Fall 2010

A hybrid problem-based and just-in-time inductive teaching method for failure analysis instruction

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Recommended Citation

Arlitt, Ryan Michael, "A hybrid problem-based and just-in-time inductive teaching method for failure analysis instruction" (2010). *Masters Theses*. 4457.
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A HYBRID PROBLEM-BASED AND JUST-IN-TIME INDUCTIVE TEACHING METHOD FOR FAILURE ANALYSIS INSTRUCTION

by

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A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

2010

Approved by

Katie Grantham, Advisor
Abhijit Gosavi
Susan Murray

PUBLICATION THESIS OPTION

This thesis consists of the following two articles that will be submitted for publication as follows:

Pages 1-26 are intended for submission to the AMERICAN SOCIETY FOR ENGINEERING EDUCATION CONFERENCE.

Pages 27-62 are intended for submission to the INTERNATIONAL JOURNAL OF ENGINEERING EDUCATION.

ABSTRACT

When engineers retire, they take their expert knowledge with them. Preservation of this expert knowledge in a usable form is beneficial for the advancement of any engineering field. Risk in Early Design (RED) is one method for preserving expert risk analysis knowledge. The first purpose of this paper is to examine the usability of RED when incorporated with a hybrid problem-based and just-in-time inductive teaching method for failure analysis instruction. The second purpose of this paper is to propose and perform steps toward verification and validation of the RED methodology and implementation. Evaluation metrics were developed, and several of these evaluation metrics were gathered in a case study. This case study was performed in a sophomore level lab class at the Missouri University of Science and Technology in the fall of 2010. The lab was designed to assist in teaching mechanics of materials, and was composed of approximately 200 students. Lab questions and a questionnaire were used to determine the students' ability to assess and mitigate risk both with and without this teaching method. The questionnaire was also used to prioritize and uncover usability issues with RED, and initial improvements were made to the RED application based on this feedback. While students were unlikely to produce an accurate failure mode assessment with or without the teaching method, results showed that students were using RED to aid their failure assessments.

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Katie Grantham, for making this research possible and for providing help and guidance.

I would also like to thank my committee members, Dr. Susan Murray and Dr. Abhijit Gosavi for serving on my thesis committee.

I would like to offer thanks to those who participated in this research, without whom I would have had very little to write about. This includes the mechanics of materials lab students and instructors at Missouri S&T for their participation in the case study, Joshua Bohde for his work on RED application, and Dr. Jeff Thomas for all of his help and input on the case study.

Still more thanks belong to Dr. Grantham's lab group for their support and input; specifically Dan Krus for his helpful input, and Kristen Balinksi for offering comments and proofreading.

Finally, I would like to thank my friends and family for their support.

TABLE OF CONTENTS

PAPER

LIST OF ILLUSTRATIONS

Figure Page

PAPER I

PAPER II

LIST OF TABLES

Table Page

PAPER I

PAPER II

PAPER

I. EVALUATION OF RISK IN EARLY DESIGN'S USABILITY IN FAILURE ANALYSIS INSTRUCTION

ABSTRACT

When engineers retire, they take their expert knowledge with them. Preservation of this expert knowledge in a usable form is beneficial for the advancement of any engineering field. Risk in Early Design (RED) is one method for preserving expert risk analysis knowledge. The purpose of this paper is to examine the usability of RED when incorporated with a hybrid problem-based and just-in-time inductive teaching method for failure analysis instruction. This test was conducted in a sophomore level lab class at the Missouri University of Science and Technology in the fall of 2010. The lab was designed to assist in teaching mechanics of materials, and was composed of approximately 200 students. A questionnaire was used to determine the usability and perception of RED. Initial improvements to the interface were made based upon feedback from the questionnaire.

1. INTRODUCTION

The goal of this research project is to test usability of the Risk in Early Design (RED) application when used as an expert knowledge source for tasks previously thought to require engineering experience. As technology progresses, it is critical that educational efforts focus on preparing students to build on the new developments, rather than continuously teaching them to "reinvent the wheel." The teaching of new technology is not limited to the integration of novel hardware and software into the engineering curriculum. It is also important to teach the next generation of engineers decision-making skills that build upon the current level of expertise in the workforce. Therefore, it is imperative that new technology also be used to prepare the engineers of tomorrow to analyze and understand engineering systems by conveying the knowledge associated with years of corporate experience during their undergraduate studies.

The teaching strategy presented in this paper is a hybrid problem-based and just-in-time inductive teaching method. The cornerstone for the method is the existence of a knowledgebase of "engineering experience." In this case, the Risk in Early Design (RED) knowledgebase was developed as part of a risk assessment project that leveraged historical failure data in electromechanical systems to predict and prevent such failures in the design of new electromechanical systems [1]. Student satisfaction with RED's usability was measured in a case study designed to leverage RED as a teaching tool. This evaluation took place in the 2010 fall semester at the Missouri University of Science and Technology (Missouri S&T).

2. SCOPE

The National Academy of Forensic Engineers (NAFE) [2] defines forensic engineering as “the application of the art and science of engineering in matters which are in, or may possibly relate to, the jurisprudence system, inclusive of alternative dispute resolution.” NAFE also asserts that “the practice of licensed Professional Engineers as Forensic Engineers is important for the protection of the public health, safety and welfare.” Preliminary interviews of engineering firms have demonstrated the need for safety engineers in industry. Currently, there is only one forensic engineering program at the graduate level [3]; none exist at the bachelor’s degree level [4]. Statistics compiled by the American Society for Engineering Education (ASEE) for the 2005-06 academic year indicate that engineering graduation and enrollment rates at U.S. universities are not reflecting the country’s increasing demand for engineering talent [5]. One reason for the gap may be that the traditional rigid engineering curriculum has not adapted to the diverse needs of a quickly changing technological world, such as the advances in the forensic engineering profession.

This paper presents research that was conducted to investigate the use of knowledgebase guided teaching strategies to enable courses with “engineering experience” as a prerequisite to be taught at the undergraduate level. This research will contribute to the formation of an undergraduate forensic engineering program that will leverage the industrial need and media popularity of forensics. This paper’s contribution to the creation of a forensics program is in the formation and verification of reverse failure analysis coursework through improvements to the RED application.

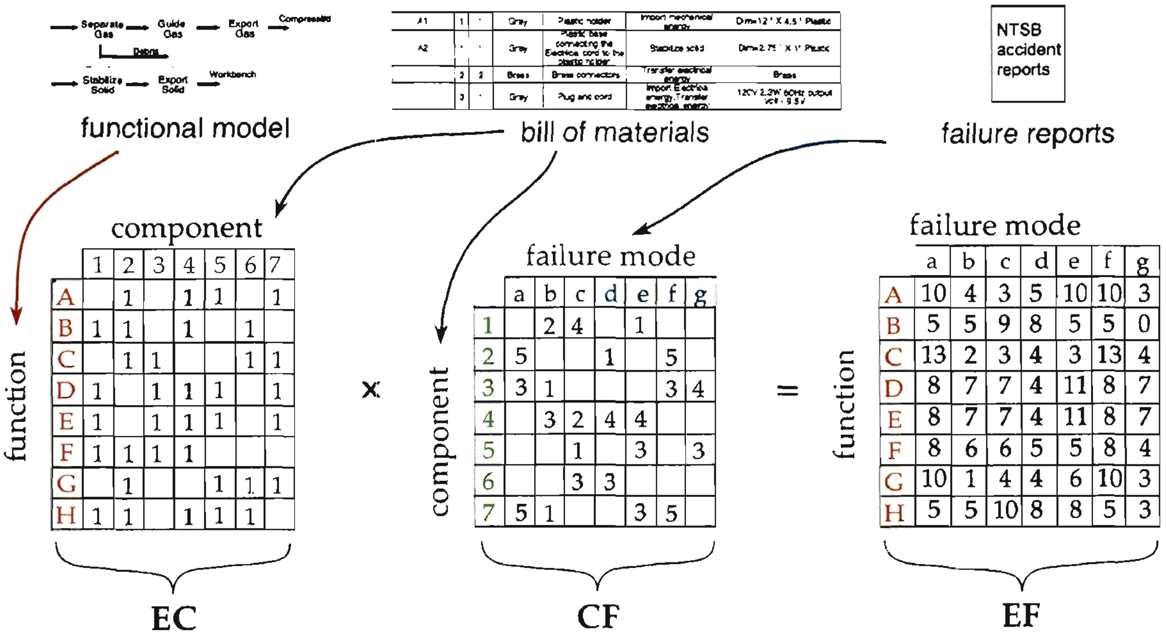
3. RISK IN EARLY DESIGN (RED)

Risk in Early Design (RED) is a probabilistic risk assessment method that leverages historical failure data to provide failure data based upon the functions that a system must perform. This is accomplished using a series of matrices that contain historical data on component function and failures, along with an algorithm that presents failure modes, likelihoods, and severities for user selected functions. RED uses simple heuristics and mathematics to communicate cataloged historical product-specific risks as early as the conceptual design phase. Given the functions of a design, RED outputs potential risks based on historical failure data [6].

3.1 RED DATABASE POPULATION

The RED database draws information from three sources in order to store failure information: functional models, bills of materials, and failure reports. Failure reports provide documented cases of system failures, cataloged using a failure mode taxonomy [7] in order to standardize the terminology used in the database. Bills of materials provide components found in those systems. The components are cataloged using a component basis [8]. Functional models, consisting of material, energy, and signal flows connecting function blocks, provide the functionality of the failed systems. Similarly to the other two elements used in RED database population, functional models follow a functional basis terminology. The functional basis terminology standardizes the language to describe product function, leading to meaningful and repeatable function representations [9].

Functions and components are drawn from these sources to populate the function-component (EC) matrix. This matrix shows which components have historically accomplished which functions, using a 1 to denote a relationship and a 0 to denote no relationship. For example, function "A" in the EC matrix Figure 3.1 has been accomplished by components 2, 4, 5, and 7. The component-failure (CF) matrix shows how often each component has failed by each failure mode. In the CF matrix shown in Figure 3.1, component 1 has failed by failure mode "b" twice, failure mode "c" four times, and failure mode "e" once. The EC and CF matrices are multiplied to produce the function-failure (EF) matrix, which shows how often each function has failed by each failure mode. For example, function "A" in the EF matrix in Figure 3.1 has failed by failure mode "a" ten times. The teaching strategy presented in this research uses an existing RED database of electromechanical failures to support RED operations.



EC (rows: function; columns: component)

	1	2	3	4	5	6	7
A		1		1	1		1
B	1	1		1		1	
C		1	1			1	1
D	1		1	1	1		1
E	1		1	1	1		1
F	1	1	1	1			
G		1			1	1	1
H	1	1		1	1	1	

CF (rows: component; columns: failure mode)

	a	b	c	d	e	f	g
1		2	4		1		
2	5			1		5	
3	3	1				3	4
4		3	2	4	4		
5			1		3		3
6			3	3			
7	5	1			3	5	

EF (rows: function; columns: failure mode)

	a	b	c	d	e	f	g
A	10	4	3	5	10	10	3
B	5	5	9	8	5	5	0
C	13	2	3	4	3	13	4
D	8	7	7	4	11	8	7
E	8	7	7	4	11	8	7
F	8	6	6	5	5	8	4
G	10	1	4	4	6	10	3
H	5	5	10	8	8	5	3

Figure 3.1. RED Database Population Sources and Matrices

3.2 RED RISK ANALYSIS PROCESS

The results from prior work [10] on developing the RED method have yielded a process for identifying and assessing risk during the conceptual design phase. This risk identification method was tested in the Missouri S&T mechanics of materials lab to determine if it can successfully provide "engineering experience" from which the students can draw on to initiate their failure investigations and classifications. The steps for using RED to guide a failure analysis investigation, shown in Figure 3.2, are: (1) generate the functional model of the failed part, (2) select the relevant functions from the historical failure database, and (3) perform risk calculations. The results displayed on the fever chart and the related risk report present students with a ranking of failures that occurred in similar components. In the example in Figure 3.2, the fever chart shows the number of failures that have occurred in the database for the selected functions at each likelihood and consequence pair. Here, five risks have occurred at a consequence of one and a likelihood of two, one risk has occurred at a consequence of four and a likelihood of one, and two risks have occurred at a consequence of three and a likelihood of four. The students used type of information to guide their investigations.

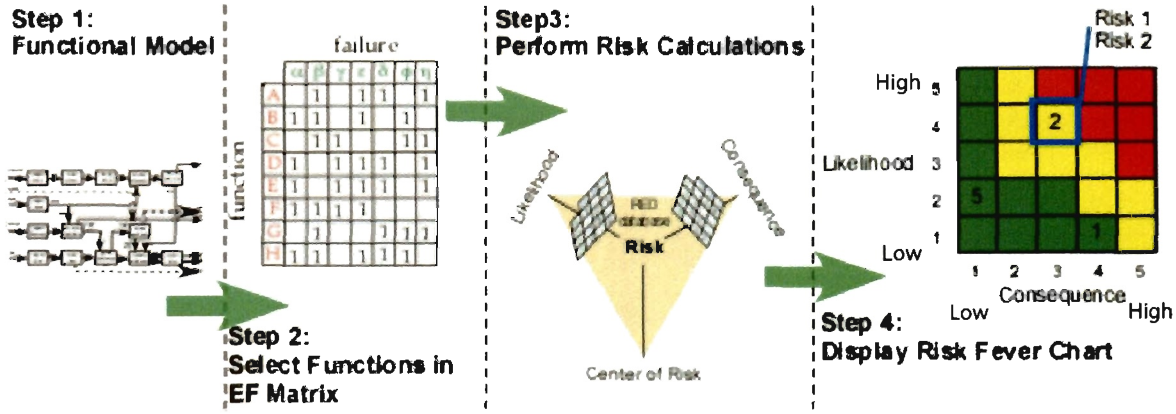


Figure 3.2. RED Process for Failure Investigation Guidance

4. RED AS A TEACHING AID

4.1 TEACHING STRATEGY

The problem-based teaching method, as its name implies, confronts students with a poorly defined, real world problem. Students work in teams to identify learning needs and develop solutions to the problem [11]. Problem-based learning has been shown to positively affect knowledge retention and skill development [12].

Just-in-time teaching typically consists of web-based preliminary exercises that the instructor uses to adjust lessons just before class based on student responses. Online enrichment pages and stand-alone instructional material support the in-class lesson. Just-in-time teaching promotes increased study outside of class and increased student-instructor interaction during class [13]. Just-in-time teaching has been assessed in physics instruction using the Force Concept Inventory, and has shown normalized student gains between 35% and 40% [11].

Both problem-based and just-in-time teaching are inductive teaching methods highlighted by Prince and Felder [11]. The authors describe inductive teaching as any teaching method that presents students with specific information that creates a need for more general facts or principles. Often this is accomplished by tasking the students with interpreting some specific data that requires these more general principles. This is highlighted as directly opposing the traditionally used deductive teaching, in which instructors present general principles and then show examples to reinforce them. The authors state that people are most strongly motivated to learn when they perceive a need to know, and that inductive teaching and learning are preferable methods of achieving this effect.

The teaching method applied in the experiment utilizes failed components, such as a bolt from a bridge, as an enabler for problem-based teaching. The students are presented with the problem of determining how the component failed, creating a need to know more general principles about failure analysis. The information that the students gain from RED is obtained just-in-time to help them analyze these failed components. In this sense, this teaching method does not conform with traditional just-in-time teaching. Whereas traditional just-in-time teaching relies on the instructor to adjust the learning material based on preliminary student feedback, in this case guidance in learning these more general failure analysis principles is provided by RED. Upon completing the lab, students should have learned general failure analysis principles based on their experiences with the specific component analyzed.

Additionally, the mechanics of materials lab course where this method was tested currently utilizes enrichment materials on its website in the form of related information that shows the materials' real-world relevance.

4.2 RED AND FAILURE ANALYSIS INSTRUCTION

For an example of how RED would typically be used, consider the situation of students in a problem-based learning exercise who were presented with a failed shaft and tasked with identifying the failure mode. Having extremely limited "engineering experience" from which to initiate their investigation, the students would use the RED method. First, the students would identify the functions of the shaft, and produce a functional model similar to the one found in Figure 4.1.

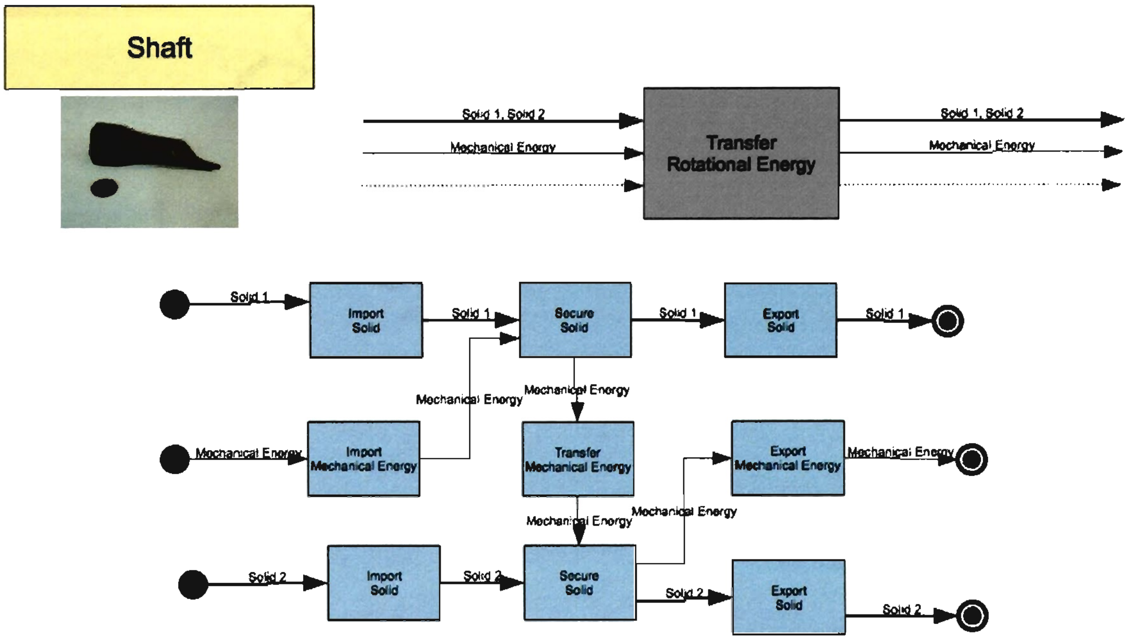


Figure 4.1. Shaft Functional Model

Next the students would enter its functions into the RED software. Sample output of the software is shown in Table 4.1. The results show that the functions transfer mechanical energy, secure solid, export mechanical energy, and import mechanical energy are most at risk of failure due to high cycle fatigue. Continuing down the report toward functions with lower severity, the solid and mechanical energy flows are also at risk due to brittle fracture and stress corrosion. These results indicate that the first course of action taken by the students would be to determine if the physical characteristics of the failed part and failure environment match with the most common type of failures provided. Continuing with this example, if the shaft experienced a significant amount of cycles and there was a physical break in the component, then the students could focus their analysis on determining if the failure was caused by high cycle fatigue. If it does not meet the criteria for high cycle fatigue, students would move down to brittle fracture and then stress corrosion. In this case, the shaft failed by brittle fracture. This teaching strategy will be assessed, and if found successful will promote more use of similar concepts to be incorporated into undergraduate curricula.

Table 4.1. Truncated RED Results for Shaft

Severity	Function	Failure Mode	Likelihood	Consequence
High	Transfer Mechanical Energy	High Cycle Fatigue	5	5
High	Secure Solid	High Cycle Fatigue	5	5
High	Export Mechanical Energy	High Cycle Fatigue	5	5
High	Import Mechanical Energy	High Cycle Fatigue	5	5
High	Export Solid	High Cycle Fatigue	4	5
High	Import Solid	High Cycle Fatigue	4	5
High	Transfer Mechanical Energy	Brittle Fracture	3	5
High	Secure Solid	Brittle Fracture	3	5
Med	Export Solid	Stress Corrosion	3	4
Med	Export Mechanical Energy	Stress Corrosion	3	4

In the context of this research, RED is presented to students as a black box. Students were provided with a functional model of their failed component, such as the one in Figure 4.1, thus removing the need for the students to be familiar with functional modeling to perform the exercise. This allowed a greater sample size of students who were able to generate RED output of potential failure modes of a failed component. Prior to performing the experiment, functional models were generated for all of the components that would be used in the lab.

5. EXPERIMENTAL DESIGN

The Missouri S&T IDE120 lab is designed to assist in teaching mechanics of materials, in which students learn about topics such as material properties, strain testing, and testing machines [14]. Students gain hands-on experience in the lab to reinforce learning of lecture topics.

In the IDE 120 Failure and Fully Plastic Action Lab, students "look at the definition of failure, failure theories, and real-life examples of failed components." Additionally, students "investigate failed components, estimate what caused the failure, and propose a remedy" [15]. These aspects of the lab make it a good fit for testing RED as a teaching method.

Evaluation of RED's usability was performed as part of a larger experiment within the Failure and Fully Plastic Action Lab found at http://classes.mst.edu/ide120/lessons/failure/index.html in the Missouri S&T mechanics of materials lab class. The experiment was designed to fit within the existing structure of the class. At the beginning of the semester, students in each section formed groups of their own choosing. These groups were typically three to four students in size. The ten lab sections were divided into an experimental group and a control group. Three sections met on Monday, three on Tuesday, two on Wednesday, and two on Thursday. The Tuesday and Thursday sections were selected as the experimental group, because one of the instructors in three of those five sections had experience with RED. This was done to mitigate the risk of any unforeseen issues with the RED deployment that might prevent students from using it. The experimental group contained a total of 101 students divided into 34 groups, and the control group contained a total of 96 students divided into 33 groups. The experimental group used the RED tool in addition to performing the lab, and the control group performed the lab without the tool.

Prior to performing the lab, each group selected a failed component to analyze from the pool of 17 available components. The students were each issued a failure mode taxonomy handout and a preliminary assessment form requesting that the student determine the failure mode of the selected failed component. The failure mode taxonomy provides the failure modes, along with a "primary identifier" and a definition of the failure mode, in order to aid failure mode identification. The primary identifier is the highest level of classification in the failure mode taxonomy, and helps to narrow one's focus to the appropriate failure mode. For instance, the primary identifier "Corrosion (Material deterioration due to chemical or electrochemical interaction with the environment)" contains twelve corrosion failure modes [7].

After completing preliminary assessments, students performed the lab. Lab activities included detailed observations of the failed component. Outside of class, the students in the experimental group ran a RED analysis on their failed item and saved the risk report to aid them in answering lab questions. These students were required to submit the risk report with their lab report to ensure that they performed the RED analysis.

All students answered questions regarding the failure and its prevention using a post-lab failure assessment form. Post-lab assessments, lab reports, and a questionnaire regarding RED were gathered digitally using an online tool. For this study, student perception of RED's usefulness and usability were gathered from the experimental group using a questionnaire.

6. RESULTS AND DISCUSSION

A survey was designed to measure the usability of the RED tool implementation, student perception of their own performance in the case study, and the usefulness of RED in the case study. The survey consisted of 13 questions on a Likert scale and two open-ended questions. The survey was deployed through the Blackboard web-based course management system after students completed the lab. Blackboard's capabilities include allowing students to download and turn in assignments and surveys online. Students were incentivized to complete the survey with bonus points, and there were 80 respondents out of a possible 101 in the experimental group.

Questionnaires were selected because they can be used to collect a large amount of data using few resources. Questions pertaining to the system's usability included questions targeted to specific areas of usability as well as open ended questions designed to uncover problems that may have been missed by tool evaluators. Questions dealing with specific areas of usability were framed after a set of Likert scale and open-ended questions designed to assess the usability of a software system, provided by Dix et al. [16]. Six of the Likert scale questions asked students to rank their level of agreement with how well the RED application addressed specific areas of usability, such as feedback, ease of navigation, and ease of access. These usability questions are seen below.

Please answer the following questions based on the following ratings:
1 - I strongly disagree
2 - I disagree
3 - I neither agree nor disagree
4 - I agree
5- I strongly agree

1. The RED application tells me what to do at each step in the risk identification process.
   1 2 3 4 5

2. It is easy to recover from mistakes I make while using the RED application.
   1 2 3 4 5

3. It is easy to get help within the RED application when needed.
   1 2 3 4 5
4. The RED application always gives me feedback to tell me what it is doing.
   1 2 3 4 5
5. It is easy to navigate through the RED application.
   1 2 3 4 5
6. The RED application was easy to access.
   1 2 3 4 5

Open-Ended Questions

1. What did you dislike about the RED application? Please suggest improvements.
2. What did you like about the RED application?

By comparing these responses for each of these usability aspects, a prioritization for addressing each was obtained. The open-ended questions asked students for likes and dislikes about the RED application, in order to uncover unanticipated problems with the usability and with RED in general. Table 7.1 shows the means of those responses, ranked from highest to lowest level of agreement. The ranking in this table provides a guide as to which aspects of the RED software possess the lowest degree of usability. Usability aspects that received lower mean scores may reflect lower levels of satisfaction with that aspect of the usability. Based on these mean scores for each response, the survey suggests the following order of importance for usability improvements: provide feedback, provide help and guidance within the application, improve navigation, improve error recovery, and improve accessibility.

Table 6.1. RED Usability Survey Results

Rank	**Question**	**Mode**	**Mean**	**Standard Deviation**
1.	The RED application was easy to access.	4	3.513	0.693
2.	It is easy to recover from mistakes I make while using the RED application.	4	3.481	0.686
3.	It is easy to navigate through the RED application.	4	3.338	0.579
4.	The RED application tells me what to do at each step in the risk identification process.	4	3.225	0.677
5.	It is easy to get help within the RED application when needed.	3	3.138	0.605
6.	The RED application always gives me feedback to tell me what it is doing.	3	3.013	0.976

The remaining questions were designed to assess the student perception of RED's helpfulness and their own performance in the exercise. The responses to these questions are summarized in Table 6.2, and provide a baseline for comparison when improvements are made to the instruction technique used in the case study. Responses to these questions indicate that students were confident in their assessments, while confidence in RED's ability to aid in failure assessment was less pronounced. After improvements are made to this teaching strategy in a future semester, this survey will be administered again to determine whether the improvements were successful.

Table 6.2. Student Perception of Failure Analysis and RED

Question	Mode	Mean	Standard Deviation
I correctly identified the conditions leading to the item's failure.	4	3.850	0.872
I correctly identified the item's failure mode.	4	3.850	1.240
I created an effective plan to prevent the failure from happening in the future.	4	3.738	1.160
I enjoyed the lab.	4	3.675	0.939
The RED application helped me to identify the conditions leading to the item's failure.	4	3.325	0.698
The RED application helped me to determine the item's failure mode.	4	3.263	0.893
The RED application helped me determine how to prevent the same failure in the future.	3	3.038	0.788

Two open-ended questions regarding the students' likes and dislikes about RED were asked in order to identify unanticipated usability problems that were not otherwise addressed by the survey. Responses to those questions were clustered into categories with responses having similar themes. After those categories were formed, they were named based on the theme associated with the cluster. Students who took the survey but did not respond to the open-ended question were placed in the "No Response" cluster. Multi-part responses that fit into multiple categories were counted once in each of those categories. For example, consider the following response to the question about dislikes:

> "The data received is slightly difficult to sift through. Possibly organize the data in a manner that will ease in finding what exactly one is looking for. Make selecting multiple functions easier to do."

This response contains two themes. First, the student indicates that they had difficulty using the RED report. Second, the student indicates difficulty with the user interface. This response was split into two responses and placed into groups with similar responses. When all clusters were formed, these two clusters were named "Report Clarity" and "Interface Clarity" respectively.

Student "likes," seen in Figure 6.1, clustered around three main categories. In order of frequency, students commonly liked RED's ease of use, thought it was useful in the exercise, and liked the large amount of information provided. In general, students felt that the instructions and procedures involved in producing the RED output were easy to understand. Additionally, many students indicated that RED was useful in determining the failure mode of the component. Similarly, students liked the large quantity of information provided by the application.

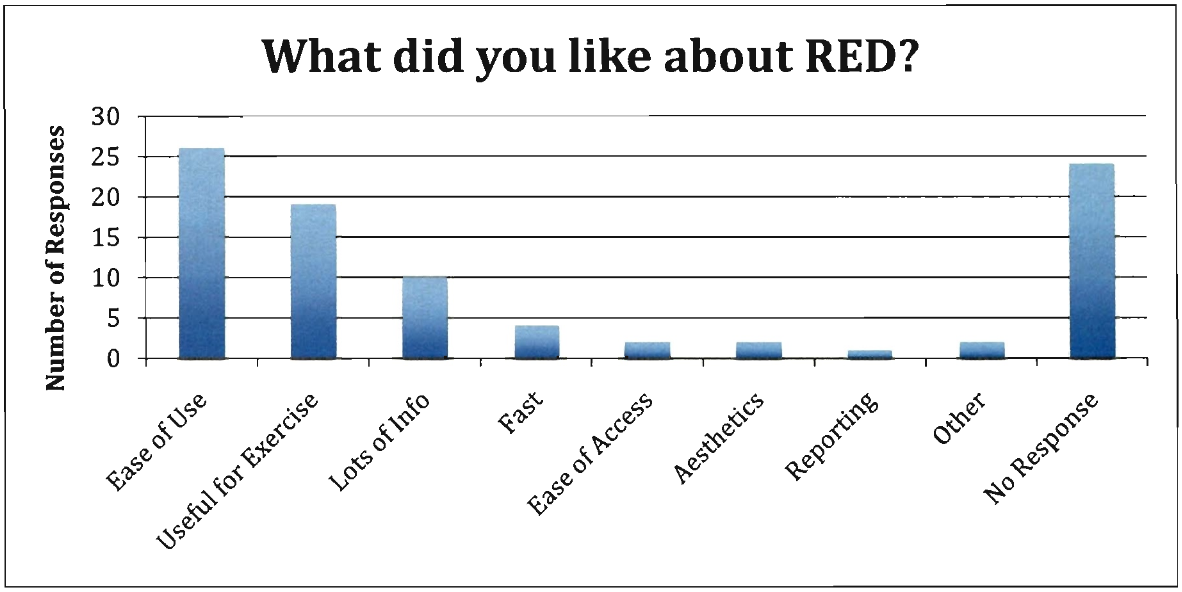


Figure 6.1. Perceived Positive RED Attributes

Student "dislikes," seen in Figure 6.2, also clustered around three main categories. Interface clarity, meaning the student had issues with performing the desired tasks due to the human interface, was mentioned the most. Report clarity, meaning that students had issues understanding the risk report, was also mentioned frequently. The report clarity cluster included difficulties choosing the correct type of report to download, difficulties formatting that report into a readable one, and difficulties interpreting what the results meant. A significant group of students also stated that RED was not useful in determining the failure mode of their failed component. This could be attributed to difficulties interpreting the report or student confidence in their initial answer. Several students also mentioned having access difficulties and problems understanding the functional model.

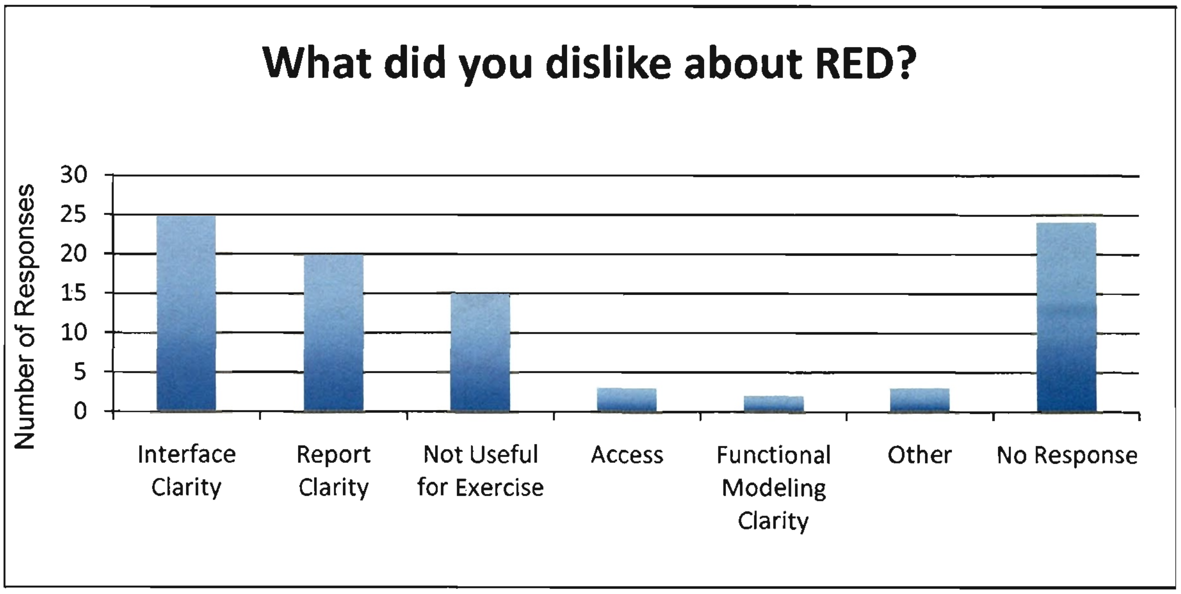


Figure 6.2. Perceived Negative RED Attributes

The disparity between having a high ease of use and poor interface clarity might be explained by the tutorial provided with the RED application. While students felt that RED was easy to use, it was likely due to the step-by-step instructions provided in the tutorial. The disparity between students who thought that RED was useful and those who did not could be explained by a perception that RED report interpretation does not require a human-in-the-loop. In order to be useful in this context, RED needs a human to select a failure mode that fits the specific case.

Based on the survey data, several improvements were identified that can increase the usability of the RED tool. A map graphic of where the user is in the RED process, accompanied by instructions and provided on every page of the application, should prevent users from getting lost or stuck by providing feedback and navigation assistance.

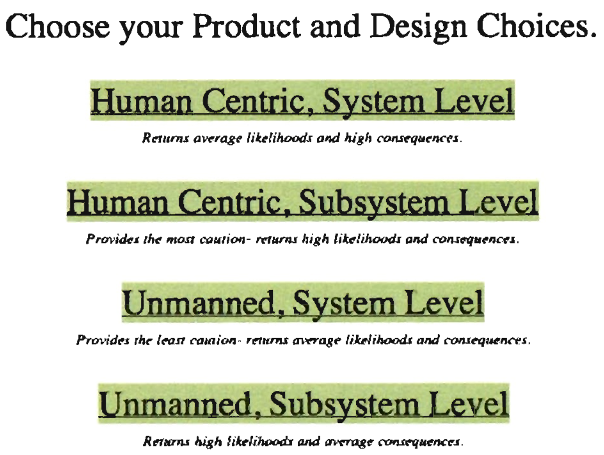
A welcome page with a basic overview and instructions on how to use the application, as well as an easily accessible link to the RED tutorial, should improve the amount of help and guidance available. Retaining function selection after the user submits would allow the user to make changes more easily if a mistake is identified, improving error recovery. Finally, students identified the function selection interface as difficult to use. Changing the scroll box to a different interface would reduce the time required to search for and double check function selections.

7. INTERFACE IMPROVEMENTS

Several improvements, which address some of the usability issues uncovered in the case study, have been made to the RED interface. These improvements are still in progress, but for now include clarifications to the heuristic selections and a greatly improved function selection interface.

7.1 HEURISTIC CLARIFICATION

A lack of instructions within the RED application was identified as one area for improvement. As a step toward providing better guidance, clarifications have been added to the heuristic selection step of the RED process as seen in Figure 7.1. This will indicate to the user the reason for making this selection as well as giving a better understanding of how their choices will affect the risk calculations.



Choose your Product and Design Choices.

Human Centric, System Level

Returns average likelihoods and high consequences.

Human Centric, Subsystem Level

Provides the most caution- returns high likelihoods and consequences.

Unmanned, System Level

Provides the least caution- returns average likelihoods and consequences.

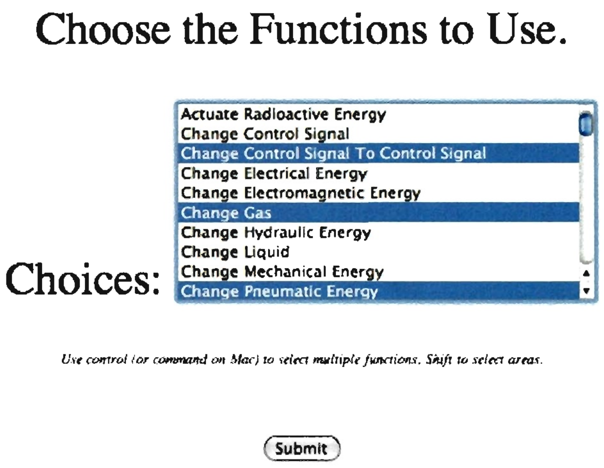
Unmanned, Subsystem Level

Returns high likelihoods and average consequences.

Figure 7.1. Heuristic Clarifications

7.2 FUNCTION SELECTION INTERFACE

Figure 7.2 depicts the function selection interface tested in the case study. This interface requires users to scroll through a list of every function that appears in the RED database and individually select functions relevant to the user's system. Survey responses revealed user issues verifying that all of the desired functions were selected. Users also experienced difficulty determining if their desired function appeared in the RED database. A new interface was developed that addresses these issues.



Choose the Functions to Use.

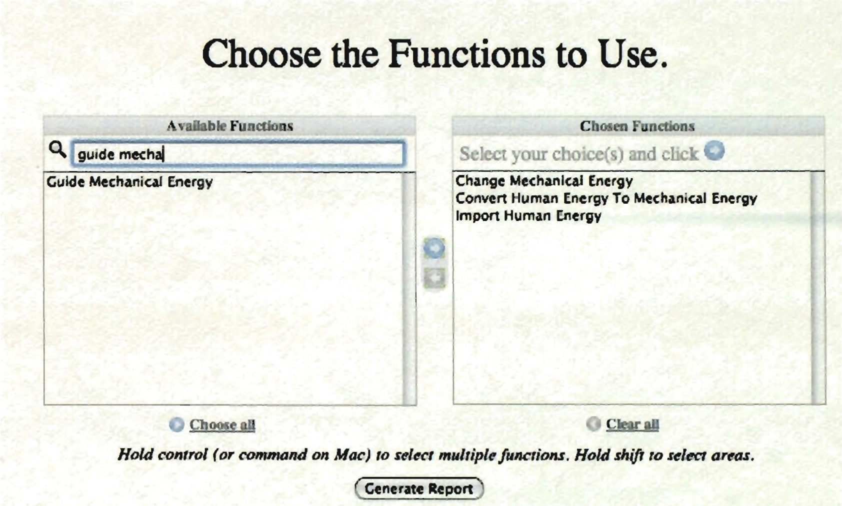
Choices:

Actuate Radioactive Energy
Change Control Signal
Change Control Signal To Control Signal
Change Electrical Energy
Change Electromagnetic Energy
Change Gas
Change Hydraulic Energy
Change Liquid
Change Mechanical Energy
Change Pneumatic Energy

Use control (or command on Mac) to select multiple functions. Shift to select areas.

Figure 7.2. Function Selection Interface Tested in Case Study

Figure 7.3 depicts the updated function selection interface. Upon first encountering the screen, the "Available functions" box on the left displays every function that has appeared in the RED database. Users can scroll through this list, select desired functions, and press the right arrow button to add to the list of "Chosen functions." Users also have the option of typing the function into text box above the function list. This action dynamically filters the list of available functions to reflect what the user has typed. The user can press enter to add the first function on the list, or choose a function from filtered list. Upon selecting all desired functions, the user can review the list of chosen functions on the right before clicking the button to generate a report. This increased clarity will decrease the effort required by users to select all desired functions and verify that function selection before generating a risk report. The redundant methods for accomplishing the same task may improve user speed and accuracy.



Choose the Functions to Use.

guide mecha

Guide Mechanical Energy

Change Mechanical Energy
Convert Human Energy To Mechanical Energy
Import Human Energy

Hold control (or command on Mac) to select multiple functions. Hold shift to select areas.

Figure 7.3. Updated Function Selection Interface

8. CONCLUSIONS

This research seeks to take a step toward the verification and validation of the Risk in Early Design tool and methodology, and to improve RED's utility as an educational tool. Based on survey data, areas for improvement and important usability aspects of the RED tool were identified. Initial improvements were made to the RED interface, and further improvements will increase the utility of RED. After these improvements are made, repeating the case study and survey will allow verification of the interface changes. Positive changes to the usability will promote better learning by reducing the barrier between the tool's interface and the information that the tool is conveying. These improvements should increase RED's utility as an expert knowledge preservation device.

9. FUTURE WORK

Future work for this research can be summarized in three parts. First, improvements to the RED application's usability will allow the application to more effectively accomplish its goals through improved user interaction. Second, improvements to RED's risk reports will enable users to more easily interpret risks. Third, work will be done to analyze the effectiveness of the hybrid problem-based just-in-time teaching method based on student failure assessments gathered in the experiment. These improvements and analyses will enable a future case study to assess the benefits of an improved RED interface.

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PAPER

II. A HYBRID PROBLEM-BASED AND JUST-IN-TIME INDUCTIVE TEACHING METHOD FOR FAILURE ANALYSIS INSTRUCTION

ABSTRACT

When engineers retire, they take their expert knowledge with them. Preservation of this expert knowledge in a usable form is beneficial for the advancement of any engineering field. Risk in Early Design (RED) is one method for preserving expert risk analysis knowledge. The purpose of this paper is to propose and perform steps toward verification and validation of the RED methodology and implementation. Evaluation metrics were developed, and several of these evaluation metrics were gathered in a case study. This case study was performed in a sophomore level lab class at the Missouri University of Science and Technology in the fall of 2010. The lab was designed to assist in teaching mechanics of materials, and was composed of approximately 200 students. Lab questions and a questionnaire were used to determine the students' ability to assess and mitigate risk both with and without this teaching method. The questionnaire was also used to prioritize and uncover usability issues with RED, and initial improvements were made to the RED application based on this feedback. While students were unlikely to produce an accurate failure mode assessment with or without the teaching method, results showed that students were using RED to aid their failure assessments.

1. INTRODUCTION

The goals of this research project are twofold. The first goal is to test the hypothesis that expert knowledge can be leveraged to provide novice engineers sufficient preparation for tasks previously thought to require a substantial amount of experience as a prerequisite. The second goal is to evaluate and improve the Risk in Early Design (RED) resource that enables this teaching method.

As technology progresses, it is critical that educational efforts focus on preparing students to build on the new developments, rather than continuously teaching them to "reinvent the wheel." The teaching of new technology is not limited to the integration of novel hardware and software into the engineering curriculum. It is also important to teach the next generation of engineers decision-making skills that build upon the current level of expertise in the workforce. Therefore, it is imperative that new technology also be used to prepare the engineers of tomorrow to analyze and understand engineering systems by conveying the knowledge associated with years of industrial experience during their undergraduate studies.

The teaching strategy tested in this paper is a hybrid problem-based and just-in-time inductive teaching method. The cornerstone for the method is a knowledgebase of "engineering experience." In this case, the RED knowledgebase was developed as part of a risk assessment project that leveraged historical failure data in electromechanical systems to predict and prevent such failures in the design of new electromechanical systems [1]. The RED method's impact on student failure assessments, including failure mode determination and failure mitigation plan scope, will be evaluated to determine RED's suitability as an alternative to engineering experience. This evaluation took place in the 2010 fall semester at the Missouri University of Science and Technology (Missouri S&T).

In order to improve RED's teaching effectiveness, several goals were defined for both the methodology itself and the implementation of the RED web application. These goals are mapped out to evaluation objectives and evaluation metrics, and methods for performing these evaluations are proposed.

2. SCOPE

The National Academy of Forensic Engineers (NAFE) [2] defines forensic engineering as "the application of the art and science of engineering in matters which are in, or may possibly relate to, the jurisprudence system, inclusive of alternative dispute resolution." NAFE also asserts that "the practice of licensed Professional Engineers as Forensic Engineers is important for the protection of the public health, safety and welfare." Preliminary interviews of engineering firms have demonstrated the need for safety engineers in industry. Currently, there is only one forensic engineering program at the graduate level [3]; none exist at the bachelor's degree level [4]. Statistics compiled by the American Society for Engineering Education (ASEE) for the 2005-06 academic year indicate that engineering graduation and enrollment rates at U.S. universities are not reflecting the country's increasing demand for engineering talent [5]. One reason for the gap may be that the traditional rigid engineering curriculum has not adapted to the diverse needs of a quickly changing technological world, such as the advances in the forensic engineering profession.

This paper presents research that was conducted to investigate the use of knowledgebase guided teaching strategies to enable courses with "engineering experience" as a prerequisite to be taught at the undergraduate level. This research will contribute to the formation of an undergraduate forensic engineering program that will leverage the industrial need and media popularity of forensics. This paper's contribution to the creation of a forensics program is in the formation and verification of reverse failure analysis coursework.

In order to provide a higher degree of utility, the Risk in Early Design (RED) will undergo verification and validation efforts. Two sets of goals were formulated for the RED methodology and the RED implementation. These goals map to evaluation objectives and the metrics associated with performing those evaluations. Methodology goals are intended to aid in evaluating how useful and effective RED is as a process, while implementation goals are intended to aid in evaluating how well the RED web application implements the RED method. These goals map to measureable metrics that will be explained in the upcoming sections.

A set of goals was created in order to organize the verification of RED. To prevent ambiguity, these goals were separated into goals for the RED methodology and goals for the RED application. Methods for performing these measurements were designed to leverage available resources at Missouri S&T.

Pertaining to the evaluation of the RED methodology's usefulness include industry independence, enabling inexperienced engineers to assess risk, providing a risk assessment that can be used during conceptual design, and reducing the resources to perform a risk analysis. Goals pertaining to the evaluation of the RED tool, independent of the method's effectiveness, include a correct implementation of the RED method's math, reduction in resources required to perform a RED analysis, a high degree of usability, and good ease of access.

The goals highlighted in Table 2.1 were addressed in the case study detailed in later sections of this paper. Additional goals and measurement methods are described in the future work section. RED's ability to provide a method that enables inexperienced engineers to assess risk was tested by comparing student failure mode assessments to expert failure mode assessments. The RED tool's usability and ease of access were assessed through a questionnaire containing Likert scale and open-ended questions.

Table 2.1. RED Goals Evaluated in Case Study

Goal	Evaluation Objective	Metric	Units
To provide a method that enables inexperienced engineers to assess risk	Assess the quality of risk analyses performed by inexperienced engineers	Quality	Rating by expert
To provide a tool that is easy to use	Assess the usability of the tool	Number of usability problems	Problems
		Severity of usability problems	Rating
To provide a tool that is easy to access	Assess ability of users to access and use the tool	User access rate	Success rate (%)

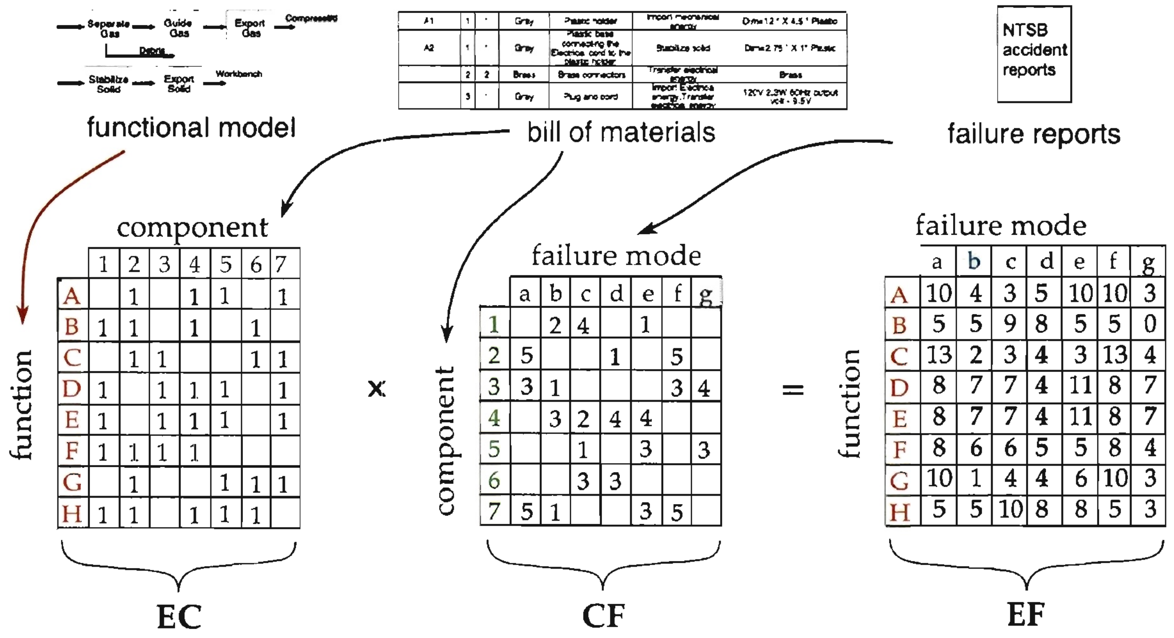
3. RISK IN EARLY DESIGN (RED) BACKGROUND

Risk in Early Design (RED) is a probabilistic risk assessment method that leverages historical failure data to provide failure data based upon the functions that a system must perform. This is accomplished using a series of matrices that contain historical data on component function and failures, along with an algorithm that presents failure modes, likelihoods, and severities for user selected functions. RED uses simple heuristics and mathematics to communicate cataloged historical product-specific risks as early as the conceptual design phase. Given the functions of a design, RED outputs potential risks based on historical failure data [5].

3.1 RED DATABASE POPULATION

The RED database draws information from three sources in order to store failure information: functional models, bills of materials, and failure reports. Failure reports provide documented cases of system failures, cataloged using a failure mode taxonomy [7] in order to standardize the terminology used in the database. Bills of materials provide components found in those systems. The components are cataloged using a component basis [8]. Functional models, consisting of material, energy, and signal flows connecting function blocks, provide the functionality of the failed systems. Similarly to the other two elements used in RED database population, functional models follow a functional basis terminology. The functional basis terminology standardizes the language to describe product function, leading to meaningful and repeatable function representations [9].

Functions and components are drawn from these sources to populate the function-component (EC) matrix. This matrix shows which components have historically accomplished which functions, using a 1 to denote a relationship and a 0 to denote no relationship. For example, function “A” in the EC matrix in Figure 3.1 has been accomplished by components 2, 4, 5, and 7. The component-failure (CF) matrix shows how often each component has failed by each failure mode. In the CF matrix shown in Figure 3.1, component 1 has failed by failure mode “b” twice, failure mode “c” four times, and failure mode “e” once. The EC and CF matrices are multiplied to produce the function-failure (EF) matrix, which shows how often each function has failed by each failure mode. For example, function "A" in the EF matrix in Figure 3.1 has failed by failure mode "a" ten times. The teaching strategy presented in this research uses an existing RED database of electromechanical failures to support RED operations.



	1	2	3	4	5	6	7
A		1		1	1		1
B	1	1		1		1	
C		1	1			1	1
D	1		1	1	1		1
E	1		1	1	1		1
F	1	1	1	1			
G		1			1	1	1
H	1	1		1	1	1	

	a	b	c	d	e	f	g
1		2	4		1		
2	5			1		5	
3	3	1				3	4
4		3	2	4	4		
5			1		3		3
6			3	3			
7	5	1			3	5	

	a	b	c	d	e	f	g
A	10	4	3	5	10	10	3
B	5	5	9	8	5	5	0
C	13	2	3	4	3	13	4
D	8	7	7	4	11	8	7
E	8	7	7	4	11	8	7
F	8	6	6	5	5	8	4
G	10	1	4	4	6	10	3
H	5	5	10	8	8	5	3

Figure 3.1. RED Database Population Sources and Matrices

3.2 RED RISK ANALYSIS PROCESS

The results from prior work [10] on developing the RED method have yielded a process for identifying and assessing risk during the conceptual design phase. This risk identification method was tested in the Missouri S&T mechanics of materials lab to determine if it can successfully provide "engineering experience" from which the students can draw on to initiate their failure investigations and classifications. The steps for using RED to guide a failure analysis investigation, shown in Figure 3.2, are: (1) generate the functional model of the failed part, (2) select the relevant functions from the historical failure database, and (3) perform risk calculations. The results displayed on the fever chart and the related risk report present students with a ranking of failures that occurred in similar components. In the example in Figure 3.2, the fever chart shows the number of failures that have occurred in the database for the selected functions at each likelihood and consequence pair. Here, five risks have occurred at a consequence of one and a likelihood of two, one risk has occurred at a consequence of four and a likelihood of one, and two risks have occurred at a consequence of three and a likelihood of four. The students used type of information to guide their investigations.

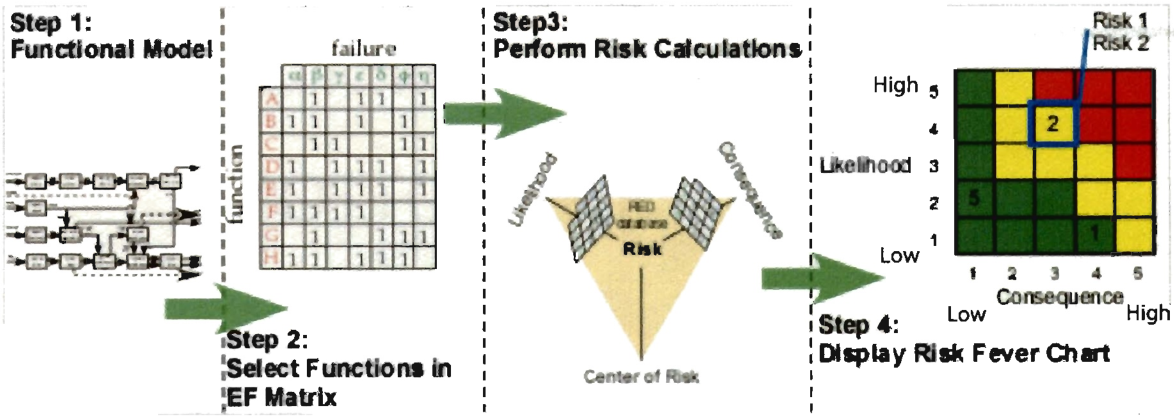


Figure 3.2. RED Process for Failure Investigation Guidance

4. RED AS A TEACHING AID

4.1 TEACHING STRATEGY

The problem-based teaching method, as its name implies, confronts students with a poorly defined, real world problem. Students work in teams to identify learning needs and develop solutions to the problem [11]. Problem-based learning has been shown to positively affect knowledge retention and skill development [12].

Just-in-time teaching typically consists of web-based preliminary exercises that the instructor uses to adjust lessons just before class based on student responses. Online enrichment pages and stand-alone instructional material support the in-class lesson. Just-in-time teaching promotes increased study outside of class and increased student-instructor interaction during class [13]. Just-in-time teaching has been assessed in physics instruction using the Force Concept Inventory, and has shown normalized student gains between 35% and 40% [11].

Both problem-based and just-in-time teaching are inductive teaching methods highlighted by Prince and Felder [11]. The authors describe inductive teaching as any teaching method that presents students with specific information that creates a need for more general facts or principles. Often this is accomplished by tasking the students with interpreting some specific data that requires these more general principles. This is highlighted as directly opposing the traditionally used deductive teaching, in which instructors present general principles and then show examples to reinforce them. The authors state that people are most strongly motivated to learn when they perceive a need to know, and that inductive teaching and learning are preferable methods of achieving this effect.

The teaching method applied in the experiment utilizes failed components, such as a bolt from a bridge, as an enabler for problem-based teaching. The students are presented with the problem of determining how the component failed, creating a need to know more general principles about failure analysis. The information that the students gain from RED is obtained just-in-time to help them analyze these failed components. In this sense, this teaching method does not conform with traditional just-in-time teaching. Whereas traditional just-in-time teaching relies on the instructor to adjust the learning material based on preliminary student feedback, in this case guidance in learning these more general failure analysis principles is provided by RED. Upon completing the lab, students should have learned general failure analysis principles based on their experiences with the specific component analyzed.

Additionally, the mechanics of materials lab course where this method was tested currently utilizes enrichment materials on its website in the form of related information that shows the materials' real-world relevance.

4.2 RED AND FAILURE ANALYSIS INSTRUCTION

For an example of how RED would typically be used, consider the situation of students in a problem-based learning exercise who were presented with a failed shaft and tasked with identifying the failure mode. Having extremely limited "engineering experience" from which to initiate their investigation, the students would use the RED method. First, the students would identify the functions of the shaft, and produce a functional model similar to the one found in Figure 4.1.

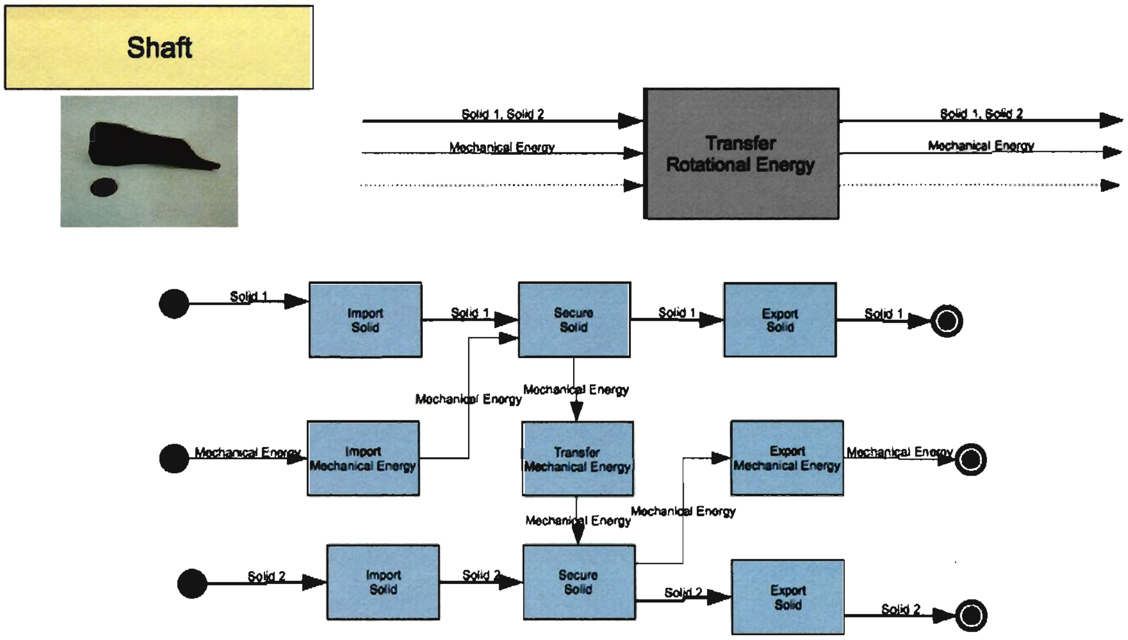


Figure 4.1. Shaft Functional Model

Next the students would enter its functions into the RED software. Sample output of the software is shown in Table 4.1. The results show that the functions transfer mechanical energy, secure solid, export mechanical energy, and import mechanical energy are most at risk of failure due to high cycle fatigue. Continuing down the report toward functions with lower severity, the solid and mechanical energy flows are also at risk due to brittle fracture and stress corrosion. These results indicate that the first course of action taken by the students would be to determine if the physical characteristics of the failed part and failure environment match with the most common type of failures provided. Continuing with this example, if the shaft experienced a significant amount of cycles and there was a physical break in the component, then the students could focus their analysis on determining if the failure was caused by high cycle fatigue. If it does not meet the criteria for high cycle fatigue, students would move down to brittle fracture and then stress corrosion. In this case, the shaft failed by brittle fracture. This teaching strategy will be assessed, and if found successful will promote more use of similar concepts to be incorporated into undergraduate curricula.

Table 4.1. Truncated RED Results for Shaft

Severity	Function	Failure Mode	Likelihood	Consequence
High	Transfer Mechanical Energy	High Cycle Fatigue	5	5
High	Secure Solid	High Cycle Fatigue	5	5
High	Export Mechanical Energy	High Cycle Fatigue	5	5
High	Import Mechanical Energy	High Cycle Fatigue	5	5
High	Export Solid	High Cycle Fatigue	4	5
High	Import Solid	High Cycle Fatigue	4	5
High	Transfer Mechanical Energy	Brittle Fracture	3	5
High	Secure Solid	Brittle Fracture	3	5
Med	Export Solid	Stress Corrosion	3	4
Med	Export Mechanical Energy	Stress Corrosion	3	4

In the context of this research, RED is presented to students as a black box. Students were provided with a functional model of their failed component, such as the one in Figure 4.1, thus removing the need for the students to be familiar with functional modeling to perform the exercise. This allowed a greater sample size of students who were able to generate RED output of potential failure modes of a failed component. Prior to performing the experiment, functional models were generated for all of the components that would be used in the lab.

5. FAILURE INSTRUCTION CASE STUDY

RED was tested as a tool for failure analysis instruction in a sophomore level lab class at the Missouri University of Science and Technology in the fall of 2010. The lab was designed to assist in teaching mechanics of materials, and was composed of approximately 200 students. Lab questions and a questionnaire were used to determine the student's ability to assess and mitigate risk both with and without RED. Students were unlikely to produce an accurate failure mode assessment with or without RED, although results showed that students were using the tool to aid their failure assessments. This case study allowed for evaluation of RED's usability and ability to provide a method that allows inexperienced engineers to assess risk.

5.1 RED VERIFICATION WITH EXPERTS

An expert group of two PhDs, one PhD candidate, and one master's student assessed the failure mode of each of the seventeen components used in the case study. These assessments were performed in a group to reach a consensus. Assessments were made using expert knowledge and reference material based upon limited component history information, component type, and appearance of the failure. For instance, the shaft was determined to have failed in torsion by brittle fracture due to the fracture surface's flat shape and granular appearance.

These assessments were independently compared to the RED output for the functional models of each component. Table 5.1 shows that with the exception of polymer failure modes (which are currently not in the RED database), RED reports largely contain the same failure mode as that suggested by expert analysis. This validates RED as a failure mode information source for 12 of the 17 components analyzed. Based on this comparison, results will be examined both in their entirety and excluding those not provided by RED analysis. To ensure a fair evaluation of RED report failure mode suggestions, none of the components examined were in the RED database.

Table 5.1. Expert Failure Analysis and RED Suggestion

Component Name	Expert Predicted Failure Mode	RED
Carriage Bolt	Yielding	Yes
Hex Bolt	Brinelling	No
Cap Screw	Brittle fracture	Yes
Pliers	Brittle fracture	Yes
Drill Chuck	Brittle fracture	Yes
Bolt-Testing Fixture	Yielding	Yes
Bicycle Pedal	Polymer failure mode	No
Swing Hook	Ductile rupture	Yes
Bridge Bolt	Yielding	Yes
Pressure Vessel	Ductile rupture	Yes
Handle	Brittle fracture (polymer)	No
Shaft	Brittle fracture	Yes
Splined Shaft	Ductile rupture	Yes
Pressurized Bottle	Ductile rupture	Yes
Lawn-Mower Piston Connecting Rod	Brittle fracture	Yes
Recycled-Plastic Lumber 1	Polymer failure mode	No
Recycled-Plastic Lumber 2	Polymer failure mode	No

5.2 EXPERIMENTAL DESIGN

The Missouri S&T IDE120 lab is designed to assist in teaching mechanics of materials, in which students learn about topics such as material properties, strain testing, and testing machines [14]. Students gain hands-on experience in the lab to reinforce learning of lecture topics.

In the IDE 120 Failure and Fully Plastic Action Lab, students “look at the definition of failure, failure theories, and real-life examples of failed components.” Additionally, students “investigate failed components, estimate what caused the failure, and propose a remedy” [15]. These aspects of the lab make it a good fit for testing RED as a teaching method.

This experiment was performed within the Failure and Fully Plastic Action Lab found at http://classes.mst.edu/ide120/lessons/failure/index.html in the Missouri S&T mechanics of materials lab class. The experiment was designed to fit within the existing structure of the class. At the beginning of the semester, students in each section formed groups of their own choosing. These groups were typically three to four students in size. The ten lab sections were divided into an experimental group and a control group. Three sections met on Monday three on Tuesday, two on Wednesday, and two on Thursday. The Tuesday and Thursday sections were selected as the experimental group, because one of the instructors in three of those five sections had experience with RED. This was done to mitigate the risk of any unforeseen issues with the RED deployment that might prevent students from using it. The experimental group contained a total of 101 students divided into 34 groups, and the control group contained a total of 96 students divided into 33 groups. The experimental group used the RED tool in addition to performing the lab, and the control group performed the lab without the tool. Student responses to lab questions were compared across the two groups.

Prior to performing the lab, each group selected a failed component to analyze from the pool of 17 available components. The students were each issued a failure mode taxonomy handout and a preliminary assessment form requesting that the student determine the failure mode of the selected failed component. The failure mode taxonomy provides the failure modes, along with a "primary identifier" and a definition of the failure mode, in order to aid failure mode identification. The primary identifier is the highest level of classification in the failure mode taxonomy, and helps to narrow one's focus to the appropriate failure mode. For instance, the primary identifier "Corrosion (Material deterioration due to chemical or electrochemical interaction with the environment)" contains twelve corrosion failure modes [7].

After completing preliminary assessments, students performed the lab. Lab activities included detailed observations of the failed component. Outside of class, the students in the experimental group ran a RED analysis on their failed item and saved the risk report to aid them in answering lab questions. These students were required to submit the risk report with their lab report to ensure that they performed the RED analysis.

All students answered questions regarding the failure and its prevention using a post-lab failure assessment form. Post-lab assessments, lab reports, and a survey regarding RED were gathered digitally using an online tool.

Accuracy of failure mode determination and scope of mitigation plans were compared between the control and experimental groups. Student failure mode responses were compared against expert evaluation of the failure modes. Failure experts assessed student mitigation plans for quality. Additionally, student perception of RED's usefulness and usability were gathered from the experimental group using a survey.

5.3 RESULTS AND DISCUSSION

Results were gathered for 29 of a possible 34 lab teams in the experimental group and 31 or a possible 33 lab teams in the control group. Several reports were missing due to students' failure to turn them in to their instructors. Lab teams typically consisted of three to four students. Eight of the 29 lab teams (28%) in the experimental group selected the same failure mode as the expert evaluators. Eleven of the 31 lab teams (35%) in the control group selected the same failure mode as the expert evaluators. Thirteen of the 29 lab teams (45%) in the experimental group changed their failure mode assessment between the preliminary and post-lab evaluations while nine of the 31 lab teams (29%) in the control group changed their response.

For the entire data set, the percentage of correct responses was similar across the control group and the experimental group. A correct response was defined as a failure mode determination that matched the expert-predicted failure mode. A failure mode response that did not match the experts' determination was deemed incorrect. Results were also examined for only the groups that selected components for which RED suggested the correct failure mode (seen in Table 5.1). Results from groups that selected one of the five other components were ignored for this part of the analysis. This did not greatly affect the percentages of correct responses.

Fisher's test for 2x2 contingency tables was performed for each of these four data sets to determine the statistical significance of these results. Fisher's test for 2x2 contingency tables was chosen because it gives the exact P value for categorical data, allowing statistical significance between two groups with two discrete outcomes to be observed [16]. In this case, the rows of the table correspond to the control and experimental group, and the columns correspond to the numbers of passes and fails for the criterion under observation. The two-tailed P values for each of these three sets indicate that the results for failure mode correctness and response changes are not statistically significant, based on the cutoff value of P=0.0500 to determine statistical significance. Therefore, it is likely that RED did not affect students' failure assessment correctness or propensity to change their responses.

However, a statistically significant number of students (P = 0.0110) in the experimental group changed their failure mode selection to high cycle fatigue after obtaining the RED report. Eight teams in the experimental group selected high cycle fatigue, while only one team in the control group selected high cycle fatigue. These results are summarized in Table 5.2.

Table 5.2. Student Failure Assessment Results Summary

Results summary	Experimental Group	Control Group	Fisher's Test P Value
Total Responses	29	31	-
Total Responses, Excluding RED Absent Components	22	25	-
Total Correct	8 (28%)	11 (35%)	0.5853
Total Correct, Excluding RED Absent Components	8 (36%)	11 (34%)	0.7668
Response Changes	13 (45%)	9 (29%)	0.2848
High Cycle Fatigue Selection	8 (28%)	1 (3%)	0.0110

The discrepancy in number of high cycle fatigue selections indicates that students may have simply chosen the riskiest failure mode in the RED report without analyzing whether that failure mode made sense for the component. None of the components used in the case study failed by high cycle fatigue according to expert evaluation, although high cycle fatigue appears first in many of the RED reports. For example, Table 5.3 shows high cycle fatigue as the riskiest failure mode, but the experts evaluated the failure as brittle fracture. The default format for RED reports is to sort first by risk level, then by consequence, then by likelihood, then alphabetically by failure mode. High cycle fatigue has historically failed at a likelihood of 5 and a consequence of 5 for many functions in the RED database. Additionally, the letter "h" appears earlier in the alphabet. These factors may combine to explain the high frequency of high cycle fatigue in student responses, and may also give deeper insight into how students were using RED.

Table 5.3. Sample RED Report for Shaft

Severity	Function	Failure Mode	Likelihood	Consequence
High	Transfer Mechanical Energy	High Cycle Fatigue	5	5
High	Secure Solid	High Cycle Fatigue	5	5
High	Export Mechanical Energy	High Cycle Fatigue	5	5
High	Import Mechanical Energy	High Cycle Fatigue	5	5
High	Export Solid	High Cycle Fatigue	4	5
High	Import Solid	High Cycle Fatigue	4	5
High	Transfer Mechanical Energy	Brittle Fracture	3	5
High	Secure Solid	Brittle Fracture	3	5
Med	Export Solid	Stress Corrosion	3	4
Med	Export Mechanical Energy	Stress Corrosion	3	4

This suggests that students may see better results with RED if it is used to create a smaller pool of potential failure modes to examine before a failure mode selection is made. Students could then examine the failed component for a subset of potential failure modes using the failure mode taxonomy, which would likely lead to increased accuracy. In the case of the shaft, Figure 5.1 shows the failure modes that students would examine if going down the list failure modes for the shaft in order of severity. The "granular, multifaceted surface" described in the taxonomy matches the surface of the shaft break, meaning that students following this method would likely only need to look at two failure modes before arriving at the correct failure mode.

Brittle fracture	Primary interatomic bonds being broken as a result of elastic deformation and the member, which exhibits brittle behavior, separates into two or more pieces. The fracture exhibits a granular, multifaceted surface.
High cycle fatigue	The sudden separation of a machine part into two or more pieces occurring when loads or deformations are of such magnitude that more than 10,000 cycles are required to produce failure.

Figure 5.1. Brittle Fracture and High Cycle Fatigue Definitions from Failure Mode Taxonomy

Students were also asked to indicate which resources helped them to determine the failure mode of their component, as seen in Table 5.4. Fisher's test for 2x2 contingency tables was performed for each criterion to determine the statistical significance of these results. The two-tailed P values for each of the possible resources signify that the relationship between what students indicated was a helpful resource and correctness of failure mode determination are not statistically significant.

Table 5.4. Student Indication of Useful Resources Summary

	Experimental Group			Control Group			
	Positive Responses	Correct Assessments	Incorrect Assessments	Positive Responses	Correct Assessments	Incorrect Assessments	Fisher's Test P Value
Total Responses	27	8	19	30	11	19	-
Failure Mode Taxonomy	18	7	11	20	7	13	1
Detailed Observations of the Component	21	7	14	22	7	15	1
Answering Lab Questions	7	3	4	4	1	3	1
RED Analysis	11	1	10	NA	NA	NA	NA
Other	4	2	2	2	0	2	0.4667

Statistical significance of the relationship between student indication that RED analysis was helpful and response correctness was compared within the experimental group.

Response correctness was compared between groups that indicated RED was helpful and groups who did not indicate that RED was helpful. One of the eleven groups (9%) indicated that RED was helpful and produced the correct response, while seven of the 16 groups (44%) did not indicate that RED was helpful and produced the correct response. Fisher's test gives a two-tailed P value of 0.0899, indicating by common convention that this relationship is almost statistically significant. This could be an indication, combined with the observation that high cycle fatigue appeared so often in the experimental group, that students who relied on RED the most also interpreted the risk report incorrectly.

Members of the expert group independently assessed the scope of student mitigation plans. These mitigation plans were formed by the students in response to the question in the post-lab evaluation, "What do you think could be done to prevent this failure from occurring again?" Evaluations were performed separately and then aggregated. Specific measures for whether a mitigation plan addressed a criterion were not defined, and each evaluator was responsible for judging whether a plan did or did not address the criteria. Aggregation in this way was intended to account for the variation due to subjectivity of these analyses caused by the lack of specific metrics.

Several groups' mitigation plans were missing because students did not turn them in with their reports. A total of 28 of a possible 34 mitigation plans were collected from the experimental group, and 29 of a possible 33 were collected from the control group.

Each mitigation plan was rated in the categories of likelihood change, consequence change, design change, and environment change. Likelihood change was defined as risk reduction by reducing the chance that the failure will occur; consequence change was defined as risk reduction by reducing the harmful effects of the failure, should that failure occur; design change was defined as change of parameters that can be altered by the designer; and environmental change was defined as change of parameters dependant on the situation the system is in, and the designer has limited control over. Evaluations were performed on a binary basis; either the mitigation plan addressed the criterion or it did not. A score of 1 was assigned by the evaluator if the mitigation plan was judged to meet the criterion. Otherwise, a score of 0 was assigned.

Scores were totaled for all of the evaluators for each of the criteria, shown in Table 5.5. For example, the likelihood criterion in the experimental group received a total of 97 1's from the evaluators, and 15 0's. Fisher's test was performed for the 2x2 contingency tables produced by each of the criteria. As seen in Table 5.5, mitigation plan emphasis was not statistically significant between the experimental and control groups, with the exception of a near statistical significance (P = 0.0611) for design parameter emphasis. This similarity may be explained by the chronological placement of RED and the post-lab assessment in the exercise. It is possible that students decided upon a mitigation plan before performing RED analysis, removing RED as a factor. Alternatively, the simple mention of likelihood and consequence provided in the RED report may not provide sufficient guidance to result in mitigation plans of greater scope. The possible difference in design parameter emphasis may be explained by the lab questions' focus on the design of the part. Given fewer resources to focus on, students in the control group may have placed increased emphasis on the ideas produced by answering these questions.

Table 5.5. Student Mitigation Plan Scope Evaluation

	Experimental Group		Control Group		
	Addressed	Not Addressed	Addressed	Not Addressed	Fisher's Test P value
Likelihood	97	15	103	13	0.6886
Consequence	8	104	4	112	0.3753
Design Parameters	72	40	88	28	0.0611
Environmental Parameters	50	62	47	69	0.5924

A survey was designed to measure the usability of the RED tool implementation, student perception of their own performance in the case study, and the usefulness of RED in the case study. The survey consisted of 13 questions on a Likert scale and two open-ended questions. The survey was deployed through the Blackboard web-based course management system after students completed the lab. Blackboard's capabilities include allowing students to download and turn in assignments and surveys online. Students were incentivized to complete the survey with bonus points, and there were 80 respondents out of a possible 101 in the experimental group.

Questionnaires were selected because they can be used to collect a large amount of data using few resources. Questions pertaining to the system's usability included questions targeted to specific areas of usability as well as open ended questions designed to uncover problems that may have been missed by tool evaluators. Questions dealing with specific areas of usability were framed after a set of Likert scale and open-ended questions designed to assess the usability of a software system, provided by Dix et al. [17]. Six of the Likert scale questions asked students to rank their level of agreement with how well the RED application addressed specific areas of usability, such as feedback, ease of navigation, and ease of access. These usability questions are seen below.

> Please answer the following questions based on the following ratings:
> 1 - I strongly disagree
> 2 - I disagree
> 3 - I neither agree nor disagree
> 4 - I agree
> 5- I strongly agree
>
> 1. The RED application tells me what to do at each step in the risk identification process.
>   1 2 3 4 5
>
> 2. It is easy to recover from mistakes I make while using the RED application.
>   1 2 3 4 5
>
> 3. It is easy to get help within the RED application when needed.
>   1 2 3 4 5
>
> 4. The RED application always gives me feedback to tell me what it is doing.
>   1 2 3 4 5
>
> 5. It is easy to navigate through the RED application.

1 2 3 4 5

6. The RED application was easy to access.
   1 2 3 4 5

Open-Ended Questions

1. What did you dislike about the RED application? Please suggest improvements.
2. What did you like about the RED application?

By comparing these responses for each of these usability aspects, a prioritization for addressing each was obtained. The open-ended questions asked students for likes and dislikes about the RED application, in order to uncover unanticipated problems with the usability and with RED in general.

Table 5.6 shows the means of those responses, ranked from highest to lowest level of agreement. The ranking in Table 5.6 provides a guide as to which aspects of the RED software possess the lowest degree of usability. Usability aspects that received lower mean scores may reflect lower levels of satisfaction with that aspect of the usability. Based on these mean scores for each response, the survey suggests the following order of importance for usability improvements: provide feedback, provide help and guidance within the application, improve navigation, improve error recovery, and improve accessibility.

Table 5.6. RED Usability Survey Results

Rank	Question	Mode	Mean	Standard Deviation
1.	The RED application was easy to access.	4	3.513	0.693
2.	It is easy to recover from mistakes I make while using the RED application.	4	3.481	0.686
3.	It is easy to navigate through the RED application.	4	3.338	0.579
4.	The RED application tells me what to do at each step in the risk identification process.	4	3.225	0.677
5.	It is easy to get help within the RED application when needed.	3	3.138	0.605
6.	The RED application always gives me feedback to tell me what it is doing.	3	3.013	0.976

The remaining questions were designed to assess the student perception of RED's helpfulness and their own performance in the exercise. The responses to these questions are summarized in Table 5.7, and provide a baseline for comparison when improvements are made to the instruction technique used in the case study. Responses to these questions indicate that students were confident in their assessments, while confidence in RED's ability to aid in failure assessment was less pronounced. After improvements are made to this teaching strategy in a future semester, this survey will be administered again to determine whether the improvements were successful.

Table 5.7. Student Perception of Failure Analysis and RED

Question	Mode	Mean	Standard Deviation
I correctly identified the conditions leading to the item's failure.	4	3.850	0.872
I correctly identified the item's failure mode.	4	3.850	1.240
I created an effective plan to prevent the failure from happening in the future.	4	3.738	1.160
I enjoyed the lab.	4	3.675	0.939
The RED application helped me to identify the conditions leading to the item's failure.	4	3.325	0.698
The RED application helped me to determine the item's failure mode.	4	3.263	0.893
The RED application helped me determine how to prevent the same failure in the future.	3	3.038	0.788

Two open-ended questions regarding the students' likes and dislikes about RED were asked in order to identify unanticipated usability problems that were not otherwise addressed by the survey. Responses to those questions were clustered into categories with responses having similar themes. After those categories were formed, they were named based on the theme associated with the cluster. Students who took the survey but did not respond to the open-ended question were placed in the "No Response" cluster. Multi-part responses that fit into multiple categories were counted once in each of those categories. For example, consider the following response to the question about dislikes:

> "The data received is slightly difficult to sift through. Possibly organize the data in a manner that will ease in finding what exactly one is looking for. Make selecting multiple functions easier to do."

This response contains two themes. First, the student indicates that they had difficulty using the RED report. Second, the student indicates difficulty with the user interface. This response was split into two responses and placed into groups with similar responses. When all clusters were formed, these two clusters were named "Report Clarity" and "Interface Clarity" respectively.

Student "likes," seen in Figure 5.2, clustered around three main categories. In order of frequency, students commonly liked RED's ease of use, thought it was useful in the exercise, and liked the large amount of information provided. In general, students felt that the instructions and procedures involved in producing the RED output were easy to understand. Additionally, many students indicated that RED was useful in determining the failure mode of the component. Similarly, students liked the large quantity of information provided by the application.

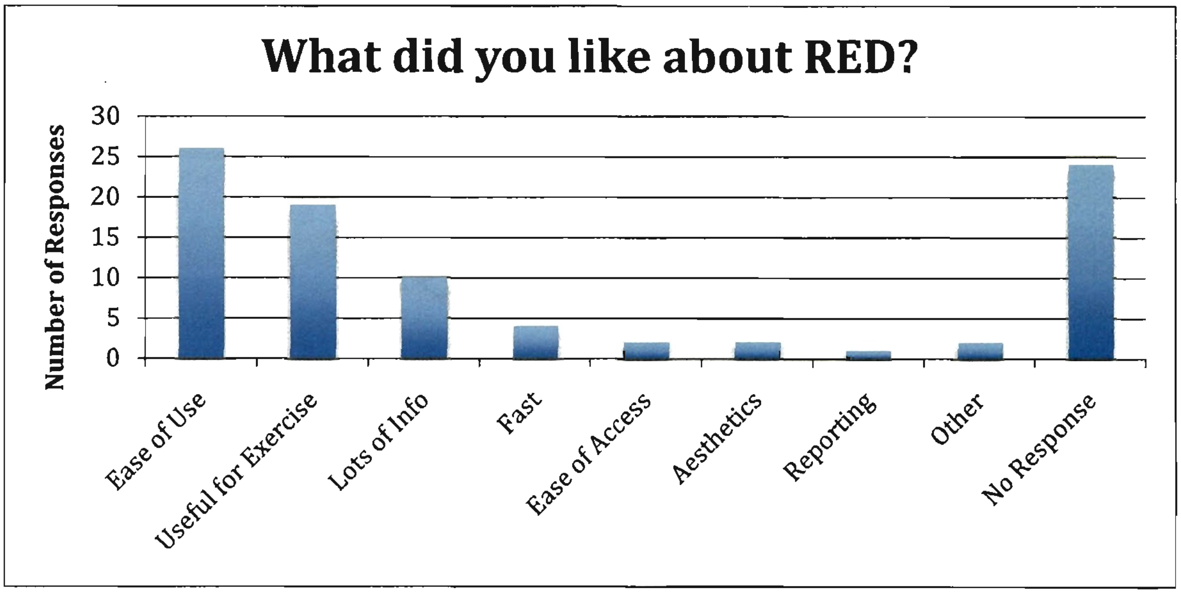


Figure 5.2. Perceived Positive RED Attributes

Student "dislikes," seen in Figure 5.3, also clustered around three main categories. Interface clarity, meaning the student had issues with performing the desired tasks due to the human interface, was mentioned the most. Report clarity, meaning that students had issues understanding the risk report, was also mentioned frequently. The report clarity cluster included difficulties choosing the correct type of report to download, difficulties formatting that report into a readable one, and difficulties interpreting what the results meant. A significant group of students also stated that RED was not useful in determining the failure mode of their failed component. This could be attributed to difficulties interpreting the report or student confidence in their initial answer. Several students also mentioned having access difficulties and problems understanding the functional model.

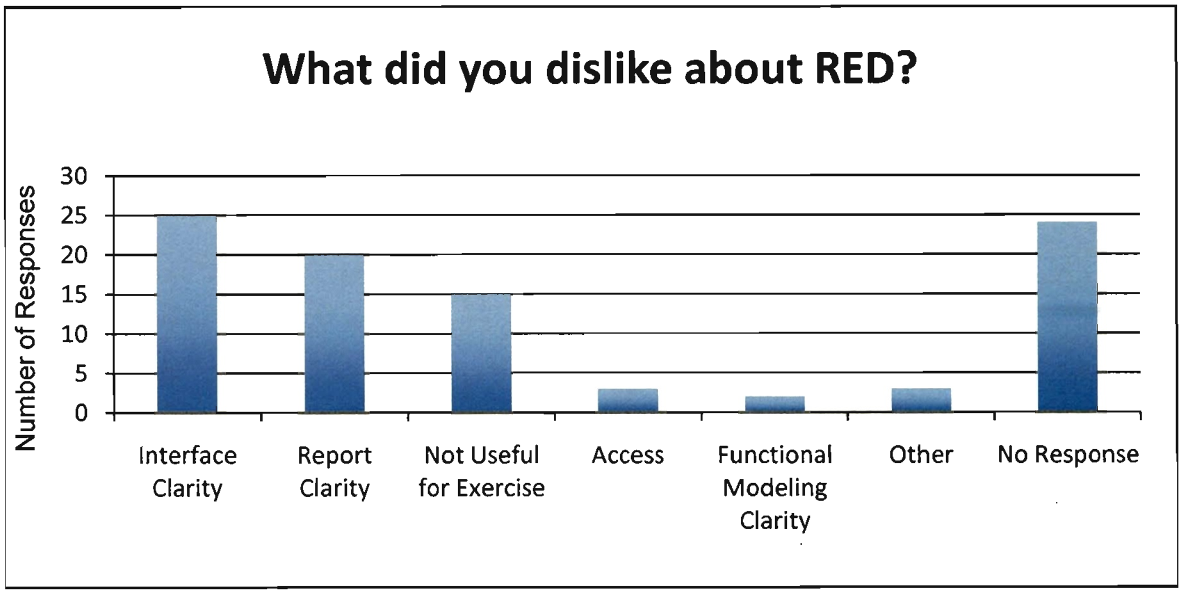


Figure 5.3. Perceived Negative RED Attributes

The disparity between having a high ease of use and poor interface clarity might be explained by the tutorial provided with the RED application. While students felt that RED was easy to use, it was likely due to the step-by-step instructions provided in the tutorial. The disparity between students who thought that RED was useful and those who did not could be explained by a perception that RED report interpretation does not require a human-in-the-loop. In order to be useful in this context, RED needs a human to select a failure mode that fits the specific case.

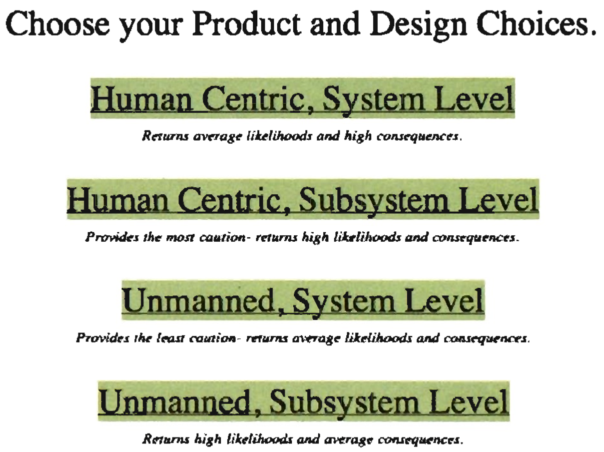
Based on the survey data, several improvements were identified that can increase the usability of the RED tool. These changes address student complaints concerning the usability of the application. A map graphic of where the user is in the RED process, accompanied by instructions and provided on every page of the application, should prevent users from getting lost or stuck by providing feedback and navigation assistance. A welcome page with a basic overview and instructions on how to use the application, as well as an easily accessible link to the RED tutorial, should improve the amount of help and guidance available. Retaining function selection after the user submits would allow the user to make changes more easily if a mistake is identified, improving error recovery. Finally, students identified the function selection interface as difficult to use. Changing the scroll box to a different interface would reduce the time required to search for and double check function selections.

6. INTERFACE IMPROVEMENTS

Several improvements, which address some of the usability issues uncovered in the case study, have been made to the RED interface. These improvements are still in progress, but for now include clarifications to the heuristic selections and a greatly improved function selection interface.

6.1 HEURISTIC CLARIFICATION

A lack of instructions within the RED application was identified as one area for improvement. As a step toward providing better guidance, clarifications have been added to the heuristic selection step of the RED process as seen in Figure 6.1. This will indicate to the user the reason for making this selection as well as giving a better understanding of how their choices will affect the risk calculations.



Choose your Product and Design Choices.

Human Centric, System Level

Returns average likelihoods and high consequences.

Human Centric, Subsystem Level

Provides the most caution- returns high likelihoods and consequences.

Unmanned, System Level

Provides the least caution- returns average likelihoods and consequences.

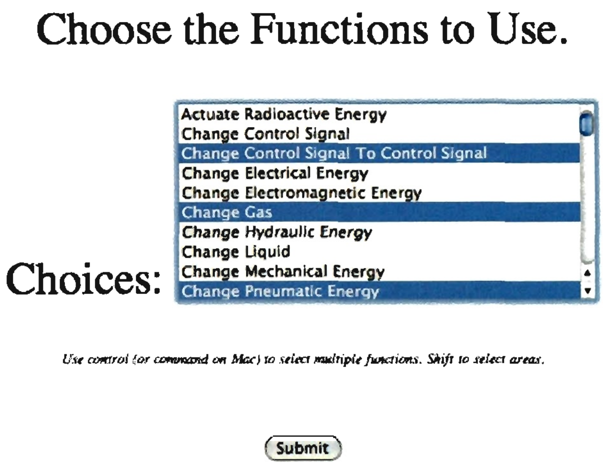
Unmanned, Subsystem Level

Returns high likelihoods and average consequences.

Figure 6.1. Heuristic Clarifications

6.2 FUNCTION SELECTION INTERFACE

Figure 6.2 depicts the function selection interface tested in the case study. This interface requires users to scroll through a list of every function that appears in the RED database and individually select functions relevant to the user's system. Survey responses revealed user issues verifying that all of the desired functions were selected. Users also experienced difficulty determining if their desired function appeared in the RED database. A new interface was developed that addresses these issues.

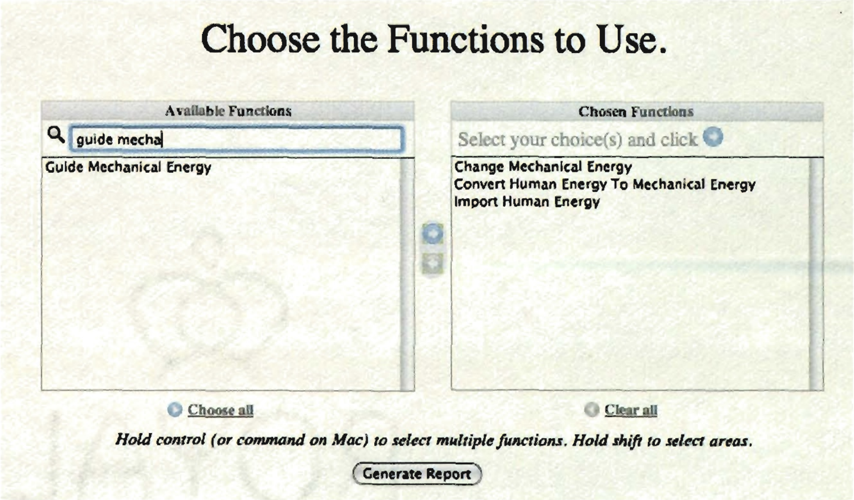


Choose the Functions to Use.

Use control (or command on Mac) to select multiple functions. Shift to select areas.

Figure 6.2. Function Selection Interface Tested in Case Study

Figure 6.3 depicts the updated function selection interface. Upon first encountering the screen, the "Available functions" box on the left displays every function that has appeared in the RED database. Users can scroll through this list, select desired functions, and press the right arrow button to add to the list of "Chosen functions." Users also have the option of typing the function into text box above the function list. This action dynamically filters the list of available functions to reflect what the user has typed. The user can press enter to add the first function on the list, or choose a function from filtered list. Upon selecting all desired functions, the user can review the list of chosen functions on the right before clicking the button to generate a report. This increased clarity will decrease the effort required by users to select all desired functions and verify that function selection before generating a risk report. The redundant methods for accomplishing the same task may improve user speed and accuracy.



Choose the Functions to Use.

Available Functions

guide mecha

Guide Mechanical Energy

Chosen Functions

Select your choice(s) and click

Change Mechanical Energy
Convert Human Energy To Mechanical Energy
Import Human Energy

Hold control (or command on Mac) to select multiple functions. Hold shift to select areas.

Figure 6.3. Updated Function Selection Interface

7. CONCLUSIONS

This research seeks to take a step toward the verification and validation of the Risk in Early Design tool and methodology, and to improve RED's utility in failure analysis instruction. It was expected that the RED-provided failure modes with the highest likelihood ratings would focus the students' attention on a smaller subset of potential failure modes. Using this added guidance, students were expected to have increased accuracy in failure mode assessment when compared to students that did not have similar guidance. Instead, there was no significant difference in failure assessment accuracy between students using RED and students not using RED. It was also expected that RED outputs might increase the scope of student risk mitigation plans by associating both likelihood and consequence values to their selected failure mode. For example, a failure mode with high likelihood and high consequence scores may prompt students to create mitigation plans that reduce both aspects of risk rather than simply reducing the likelihood. Instead, there was not a significant relationship between any of the mitigation plan criteria examined, except for design change emphasis. Students who did not use RED tended to emphasize design parameter changes to mitigate failures significantly more than students who used RED.

Therefore, the hybrid problem-based and just-in-time inductive teaching method, as implemented in this case study, did not provide evidence of significant benefit over more traditional instruction. RED's suitability as an alternative to engineering experience in failure assessment was tested, and problems with the approach were identified. It was determined that this method of failure analysis instruction does affect students' thought process, but it must be implemented differently in order to provide significant benefit. Repeating the case study with several changes will allow a better examination of the potential of this teaching method. Restructuring the class to have students perform RED analysis before coming to lab rather than after may increase both learning and the number of correct student failure assessments. Based on evaluation of student failure assessments, it was determined that students are prone to misinterpreting RED reports. Based on survey data, areas for improvement and importance of areas of improvement were identified. RED enables the problem-based just-in-time teaching method, but modifications will be necessary to see significant benefit over more traditional instruction. The problem-based just-in-time inductive teaching method effective's effectiveness cannot be determined based on the case study presented in this paper.

8. FUTURE WORK

Future work for this research includes the execution of the evaluation methods outlined in the goals chart, and improvements to the Risk in Early Design method and tool based on feedback from those evaluation methods. For the method this includes an evaluation of industry independence, continued refinement and testing of the method for teaching experienced engineers to assess risk, evaluation of the method's usefulness in conceptual design, and evaluation of resources required to perform RED analysis. For the tool, future work includes ongoing usability study and improvements, assessment of ease of access, and evaluation of resources required to use the tool.

Future evaluations of RED will be carried out according to the goals identified in Table 8.1.

Table 8.1. Future Evaluation Goals

Goal	Evaluation Objective	Metric	Units
To provide an industry independent risk assessment method	Assess the method for usefulness of results within different domains	Domain expert rating	Survey rating
To provide a risk assessment method that can be used as early as the conceptual design phase of product design	Assess the accuracy with which early risk assessments predict failures	Accuracy	Percent
To provide a tool that reduces the resources required to perform a RED analysis	Compare times to perform a RED analysis with and without the tool	Time	Seconds
To provide a tool that is easy to use	Assess the usability of the tool	Number of usability problems	Problems
		Severity of usability problems	Rating

Measurement data to assess the industry independence of the RED method will be collected from engineers in industry who have RED tool experience from coursework at Missouri S&T. A questionnaire will be distributed to assess their opinions on how beneficial the RED tool's electromechanical database feedback would be in their respective engineering domain. Based on these responses, RED's usefulness across a variety of industries can be gauged. Separately, continued development of the lean and software databases will enable future testing of RED for solution independence.

The ability of RED to predict failures in the conceptual design phase will be measured using a classroom case study exercise that incorporates product design and RED analysis. A product with extensive documented failure information will be selected, and students will be tasked with designing a similar product. Students will be required to create a functional model for the product, and then utilize RED tool electromechanical failure outputs to assist in formulating their design. Upon assignment completion, the product that the assignment was based upon will be revealed and student designs will be examined for safety mechanisms that would prevent the documented failure from occurring.

Because of their versatility, questionnaires will also be used to augment other goal measurements as applicable. For example, questionnaires were utilized in the mechanics of materials case study to assess the perception of RED's usefulness, in addition to its usability.

Another avenue of investigation will seek to identify usability problem areas with an independent usability study. The tool will be submitted for study in the S&T human factors class as a possible group project. If the RED tool is accepted as a class project, the students will provide a different perspective on the tool's usability. This diversity of viewpoints will likely lead to an increased number of usability problems detected and fixed.

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