is used to estimate the likelihood of these missing pairs.

3.3 Case Study

To demonstrate how this method is useful in a design setting, a thermal control subsystem is presented as an example. This thermal control subsystem is an example of a subsystem designed for use in space missions by Team X, NASA's Jet Propulsion Laboratories Concept Design Team [21]. This subsystem is an example that would be found in such systems as a launch vehicle or a spacecraft itself [22]. The function model for the thermal control subsystem is presented in Figure 7. In this model, there are several flows that pass through the system that failure can propagate along. For example, the "Gas" flow passes through "import," "store," "supply," "guide," "stop," "regulate," and "mix" functions. Any failures in these functions can propagate along the "Gas" flowing through the system and spread to other functions downstream.
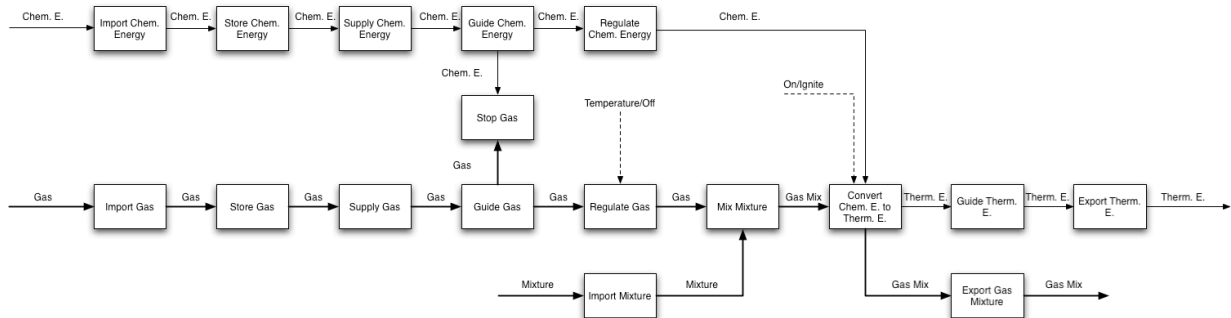

Figure 7. Thermal Control Subsystem Functional Model

In Figure 8, the initiating functions are shown across the top of the matrix, and the dependent functions are listed along the side. The function A on the top of the matrix corresponds to function A on the side, in this case, "import chemical energy." A function can have multiple functions directly dependent on them, as shown by having multiple likelihoods in their column. In this functional model, the energy flow of "gas" flows from "guide gas" to both "stop gas" and "regulate gas." Thus, the function "guide gas" directly affects both "regulate gas" and "stop gas."

Dependant Function		Initiator Function					
		G	H	I	J	K	L
Import Gas	G						
Store Gas	H	0.03					
Supply Gas	I		0.03				
Guide Gas	J			0.17			
Regulate Gas	K				0.03		
Mix Mixture	L					0.07	

Figure 8. Partial Functional Dependency Matrix for Thermal Control Subsystem

Next, a tree is created, starting from the "top" function and linking it to each function that can propagate to it. Much like the fault tree, each of these functions branches to others that can propagate to them, until a chosen "initiating" function is at the tip of each branch. This is repeated for each pair of functions in the system. Figure 9 gives an example failure propagation tree for the thermal control subsystem. In this example, the top function is "mix mixture," and the initiating functions are "import gas," "store gas," "supply gas," "guide gas," and "regulate gas." Each of these chains is linear, that is, having only one path from the initiator to the top function.
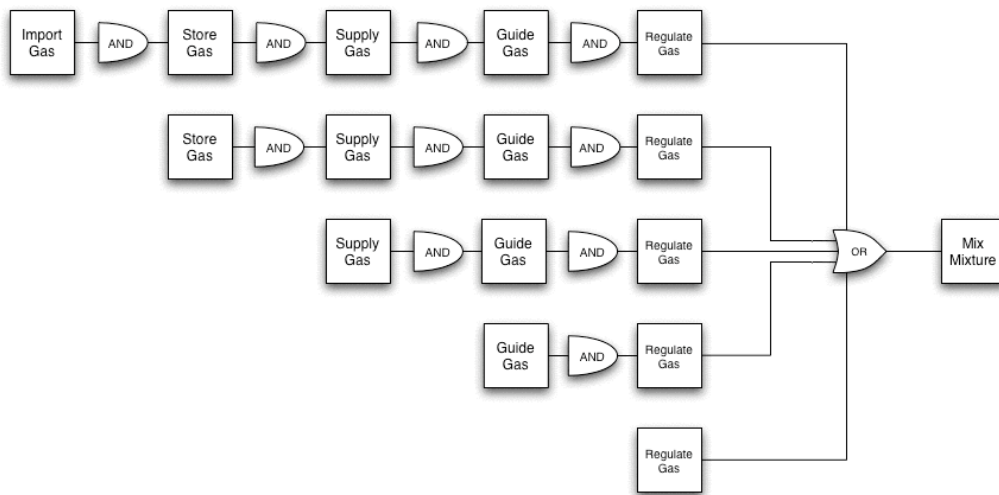

Figure 9. Failure Propagation Tree for Mix Mixture

Once these trees have been created, the likelihoods of propagation are then used to calculate the total likelihood of propagation for each function. The following calculations give an example of calculating the overall likelihood of propagation for the "supply gas" function. The "supply gas" function has two possible initiator functions: "import gas" and "store gas." As in the previous example, each of these chains is linear and has only one path to the top function. From the functional dependency matrix, the likelihood of propagation from "import gas" to "store gas" is .03 and from "store gas" to "supply gas" is .03. Following the calculations, the total likelihood of propagation is .031, as shown in Equations (6-10).

$$L_{SupplyGas} = \left(l_{IG,Sg} \bigcup l_{Sg,SG} \right) \bigcap \left(l_{Sg,SG} \right) \qquad (6)$$

$$L_{SupplyGas} = \left(l_{IG,Sg} \times l_{Sg,SG} \right) \bigcap \left(l_{Sg,SG} \right) \qquad (7)$$

$$L_{SupplyGas} = 1 - \left(\left(1 - \left(l_{IG,Sg} \times l_{Sg,SG} \right) \right) \times \left(1 - l_{Sg,SG} \right) \right) \qquad (8)$$

$$L_{SupplyGas} = 1 - \left(\left(1 - \left(.03 \times .03 \right) \right) \times \left(1 - .03 \right) \right) \qquad (9)$$

$$L_{SupplyGas} = .031 \qquad (10)$$

In these equations, $L_{SupplyGas}$ is the total likelihood that failure will propagate to the "supply gas" function. $l_{IG,Sg}$ and $l_{Sg,SG}$ are the likelihoods of failure propagating from "import gas" to "store gas" and "store gas" to "supply gas," respectively. Equation (6) shows each of the branches in the propagation tree, separated by "Or" operators. The first branch contains two likelihoods, combined with the "And" operator. The "And" operator can be replaced with a simple multiplication, as shown in Equation (7). Likewise, the "Or" operator can be replaced with its equivalent expression, as shown in Equation (8). In (9), each of the likelihoods taken from the functional dependency matrix is substituted into the equation, and solved in Equation (10). In this manner, the likelihood of propagation of each of the other functions in the model is calculated as additional failure modes.

Following this procedure for the entire "mix mixture" tree, it can be seen the individual likelihoods of each branch and determine the most likely branch of the tree. From looking at Figure 10, the lowest branch of the tree, which is also the shortest, is the most likely branch to occur. Whenever many linear branches to a tree occur, the shortest branch will be the most likely occurrence. The total likelihood for this function is the likelihood that any of these branches will occur. Once the most likely branch has been determined, the results from this analysis can then be paired with other risk analysis methods, such as RED, to link a consequence of failure to each branch.

Branch	Total Likelihood
Import Gas, Store Gas, Supply Gas, Guide Gas, Regulate Gas, Mix Miture	0.0000003213
Store Gas, Supply Gas, Guide Gas, Regulate Gas, Mix Miture	0.0000107
Supply Gas, Guide Gas, Regulate Gas, Mix Miture	0.000357
Guide Gas, Regulate Gas, Mix Miture	0.0021
Regulate Gas, Mix Miture	0.07
Full Tree	0.07229

Figure 10. Compiled Likelihoods of Mix Mixture Tree

For the thermal control subsystem, the RED results shown in Figure 11 show the highest risk elements to be "export thermal energy," "guide gas," and "import gas" all failing due to high cycle fatigue. Each of these components have a high likelihood of occurrence and a high consequence of failure. Using this information and the functional model, the high cycle fatigue failure in "export thermal energy" cannot propagate to other functions, as there are no other functions downstream of it. From the other two function-failure combinations, they can propagate along the flow of "gas" to other functions. In terms of failure propagating to "mix mixture," the other functions in the chain are less likely to start the chain.
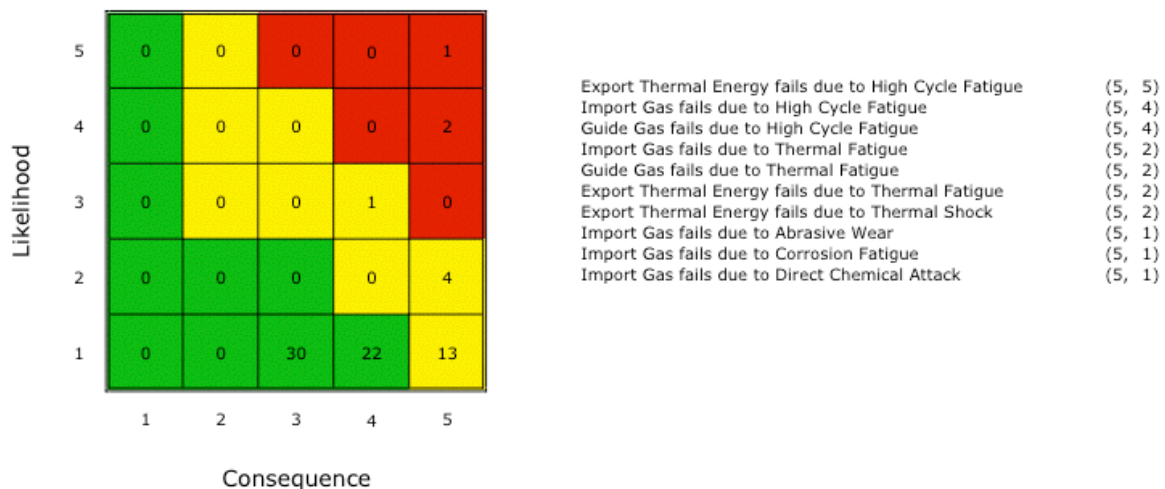

Figure 11. Thermal Control Subsystem Results

Based on the RED results, the first and fourth branches would be the most likely failure propagation paths to "mix mixture," as these branches start with "import gas" and "guide gas." Then, examining the failure propagation results, of the two branches, it is more likely that "guide gas" will propagate to "mix mixture" than "import gas." Thus, to protect "mix mixture," the branch from "guide gas" to "mix mixture" should be focused on to prevent the high cycle fatigue or thermal fatigue of "guide gas" from propagating to "mix mixture" or further.

4 CONCLUSIONS AND FUTURE WORK

Functional-based failure propagation provides a method of failure analysis that can be performed in the conceptual design phase given only a functional model, thus saving potential resources later on in the design process. Next, it views functions not only as stand alone events, but also as dependent on other functions based on their connection by flows. Finally, it delivers a single likelihood of propagation for each function as well as calculates the likelihood of propagation of any function to another. However, it does not provide the consequences of risk for the functions in the model, requiring another method to provide the data it lacks.

In order to verify this method, the Bell helicopter that was used for the collection of historical data will be analyzed using this method, and the results compared with the actual accident reports. Secondly, only the likelihoods of failure propagation are considered for each function. A method for considering the consequence of the failures in the analysis is needed to fully understand the risk to the system. Finally, more data pertaining to the propagation of failure is necessary to fully implement this method on a broad number of different products.

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