AC 2007-2705: ENABLING PROBABILISTIC RISK ASSESSMENT INSTRUCTION DURING THE CONCEPTUAL DESIGN PHASE: FUNCTION-BASED RISK ANALYSIS

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Enabling Probabilistic Risk Assessment Instruction During the Conceptual Design Phase: Function Based Risk Analysis

Abstract

Most decisions about a product, i.e. form, function, aesthetics, etc, are made during the conceptual phase of product design. Since those decisions not only impact product performance but also product failures, methods to address the potential product failures (risks) should be initiated during this design phase, before a product has assumed physical form. This paper presents the Risk in Early Design (RED) method as the backbone of the graduate level Function Based Risk Assessment course to teach an interdisciplinary group of engineers how to use traditional PRA techniques such as failure modes and effects analysis (FMEA), fault trees, and event trees in conceptual product design. The innovative use of specific engineering taxonomies and knowledge-base failure data representation allows RED to identify product risks armed only with product function. Moreover, the engineering taxonomies used in RED drastically reduce communication issues prevalent in risk assessment due to natural language. RED provides the students with a database of expertise from which to draw their engineering knowledge in order to perform other PRA techniques successfully and in the process builds each student's own knowledge-base, or experience, of relevant product failures.

1 Introduction

The conceptual phase of product design is the one in which the design problem is defined and analyzed leading to concept formations. The concept formations include most decisions about a product, i.e. form, function, aesthetics, etc. These decisions made during the conceptual phase of product design impact not only product performance but also product failures. Moreover, up to 85% of the life-cycle costs of a product are determined during this design stage while only about 5% have been spent [1] Therefore, methods to address the potential product failures (risks) should be initiated during the conceptual design phase, before a product has assumed physical form, to maximize their chances of mitigating potential product failures while minimizing their cost of implementation.

Very little detailed information about a product, such as material type, dimensions, performance environment, etc, is available during this phase of design. This lack of information causes traditional approaches to probabilistic risk assessment (PRA) to fall short during the conceptual design phase because they require a significant amount of detailed data to be performed. Moreover, these methods also require a significant amount of expertise on the product, its systems, and its environment to identify potential failures to analyze. Often a designer, assigned to the conceptual phase of product design, is not an expert on system operation, rather the process of creating the system. Therefore, a risk assessment method that could be applied during the conceptual design phase without a significant amount of expertise is beneficial in reducing life cycle cost and preventing product failures. One such method is the Risk in Early Design (RED) method[**2, 3, 4**].

This paper presents the RED method as the backbone of the Function Based Risk Assessment course to teach an interdisciplinary group of engineers how to use traditional PRA techniques and newer function based PRA (FuPRA) techniques. RED is a PRA that only requires information on product function to generate a list of potential failures. This list of potential failures from RED serves as the data one would obtain from a system expert to initiate other useful PRA techniques such as failure modes and effects analysis (FMEA), fault trees, and event trees in conceptual product design. The material presented in the course not only educates engineers on risk and risk assessment techniques, the data generated from RED can serve to populate their own knowledge base of relevant failure experience.

2 Background

2.1 Risk Teaching Methods

While the concept of risk is simple, risk education is more complex. Risk analysis methods require risk identification before any form of analysis can begin [**5, 6, 7, 8**]; therefore risk education requires that students be able to identify risks in order to learn the particular analysis in question. Risk identification is often not taught and left up to the students to rely on their experience. Aspiring engineers, however, often do not have a significant amount of corporate experience and cannot adequately identify product risks. The lack of risk identification ability often prevents engineering students from being able to learn valuable probabilistic risk assessment (PRA) techniques in college that they will be required to use in the workforce. Therefore they are forced to learn both the risk assessment techniques and the ability to identify risks on the job. Companies spend a tremendous amount of money employing outside sources to teach standardized risk assessment procedures such as the FMEA procedure in the Reference Manual [9] for companies subscribing to the Quality System (QS-9000)[9]. Therefore, it would be beneficial to the student engineers, as well as their future employers to overcome the risk identification hurdle and educate the engineers on PRA during their collegiate training.

2.2 The Risk in Early Design Method (RED)

Early identification and mitigation of risk is crucial to the success of products. In order to mitigate risk and failures research has been performed to link failures to product function. This linkage provides designers the ability to use catalogued historical failures as a tool to prevent failures in the new designs. Also, by exploiting the linkage between function and failure, designers can begin reliability analyses during the conceptual phase of product design, before the product has assumed a physical form.

Through research with NASA, a study was performed that focused specifically on the relationship between function and risk in early design by presenting a mathematical mapping from product function to likelihood and consequence risk assessments that can be used in the conceptual design phase. The resulting risk assessment method, Risk in Early Design (RED), is a tool that will aid designers by identifying risks early and by reducing the amount of subjective risk value by deriving subjective risk from catalogued historical events[**2, 3, 4**]. Also, this method is relatively simple to implement and provides a means for inexperienced designers to effectively address risk in the conceptual design phase.

The communication of the risks are manipulated so that they are compatible with a risk fever chart. This chart, originated by the Defense Acquisition University (DAU)[10], is used widely in industry, such as NASA[11] and Boeing [12]. The fever chart allows the quantification of risk with clear risk communication across all realms from designers, engineers, managers and other decision makers. While it is true that some information is lost in the discretization, there are great communication benefits, such as clearly presented high, moderate, and low-risk elements. An example of RED results is shown in Fig. 1. In this figure a RED risk statement generated from a channel signal function, part of the optics system on a space telescope, shows that it has historically failed due to high cycle fatigue, for the optics case this probably occurred during launch. Also, the risk statements risk level is plotted on the Fever Chart as Consequence 3, Likelihood 5, or High Risk. This type of historically significant complete function-failure information data produced by RED makes it ideal for the education of young engineers about risk and failure; a discipline that often requires years of experience as a prerequisite.

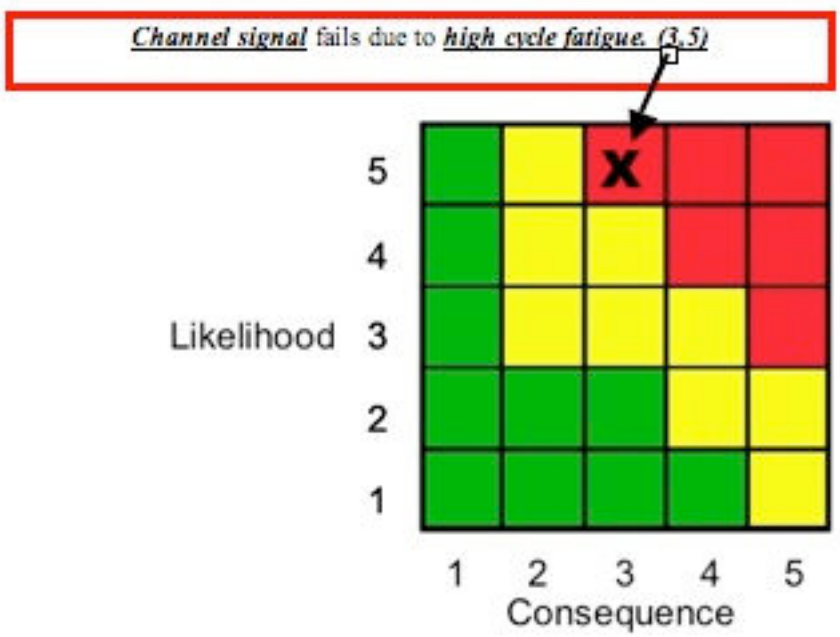


Figure 1. Sample RED Results

3 Function Based Preliminary Hazard Analysis with RED

A Preliminary Hazard Analysis (PHA) is a study performed which identifies initiating events and its potential consequence. These initiating events stem from identifying potential hazards from checklists, and event sequences that transform an initiator into an accident. The PHA also attempts to identify corrective measures and consequences of the accident [13]. A hazard is defined as an initiating event coupled with its potential consequence. After the hazards are identified they are characterized according to their effects. In the nuclear industry, Holloway classifies initiating events and consequences according to their annual frequencies and severities, respectively.

Most Probabilistic Risk Assessment (PRA) methods require a PHA to be performed at the outset of their respective analysis[8]. Often a PHA requires an expert, or team of experts, to combine their experiences and brainstorm potential hazards to a product or system. Since this class is composed of aspiring engineers the expertise to perform a traditional PHA is not available; therefore, some other means must be employed to provide the students with this necessary information in order to learn valuable risk analysis methods. The RED method is taught to the students so that they are able to perform critical risk identification step in the PRA process. When given a functional model of a product, RED can automatically generate historically significant risks to the product.

3.1 Process of System/Subsystem Description – Functional Models

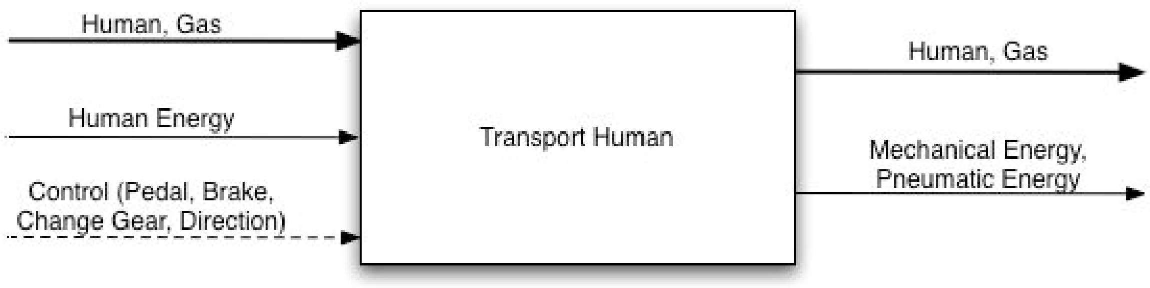
The product information required to perform RED is the functional model. A functional model is a description of a product or process in terms of the elementary operations or functions that are required to transform its input flows of energy, material, or signal into desired output flows. Functional models are form independent blueprints of a product that can be derived early in the conceptual design phase from high-level customer needs [14]. Since the generation of functional models only requires information about customer needs, the student engineers can complete this type of system description without the wealth of experience necessary to perform most PHAs. Moreover, it is the ability to generate risks based on function that allows RED to be used as early as the conceptual phase of product design, before physical form of the product has been determined.

An example of a mountain bike product functional model generation is shown in Table 1 and Fig. 2. Table 1 is a list of customer needs from the mountain bike. After the customer needs have been identified, the next step in the functional model process is to identify the flows associated with satisfying the need. For example, the human flow will affect the customer need of a comfortable seat. Next the flows are used in conjunction with the functions that must be performed by the mountain bike to generate a functional model, see Fig. 2. These functions will be used to generate the list of potential risks for the mountain bike.

Table 1. Sample Customer Needs: Mountain Bike

Customer Need	Flows
Comfortable Seat	Human
Fast	Mechanical Energy
Easy to Pedal	Human Energy, Mechanical Energy
Stop, slow down smoothly	Mechanical Energy, Control (Brake, Stop)
Usable on rough terrain	Mechanical Energy, Pneumatic Energy, Gas (Air)
Can carry human	Human
Multiple speeds	Mechanical Energy, Control (Shift Gear)

Can control direction	Mechanical Energy, Control (Direction)
Can handle Shocks	Mechanical Energy, Pneumatic Energy, Gas (Air)
Is powered by a human	Human Energy
Adjustable for different sizes	Human, Mechanical Energy



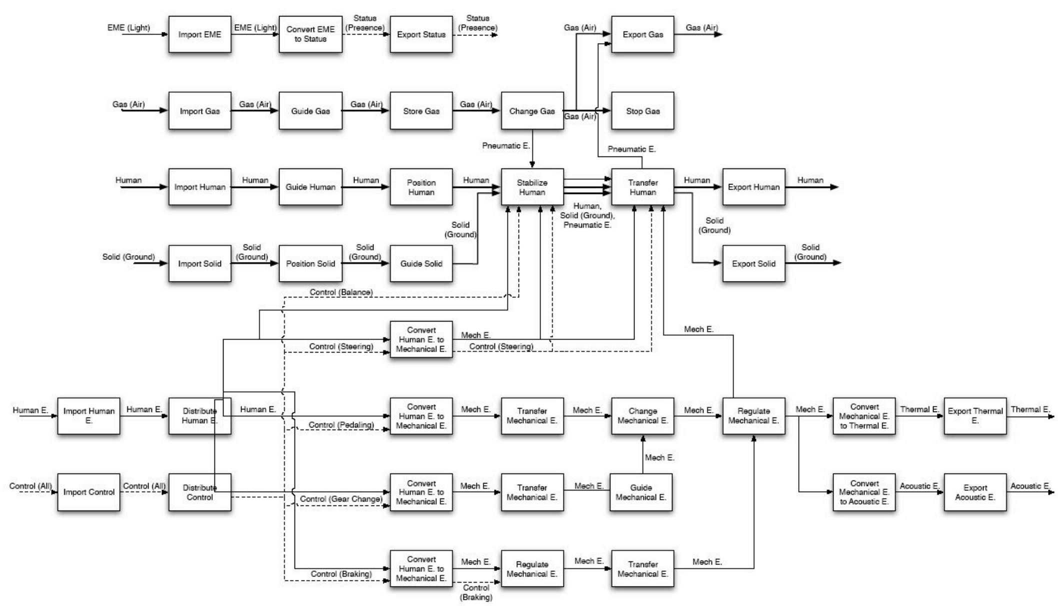


Figure 2. Sample Functional Model: Mountain Bike

3.2 Design Taxonomies

The use of specific design taxonomies for functions in functional models, as well as components and failure modes enable RED to store valuable historic failure information in a knowledgebase and to recall relative risk information when given a functional model of a system. The three significant languages here are the functional basis [14] for functional modeling, component taxonomy[15] and failure mode taxonomy[16] for recording and categorizing reported failure data. Moreover, these languages ensure consistency and completeness of risk information and communication to all parties interested in the risk analysis.

3.3 Performing PHA with RED

Since aspiring engineers do not have significant industrial experience, it is necessary to supplement their current knowledge of engineering failures with the RED knowledge base. This is done by using the functional models of the systems under analysis to query the RED knowledgebase, through calculations, for historical failures relevant to their system. This automatically generated risk list from RED will serve as a PHA and allow them to learn and use other PRA techniques. The first step in performing a RED preliminary risk assessment is to develop a functional model for the product that will be assessed for risks. The remaining steps involve calculating and communicating the risk results as described in the following steps.

Step 1: Functional Modeling

Functional modeling, as described in Section 3.1, is a form independent blueprint of a product that describes what the product will do. Functional models are created with a process that places an emphasis on customer needs. Once a product's functional model has been created, it can be used to calculate product risks.

Step 2: Risk Calculations

The risk calculations vary for different types of systems used. The engineer selects appropriate risk calculations based on system characteristics such as whether the system is manned or unmanned, or the design level of the system (system design or subsystem design). After the appropriate mappings for both risk likelihood and consequence have been selected, corresponding equations [**3**] are applied to the functions of the product.

Step 3: Risk Result Communication

The information provided by the risk calculations yields four important pieces of information for each product risk (function, failure mode, consequence, and likelihood). These risk elements must be communicated in such a way that it is easy to understand the current risk state of the product. Therefore, these items are plotted on a risk fever chart. This is done by entering the number of risk elements that have a particular risk coordinate in that location on the 5x5 risk grid. This grid is overlaid with green, yellow, and red colors with indicate low, moderate, and high-risk respectively. This indicates the overall product risk. Depending on the number of risk elements and the communication space available, they can be shown along side the grid accompanied with their risk coordinates, or in accompanying documents. This type of communication presents the general product picture as well as directs specific attention to risk areas and identifies them with particular functions and failure modes. A sample of a RED risk grid for the mountain bike is shown in Fig. 3. From the figure, it can be determined that there are 69 preliminary risks for the mountain bike, 13 moderate risks and 56 low risks. These results shown that a mountain bike is not the most risky product when compared to the products that populated the current RED database. Since the current RED database is populated with spacecraft and rotorcraft data, the moderate and low risk results are expected. The risk statements are shown in the appendix.

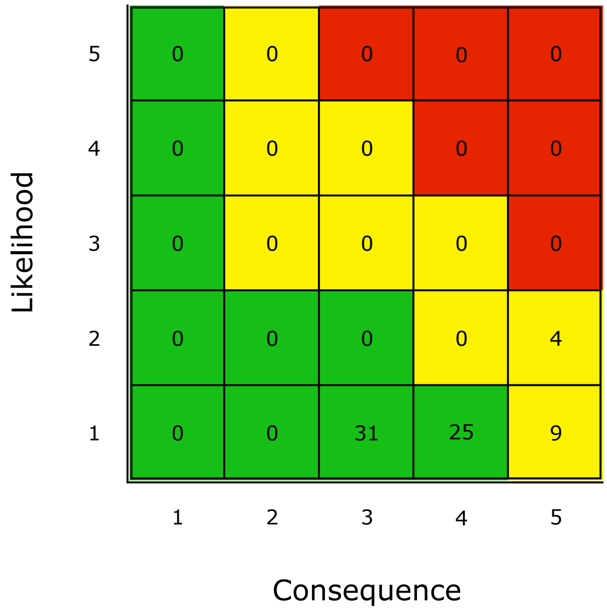


Figure 3. Sample RED Fever Chart Results: Mountain Bike

4 Teaching Probabilistic Risk Assessment Techniques Building on RED Results

In the course implementation, the general syllabus used is shown in Fig. 4. As shown by the course topics in the figure, the RED method (as summarized in Section 3) is integrated throughout the course. First the students are introduced to the formal concepts of function and risk as they are used in the course material. Then, the students are taught the standard industry risk assessment techniques FMEA, ETA, and FTA. The initial risk assessment assignments require the students to use their current level of experience to perform these PRA techniques on three consumer products which have failed and are reported by the Consumer Product Safety Commission (CPSC), www.cpsc.gov. This assignment is designed to give the students hands-on experience with thoroughly identifying and analyzing risks. Expected (and observed) outcomes include the realization that risk assessment is not a trivial task and that they possess a limited set of concrete experiences to draw from for the analysis. Therefore, they are motivated to learn PRA tools and skills that are in high demand by many employers and that will close that knowledge gap.

Next, the students are introduced to the RED method. The PHA provided by the RED results allows students to learn the mechanics of the more detailed risk assessments used in industry. Among the PRA methods in commercial use, Failure Modes and Effects Analysis (FMEA), Event Tree Analysis (ETA), and Fault Tree Analysis (FTA) are taught in the Function Based Risk Analysis course. The students not only learn how to employ the techniques, they also learn to be mindful of risks during the design of the product, rather than post–design, due to the function-based nature of the RED risks. A synopsis of the FMEA, ETA and FTA content covered in the course is presented in the following sub-sections.

IDE 401 – Function-Based Risk Analysis
University of Missouri at Rolla, Fall Semester 2006

Week	Date	Topic	Assignment
1	21-Aug	Introduction-What is Risk? Risk Communication	Risk & Function definitions paper.
	23-Aug	Functional modeling	
2	28-Aug	Existing failure analysis methods overview	Failure Analysis Homework
	30-Aug	Existing failure analysis methods overview (2)	
3	4-Sep	Labor Day Holiday	Enjoy
	6-Sep	Functional modeling 2; Component basis	FM of CPSC case products
4	11-Sep	Engineering Disasters	FM of 3 Engineering Disaster Systems
	13-Sep	Evolution of Products due to Failures	NASCAR evolution paper.
5	18-Sep	Failure Modes & Function-failure design method (FFDM)	FFDM application to CPSC case products
	20-Sep	FFDM (2)	
6	25-Sep	Risk in Early Design (RED) Method	RED application to CPSC case products
	27-Sep	RED (2), The UMR Design Repository	Midterm project assignment
7	2-Oct	Design Show Project	
	4-Oct	Design Show Project	
8	9-Oct	RED & FMEA	FMEA of CPSC products
	11-Oct	RED and Event Trees, Fault Trees	
9	16-Oct	RED and Event Trees, Fault Trees	Failure equations assignment
	18-Oct	RED and Event Trees, Fault Trees	
10	23-Oct	Midterm Project Presentations	Fault Trees & Event Trees of CPSC Products
	25-Oct	Product Risk Portfolio	
11	30-Oct	Electronic Risk Portfolios (in class)	CPSC Risk Portfolio Assignment, Semester project proposal
	1-Nov	RED & Engineering Failure Analysis Function based failure/risk mitigation	Failure Equations Assignment addition to risk portfolio
12	6-Nov	Fault Tree Review	
	8-Nov	Event Tree Review	
13	13-Nov	Electronic Risk Portfolio (in class)	
	15-Nov		Semester project proposal due
14	20-Nov	Thanksgiving Break	Enjoy
	23-Nov	Thanksgiving Break	Enjoy
15	27-Nov	Function based failure/risk mitigation	
	29-Nov	Risk Mitigation (2)	
16	4-Dec	Summary, Semester Project Presentations	
	6-Dec	Semester Project Presentations	
	11-Dec	Finals week	Semester Project Papers Due

Figure 4. Function Based Risk Analysis Syllabus

4.1 FMEA

FMEA is an inductive analysis that systematically detains, on a component-by-component bases, all possible failure modes and identifies their resulting effects on the plant [17]. It attempts to improve engineering quality by analyzing each component and associated subassembly in a system to determine its possible failure modes. During an FMEA or FMECA the following process is used to attempt to improve engineering quality [18].

1) List each sub assembly and component number, along with the basic functions or function chains of the component.
2) Identify and list the potential failures for each product component.
3) List possible potential causes or mechanisms of failure modes.
4) List the potential effects of the failure, including impact on the environment, property, or hazards to human users.
5) Rate the likelihood of occurrence of the failure.
6) Estimate the potential severity of the failure and its effect.
7) List current or expected design controls/tests for detecting the failure before the product is released for production.
8) Calculate the risk priority number. A RPN prioritizes the relative importance of each failure mode and effect. It is a multiplicative combination of likelihood, consequence, and deductibility.
9) Develop recommended actions for the failure modes.

The RED results provide the list of functions of the component (1), identify and list the potential failures for the functions (2), rate the likelihood of the failure (5), and estimate the potential severity of the failure (6). Therefore the students are able to focus on completing the FMEA by performing steps 3, 4, 7, 8, and 9. These steps include listing possible potential causes or mechanisms of failure modes (3), listing the potential effects of the failure (4), listing current or expected design controls (7), calculating a risk priority number (8), and developing recommended actions for the failure modes. Also, the students are encouraged to use the RED results as a starting point to either add to the list of forecasted risks or remove those risks that will not apply to their product.

A sample FMEA analysis performed in conjunction with the RED method is presented in Fig. 5 for a mountain bike. Columns 2, 3, 5, and 7 are directly from the RED method results generated for the mountain bike. This information provided a solid foundation to generate a quality FMEA report. The remaining parts of the FMEA after filling in the RED results include the identification of the components of the product, possible effects of the failure, current design controls, and recommended actions. With the RED results as a starting point, most of the students analysis time is spent on understanding the effects of the failure and recommending actions. This helps provide a more well rounded risk identification and mitigation education exercise.

Component	Function(s) of Component	Failure Mode	Effects of Failure	Severity	Potential Cause of Failu	Occurance	Current Design Controls	Detection	RPN	Recommended Actions
Air Inlet Vlave	Export Gas, Import Gas,	Abrasive Wear	Damage to valve, uncontrolled release of air	5	Riding over rough terrain, improper assembly of tire	1	Metal of valve is damaged, rubber is worn	4	20	Thicker rubber and little exposed metal
	Guide Gas	Corrosion Fatigue	Valve sticks or is similarly damaged, potential release of air	5	Exposure to atmosphere, normal operation	1	Metal of valve is worn, pin damaged or destroyed	4	20	Use non-oxydizing metals, covers to protect from atmosphere
		Pitting Corrosion	Damage to valve, uncontrolled release of air	5	Impact of foreign material	2	Valve is visibly damaged, gashes or holes in rubber	7	70	Thicker rubber used than for rest of tire
Gear Shifter	Guide Mechanical Energy	Abrasive Wear	Damage to shifter, potential loss of motion	3	Prolonged normal use	1	Shifter pins appear worn, harder to shift gears	3	9	Wear resistant metals used, lubrication
		Corrosion Fatigue	Damage to shifter, potential loss of motion	3	Exposure to atmosphere, normal operation	1	Shifter pins appear rusted, harder to shift gears	3	9	Use non-oxydizing metals
		Creep	Decreased performance of shifter, inability to use certain gears	4	Prolonged time in one position	1	Dificulty when trying to shift gears	3	12	Use shifter normally to prevent binding
		Galling	Shifter becomes stuck, hard to use	6	Prolonged normal use, Debris	1	Gears do not shift	1	6	Cover to prevent debris from entering
		High Cycle Fatigue	Damage to shifter, potential loss of motion	3	Long life cycle of system	1	Shifter breaks off, or damage to shifter	3	9	Use stronger materials
		Pitting Corrosion	Damage to shifter, potential loss of motion	3	Impact of foreign material	1	Shifter becomes loose or damaged, difficult to shift gears	3	9	Cover to prevent debris from entering
		Seizure	Shifter becomes fused in place, impossible to use	6	Prolonged normal use, Debris	1	Gears do not shift	1	6	Cover to prevent debris from entering
Gears	Change Mechanical Energy	Galling	Gear becomes stuck to chain, bike unusable	7	Exposure to debis, rusting	1	Gear sticks to chain, cannot pedal bike	3	21	Use non-oxidyzing material, cover to protect from debris
		High Cycle Fatigue	Gear teeth or gear fracture, possible inablity to use bike	6	Prolonged normal use	2	Teeth missing from gear, or visible damage to gear	4	48	Use stronger materials
		Seizure	Gear becomes fused to chain, bike unusable	7	Exposure to debris	1	Gear sticks to chain, cannot pedal bike	3	21	Use non-oxidyzing material, cover to protect from debris
Tire Intertube	Change Gas, Store Gas	Corrosion Fatigue	Tire becomes worn, easier to damage; tire bursts	5	Exposure to atmosphere, normal operation	3	Intertube appears old and worn	6	90	Protection from environment, better tire
		High Cycle Fatigue	Tire becomes worn, easier to damage; tire bursts	5	Prolonged normal use, usage in rough terrain increases frequency of cycles	3	Intertube is worn and possibly has holes	6	90	More wear resistant rubber used
	Store Gas	Pitting Corrosion	Tire becomes worn, easier to damage; tire bursts	5	Impact of foreign material	3	Intertube is worn and possibly has holes	6	90	Cover to prevent debris from entering
		Yielding	Tire may become thin in areas; tire bursts	5	Tire is overfilled; extended normal operation	3	Tire cannot be compressed	4	60	Do not overfill

Figure 5. Sample FMEA Analysis: Mountain Bike

4.2 Event Tree Analysis

Event tree analysis is a PRA that begins with an initiating event and uses forward logic to propagate this event through the system [8]. To propagate the event, all the possible ways that it can affect the behavior of the system or subsystem are considered. The nodes of an event tree represent the possible functioning or malfunctioning of a subsystem. Paths through an event tree resulting in accidents are called accident sequences.

Performing an event tree analysis requires more information that the RED results. The initiating events are generated by the customer needs of the product. Next the event is propagated through the functional model. The conditions for the functioning or malfunctioning of each node of the event tree is provided by the RED results. Therefore, the students have an arsenal of resources to use while learning to generate an event tree analysis.

A sample event tree for the mountain bike example is presented in Fig. 6. The event tree analysis begins with the identification of the initiating event. The procedure suggested to the students in selecting the initiating event is to choose a customer need from the list generated to construct the functional model. For this example, the customer need selected for the event is "Stop, slow down smoothly" from Table 1. For the event tree the customer need is reworded to the action "Breaks are applied." Then the students select the functions that are affected by the event and propagate the event through that portion of the functional model. The remaining portion of the event tree generation and calculation follows the standard event tree analysis procedures. Fig. 6 demonstrates the role that the function based risk assessment approach plays in providing a starting point for the event tree analysis.

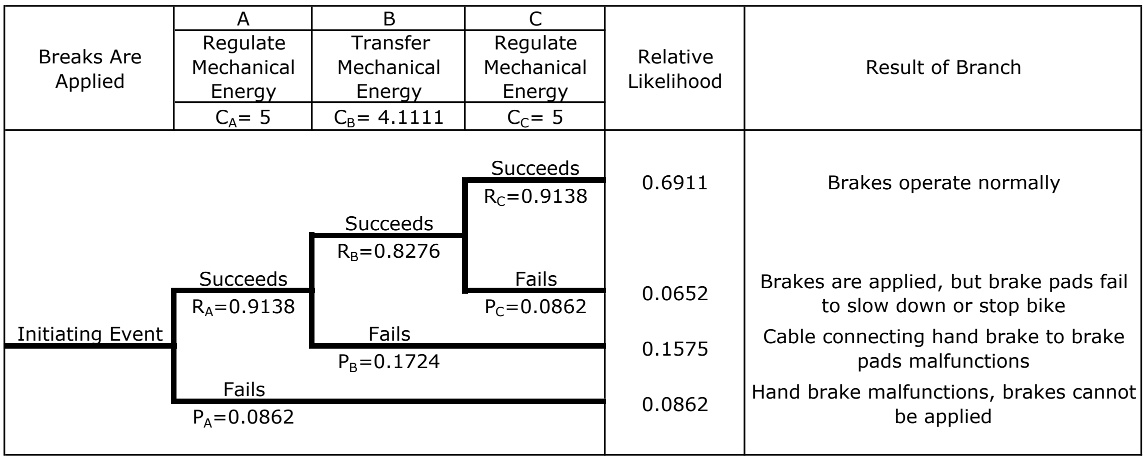


Figure 6. Sample Event Tree: Mountain Bike

4.3 *Fault Tree Analysis*

Fault tree analysis is the final type of PRA taught in the function based risk analysis course. It begins with a particular failure, the top event, and seeks component failures that contribute to the system failure through backward logic. The aim of the fault tree analysis is to develop deterministic descriptions of events interims of the occurrence or non-occurrence of intermediate events [19].

Again, the customer needs are used to generate the "top event" failure. However, unlike the event tree, in the fault tree, the "top event" is the failure to meet the customer need. The functional model is then used to identify the subsystems that are associated with the top event. The association is derived from flow linkages in the functional model. When combined with the RED results for ideas of functions that can fail and their effect on the system, the faults are propagated through the system backwards to identify their root cause. The procedure of identifying how a seemingly minor fault can propagate through a system resulting in a failure provides valuable insight to the aspiring engineers.

A fault tree analysis stemming from the function based risk assessment techniques was performed on the mountain bike, as shown in Fig. 7. The customer need selected for the top event was "Can control direction" from the list of customer needs in Table 1. Following the procedure for the function based fault tree, the top even then becomes, "Lose control of bike", i.e. the failure is the lack of meeting the customer need. From there the flows associated with the customer need recalled from Table 1, mechanical energy and control (direction). Following the flows through the functional model the related bike subsystems were identified as wheels, brakes, and steering. Those subsystems are written as failures on the next branch of the fault tree. The procedure is repeated through the system until the low level failures are identified. Some of them from Fig. 7 include “Gear broken” and “Gear rusted”. These low level faults were generated by the RED results. The “Gear broken” fault corresponds to the RED risk statement “Change mechanical energy fails due to high cycle fatigue”; and, the “Gear rusted” fault corresponds to the RED risk statement “Guide mechanical energy fails due to corrosion fatigue.” Thus it is clear that the difficult process of inexperienced students identifying system failures, propagating those failures through a system, and identifying root cause faults is aided by using the function based risk analysis techniques.

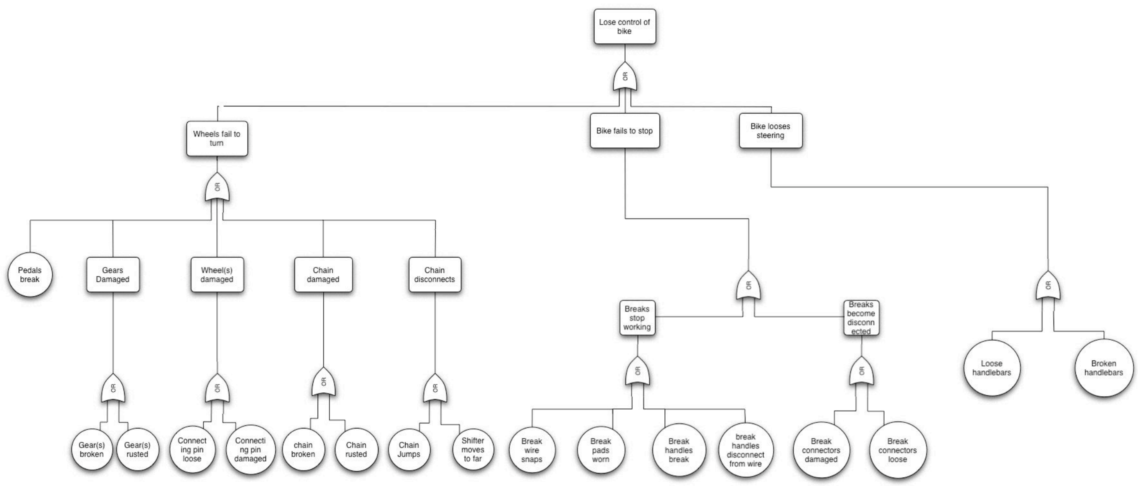


Figure 7. Sample Fault Tree: Mountain Bike

5 Conclusions

By initiating the Function-Based Risk Analysis course with the RED method and prescribing active experimentation on a product set that has experienced real world failure, students see how to leverage those results to perform high quality PRA analyses of products. Moreover, the failure results from the CPSC website provide the students with a mechanism to learn how to create a RED failure database. Besides the ongoing project of analyzing three consumer products throughout the semester, the students are also required to complete an end of the semester research project that incorporates the risk assessment techniques presented in the course into their current graduate research projects.

After two semesters of teaching this new course, it is our conclusion that integrating new, knowledge-based techniques like RED can enrich the learning experience of courses covering PRA topics. In the context of this graduate level course implementation, RED provides the students with a list of historically significant potential failures relative to the product under investigation. The list of potential risks enables students to perform more advanced risk analysis techniques that they will encounter in industry such as FMEA, ETA, and FTA. The use of actual failure cases, such as the Consumer Products Safety Commission (CPSC) recall list, gives the course topics a relevance that other typical PRA examples may lack. The semester project of creating a database of CPSC product failures increases the students' knowledge of failure cases and the associated components and environment involved.

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Appendix
Figure 8. Sample RED Risk Results: Mountain Bike

Risk Statement	Consequence	Likelihood
Guide Mechanical Energy fails due to High Cycle Fatigue	(5	2)
Import Gas fails due to High Cycle Fatigue	(5	2)
Guide Gas fails due to High Cycle Fatigue	(5	2)
Export Gas fails due to High Cycle Fatigue	(5	2)
Change Mechanical Energy fails due to Galling	(5	1)
Change Mechanical Energy fails due to Seizure	(5	1)
Guide Mechanical Energy fails due to Galling	(5	1)
Guide Mechanical Energy fails due to Seizure	(5	1)
Import Gas fails due to Corrosion Fatigue	(5	1)
Guide Gas fails due to Corrosion Fatigue	(5	1)
Store Gas fails due to High Cycle Fatigue	(5	1)
Change Gas fails due to High Cycle Fatigue	(5	1)
Export Gas fails due to Corrosion Fatigue	(5	1)
Change Mechanical Energy fails due to Electrostatic Discharge	(4	1)
Change Mechanical Energy fails due to High Cycle Fatigue	(4	1)
Change Mechanical Energy fails due to Thermal Shock	(4	1)
Guide Mechanical Energy fails due to Corrosion Fatigue	(4	1)
Guide Mechanical Energy fails due to Creep	(4	1)
Guide Mechanical Energy fails due to Electrical Overstress	(4	1)
Guide Mechanical Energy fails due to Electrostatic Discharge	(4	1)
Guide Mechanical Energy fails due to Thermal Shock	(4	1)
Guide Mechanical Energy fails due to Undercurrent	(4	1)
Guide Mechanical Energy fails due to Yielding	(4	1)
Import Gas fails due to Electrical Overstress	(4	1)
Import Gas fails due to Undercurrent	(4	1)
Import Gas fails due to Yielding	(4	1)
Guide Gas fails due to Electrical Overstress	(4	1)
Guide Gas fails due to Undercurrent	(4	1)
Guide Gas fails due to Yielding	(4	1)
Store Gas fails due to Corrosion Fatigue	(4	1)
Store Gas fails due to Electrical Overstress	(4	1)
Store Gas fails due to Undercurrent	(4	1)
Store Gas fails due to Yielding	(4	1)
Change Gas fails due to Corrosion Fatigue	(4	1)
Export Gas fails due to Electrical Overstress	(4	1)
Export Gas fails due to Intergranular Corrosion	(4	1)
Export Gas fails due to Undercurrent	(4	1)
Export Gas fails due to Yielding	(4	1)
Guide Mechanical Energy fails due to Abrasive Wear	(3	1)
Guide Mechanical Energy fails due to Cavitation Erosion	(3	1)
Guide Mechanical Energy fails due to Erosion Corrosion	(3	1)
Guide Mechanical Energy fails due to Intergranular Corrosion	(3	1)
Guide Mechanical Energy fails due to Pitting Corrosion	(3	1)
Import Gas fails due to Abrasive Wear	(3	1)
Import Gas fails due to Buckling	(3	1)
Import Gas fails due to Cavitation Erosion	(3	1)
Import Gas fails due to Erosion Corrosion	(3	1)
Import Gas fails due to Intergranular Corrosion	(3	1)
Import Gas fails due to Pitting Corrosion	(3	1)
Import Gas fails due to Thermal Shock	(3	1)
Guide Gas fails due to Abrasive Wear	(3	1)
Guide Gas fails due to Buckling	(3	1)
Guide Gas fails due to Cavitation Erosion	(3	1)
Guide Gas fails due to Erosion Corrosion	(3	1)
Guide Gas fails due to Intergranular Corrosion	(3	1)
Guide Gas fails due to Pitting Corrosion	(3	1)
Guide Gas fails due to Thermal Shock	(3	1)
Store Gas fails due to Buckling	(3	1)
Store Gas fails due to Cavitation Erosion	(3	1)
Store Gas fails due to Intergranular Corrosion	(3	1)
Store Gas fails due to Pitting Corrosion	(3	1)
Change Gas fails due to Buckling	(3	1)
Change Gas fails due to Cavitation Erosion	(3	1)
Export Gas fails due to Abrasive Wear	(3	1)
Export Gas fails due to Buckling	(3	1)
Export Gas fails due to Cavitation Erosion	(3	1)
Export Gas fails due to Erosion Corrosion	(3	1)
Export Gas fails due to Pitting Corrosion	(3	1)
Export Gas fails due to Thermal Shock	(3	1)