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A Hybrid Problem-Based and Just-in-Time Inductive Teaching Method for Failure Analysis Instruction*

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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.

Keywords: problem-based; just-in-time; risk in early design; failure analysis

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. 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].

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 engineer's 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 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).

2. Background

Introducing failure and risk analysis in to undergraduate engineering education has is difficult due to the sequential nature of engineering curricula [2] and the limitations on required credits for graduation. A common point for integration of these topics is a design course [3–5] or as a related case study [6, 7] in a traditional curriculum course. While these implementation strategies do often involve a problem or project based teaching method, students are often still missing the general knowledge of where to begin to identify potential failure modes.

2.1 Problem-based and just-in-time teaching strategies

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 [8]. Problem-based learning has been shown to positively affect knowledge retention and skill development [9]. However, in engineering education, in particular failure mode determination and/or risk analysis; the lack of structured learning support can leave students not even knowing where

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to begin. Therefore, an additional inductive teaching method, such as Just-in-time teaching [10, 11], can be used to provide some learning support.

Just-in-time teaching typically consists of preliminary exercises that the instructor uses to adjust lessons just before class based on student responses. Online enrichment pages and stand-alone instructional material can support the in-class lesson. Just-in-time teaching promotes increased study outside of class and increased student-instructor interaction during class [10, 11]. 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% [8].

Both problem-based and just-in-time teachings are inductive teaching methods highlighted by Prince and Felder [8]. 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. This paper seeks to combine these teaching methods to promote failure mode identification and risk education in the undergraduate engineering curriculum. A similar combination of inductive teaching methods (just-in-time and project-based learning) have been performed successfully with an application to water engineering with positive results [12].

2.2 *Risk in early design*

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 [13].

The results from prior work [14] 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 Fig. 1, are: (1) generate the functional model [15] 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, 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.

3. Red as a teaching tool

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.

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 Fig. 2.

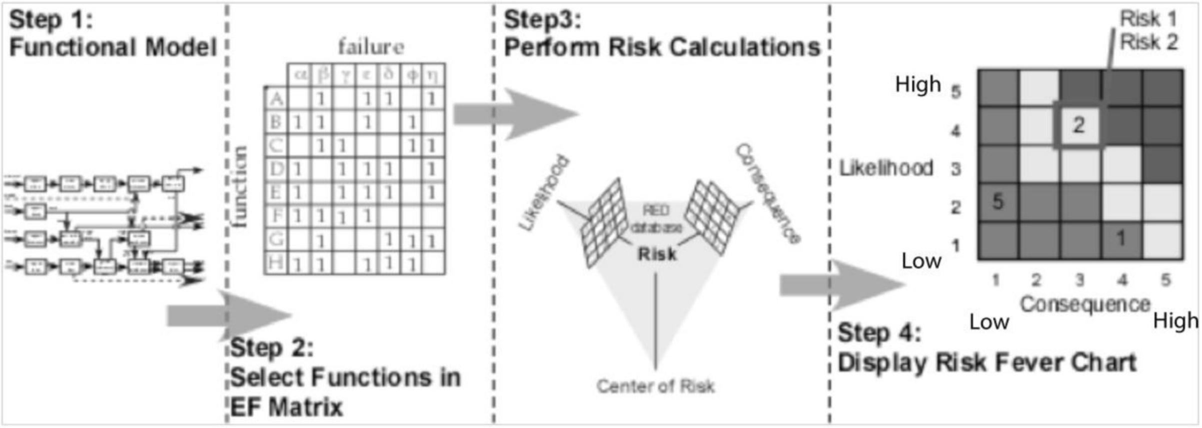

Fig. 1. RED Process for failure investigation guidance.

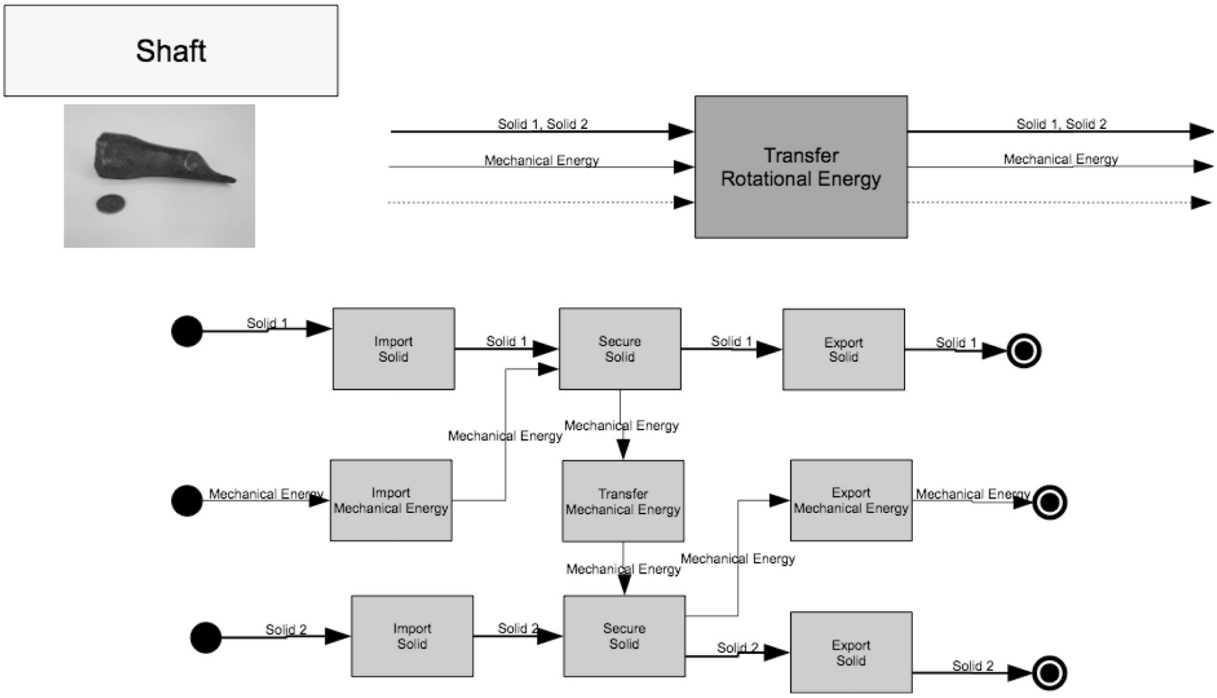

Fig. 2. Shaft functional model.

Next the students would enter its functions into the RED software. Sample output of the software is shown in Table 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, the students could then 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.

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 Fig. 2, 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

Table 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	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

the appropriate 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.

4. Experimental design

To address the goals of determining if expert knowledge, in the form of RED, can be leverage to aid novice engineers in failure mode identification and to evaluate RED as a teaching tool, an experiment was designed and conducted in the Materials Testing Laboratory course, IDE 120, during the fall semester of 2010. The experiment tests RED aid to novice engineers by comparing the performance of students who used RED in correctly identifying failure modes to those who did not use RED. It also tests its ability to aid novice engineers by collecting the student's perspective of its utility in assisting them to identify failure modes. Further, RED's effectiveness as a teaching tool was measured by comparing the students' performance on the assignment with and without RED as a tool. Also, the students' perception of RED as an instructional aid was also measured.

Prior to performing the experiment, an expert group of two PhDs, one PhD candidate, and one master's student (all mechanical engineers with an emphasis on failure mode study) 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 2 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 case study components examined was in the RED database.

Once the failure mode for each of the case study components was identified, the experiment was launched in the IDE 120 Materials Testing Laboratory. The sophomore level lab is designed to assist in

Table 2. Expert failure analysis and RED suggestion

Component name	Expert predicted failure mode	RED suggestion
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

teaching mechanics of materials, in which students learn about topics such as material properties, strain testing, and testing machines [16]. 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' [17]. 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.

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 [18].

Prior to performing the lab, each group selected a failed component to analyze from the pool of 17 available components. 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 modes were compared between the control and experimental groups. Student failure mode responses were compared against expert evaluation of the failure modes. Additionally, student perception of RED's usefulness and usability were gathered from the experimental group using a survey. These quantitative and qualitative data sets provided valuable insight that will be presented in the next section relating to the two core research questions understudy.

5. 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). 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 2 × 2 contingency tables was performed for each of these four data sets to determine the statistical significance of these results. Fisher's test for 2 × 2 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 [19]. 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 3.

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 1 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.

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, brittle fracture and high cycle fatigue are 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.

Students were also asked to indicate which resources helped them to determine the failure mode of their component, as seen in Table 4. Fisher's test for 2 × 2 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.

Statistical significance of the relationship

Table 3. 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

Table 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

Table 5. 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

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.

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. [20]. 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.

Table 5 shows the means of those responses, ranked from highest to lowest level of agreement. The ranking in Table 5 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.

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, 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

Table 6. 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

will be administered again to determine whether the improvements were successful.

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' 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.

Student 'dislikes' 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.

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. Conclusions

This research sought to both 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; and, to evaluate and improve the Risk in Early Design (RED) resource that enables this teaching method. In this study, 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 and 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. 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 to address the second research question. Also, the study's results do not provide sufficient evidence to address the first hypothesis proposed at this time.

7. 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 software 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 software tool, future work includes ongoing usability study and improvements, assessment of ease of access, and evaluation of resources required to use the tool. In addition to these tasks, it would be interesting to investigate what specific skills set experts apart from beginners and what new skills can be learned through instruction.

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