INTEGRATING RISK MANAGEMENT TECHNIQUE INTO AN INTRODUCTORY ENGINEERING COURSE

Nhut Ho

California State University, Northridge, CA, USA

Austin Davis

California State University, Northridge, CA, USA

William Munsch

Pratt & Whitney Rocketdyne, Inc., Chatsworth, CA, USA

ABSTRACT

The ability of engineering students to identify and mitigate risks in a design project is an essential skill desired for professional engineering practice. However, this skill is not adequately addressed in undergraduate curriculum. This paper discusses the utilization of the CDIO (Conceiving, Designing, Implementing, Operating) framework to adapt and integrate NASA's N x M Risk Matrix into a first year introduction to mechanical engineering course, and to evaluate student achievement. The paper first presents an overview of risk management and its application in aerospace. The paper next describes how the NASA N x M Risk Matrix is adapted and incorporated into an introduction to mechanical engineering course at California State University, Northridge, which was developed based on CDIO Standard 4. The Risk Matrix was integrated into the course's design build project, which requires students to work in teams to: 1) identify the risks in the project; 2) write simple risk statements describing the likelihood of the undesirable risk/event occurring and the severity of the consequences should the undesirable risk/event occur; 3) research, implement and document mitigation steps to reduce the risks throughout the different phases of the project; and 4) discuss how the implemented mitigation steps affect each risk statement. Evaluation results from a self-report survey and Final Design Presentation assessment show that students are able to demonstrate a working knowledge of the basic concepts, and for the most part, were able articulate those concepts correctly. Several results were identified that represent improvement opportunities for the next course, as well as ways for integrating risk mitigation method into the curriculum.

KEYWORDS*:* Risk management, introduction to engineering, CDIO Standard 4

I. INTRODUCTION

The ability of engineers to identify and mitigate risks in a design project is an essential skill desired for professional practice. When risks are not identified and/or mitigated, the consequences could translate into cost overruns and delays in delivery of products. More serious consequences could include catastrophic and fatal tragedies such as the Columbia Space Shuttle explosion in 1986, which took the lives of seven astronauts and led NASA to conclude that "… managers at NASA lacked the crucial ability to accurately evaluate how much or how little risk is associated with their decisions" [1]. Increasingly, industry and government agencies such as NASA and the DoD are adopting more effective methods to identify and mitigate risks and expecting that engineers play a significant role in risk management [2].

I.A. Risk Mitigation in Industry Practice and Training

While addressing risks is usually a required part of most engineering projects, the development and utilization of formal processes to identify and mitigate risks is relatively new and is a growing area in high-tech industries [3]. Aerospace is an example where the use of Technical Risk Management (RM) concepts have gained popularity and become a required part of all projects [4]. To meet this project requirement, engineering companies have developed and implemented various tools and training processes that cater to their specific needs. For example, at Pratt & Whitney Rocketdyne (PWR), a US leading high-technology propulsion and power company, where one of the co-authors of this paper works as a program manager, a structured RM process is utilized as an integral part of all programs' phases. The process focuses on cost, schedule and technical risks, and requires every major program area to establish a RM board, which is responsible for overseeing the activity. The program teams will support the process by bringing forward potential risks, developing well considered risk statements, developing RM plans and executing those plans. All engineers are expected to understand the basic steps of RM, the terminology, and how risks are integrated to all technical work. To facilitate these activities, a proprietary tool has been developed and is used to integrate detailed definitions for risk likelihood and risk consequence that can apply to all the various program aspects including design, fabrication, assembly, test and operation. The program teams use the tool to document the risk likelihood and risk consequence in a standardized 5 x 5 matrix which serves as a database with detailed mitigation planning, fall back planning, action tracking and various reporting features. Generally a RM focal is assigned to each program to be the keeper of the process for the program area and to provide subject matter expertise and counsel to the team members.

When an engineering college graduate is hired into PWR, he or she chooses or is assigned into a discipline. The disciplines are divided to provide leadership in key areas such as Systems Engineering, Design, Materials, Structural Analysis, Test and Systems Analysis. The new engineers will generally be assigned a mentor to help them learn the processes and technologies of interest to their discipline. In almost all disciplines, the engineer will quickly be exposed to RM activity. It could be anything from understanding the limitations of the analysis tools to recognizing the potential for a design feature to fail, to recognizing when a hardware discrepancy implies a problem with already delivered production units, or to addressing a RM board. It is common to find that the new engineer has basic knowledge of the terminology of RM and some limited application understanding, but minimal capability to independently recognize and react to a risk in the real world of their work scope. It appears that they may have been introduced to the concepts in school, but were not taught how the process is executed with variable situations and with enough repetition for it to become a strong part of their tool box.

Due to the limited academic exposure, the new engineer's risk management knowledge and skills must be developed on the job. Computer-based and workshop training is available, that introduces the tool and concepts for the various unique implementations at PWR. However, the primary method of development is through on the job training where the engineer is mentored through the process relevant to their discipline activity. This will generally take a number of cycles for the new engineer to fully understand the complete process and to be able to defend the results to experienced engineers. It generally takes a few years for enough experience to be gained in order for the engineer to be capable of leading teams in the RM process activity. More importantly, it is generally viewed that additional emphasis on RM in the undergraduate education curriculum would provide significant benefit to the companies that must develop basic capabilities in their new engineers.

I.B. Addressing Inadequacy in Risk Management Education with CDIO

The view that engineering graduates are not well prepared with RM skills has been reported in a number of studies. For instance, a survey of Electrical and Computer Engineering (ECE) Faculty's assessment of senior design project performance at University of North Carolina found that students have poor skill of foreseeing potential risks involved in their projects and creating contingency plans [5]. This skill also received the lowest rating among the skills needed to be successful in a senior design project. While a number of engineering educators have proposed ways to teach RM concepts in senior design projects [6], the teaching and integration of RM into the university classroom has not been implemented to the level commensurate with what is required in engineering practice [7], with the exception of a number of universities such as Massachusetts Institute of Technology and Stanford University that offer specific courses in this area [8, 9].

To address the inadequacy and achieve the level of proficiency desired by industry, it is important that RM concepts are explicitly integrated into the curriculum in a systematic way. The Conceive-Design-Implement-Operate (CDIO) [10] offers such a systematic framework in that:

1) It explicitly includes specific learning outcomes pertinent to RM in the CDIO Syllabus [11], a complete, consistent and generalizable set of knowledge, skills and attitudes necessary for successful new engineers. The Syllabus' goals related to RM include *Analysis with Uncertainty (2.1.4), Initiative and Willingness to Make Decisions in the Face of Uncertainty (2.4.1), Development Project Management (4.3.4), and Planning*

and Managing a Project to Completion (4.7.6). Under each of these goals, the CDIO Syllabus includes subtopics that can be used to formulate specific learning outcomes at the appropriate levels of proficiency.

2) Its 12 Standards (i.e., guiding principles for CDIO adoption and evaluation, and program continuous improvement) can be used to provide a framework for integrating the RM learning outcomes into a program. Specifically, Standard 2 can be applied to specify specific and detailed RM learning outcomes that can be validated for content and proficiency level by key stakeholders. Standards 3, 5, 6 and 7 provide guidance for introducing these learning outcomes in an integrated fashion. Standard 4 requires an introductory course that provides the framework for engineering practice in product and system building, in which RM concepts can be introduced. Implementation of Standards 8-12 ensures that faculty members have the required skills to teach RM, and that RM learning outcomes are taught with active and experiential learning methods and are evaluated for continuous improvement.

In this spirit, this paper provides a specific case study of how the CDIO framework is utilized to integrate RM into a curriculum. The scope of the paper will focus on the introduction of the RM concepts into an introduction to engineering course, and future development will focus on the integration into an entire curriculum. The rest of the paper is organized as follows. Section II of the paper describes a specific example of how the NASA NXM Risk Matrix was adapted and implemented in an introduction to mechanical engineering course at the California State University, Northridge. Section III of the paper provides an assessment of how well students are able to apply the technique in the project and discusses avenues for further developing the adoption of this technique as a generic framework so that it can be applied to the design-build projects in other courses throughout an engineering curriculum.

II. ADAPTATION AND IMPLEMENTATION OF NASA NXM RISK MATRIX

II.A. NASA NXM Risk Matrix and ME101

NASA's NXM Risk Matrix is a qualitative and semi-quantitative tool widely used by NASA, government organizations and industry for managing and communicating risk from conception to implementation of a system [12]. The matrix, shown in Figure 1, helps evaluate risk by comparing the likelihood of an unfavorable event occurring with the severity of the consequences should the unfavorable event occur. Each variable is rated on a 1 to 5 scale (N=5, M=5), with 1 being least likely or with the least consequence. Once the likelihood and consequences have been defined, a semi-quantitative measure of risk level is rated, with a corresponding risk level color with red being high, yellow being moderate and green being low. With these definitions, the matrix is used to communicate and facilitate discussion about the status and the effects of the RM measures throughout a project.

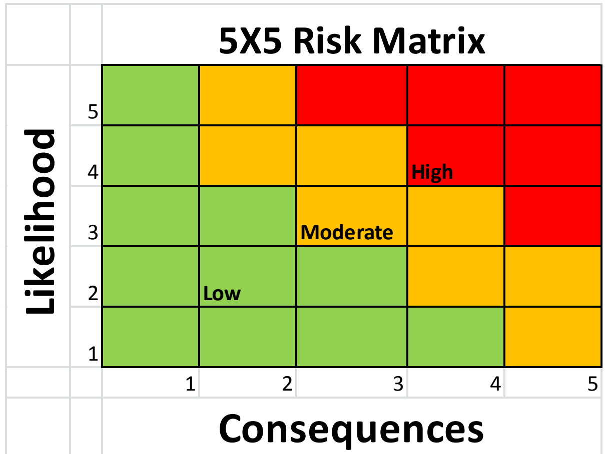

Figure 1- Risk Matrix

II.B. ME101 and RM Implementation

ME101 is an Introduction to Mechanical Engineering course at California State University, Northridge and is the first required course in the curriculum. Since 2006, it has been developed based on CDIO Standard 4 (Introduction to Engineering), which provides the framework for mechanical engineering practice in product and system building and introduces essential personal and interpersonal skills. The course introduces students to, and teaches, the Conceive-Design-Implement-Operate (CDIO) principle as context for engineering education through project-based learning. The two key learning outcomes related to the project include: 1) identify a complete mechanical design process of conceiving, designing, implementing, and operating (CDIO) a machine/product in a team-based environment; and 2) recognize key elements of project management, problem solving, critical thinking, written and oral communication skills, information searching, and engineering ethics. The first four weeks of the course cover a brief history of engineering, engineering majors, global and international engineering, future challenges in engineering, investment in engineering education and a statistical profile of the engineering profession. In the fifth week, students are introduced to their design-build project which is to be completed during the remaining 12 weeks of the course. In the design-build project, the students work in teams of four to five members to conceive, design, implement and operate two vehicles (one for distance and one for speed) powered by a mouse-trap. At the beginning of the project, each student is provided a design packet with instructions, due dates and examples. The content of the design package includes

1. Design Project Description
2. Team Contract, Code of Conduct, and Biography
3. Project Management Plan, PERT and Gantt charts
4. Engineering Design
    a. Stage 1: Identify the Problem

   b. Stage 2: Define the Working Criteria and Goals
   c. Stage 3: Research and Gather Date
   d. Stage 4: Brainstorm/Generate Creative Ideas
   e. Stage 5: Analyze Potential Solutions
      i. 5x5 Risk Matrix
      ii. Calculated Performance and Potential Solutions
      iii. Summary Chart including: Functional Requirements, Design Parameters, Analysis and References, Risk and Risk Mitigation Measures
5. Preliminary Design Presentation
6. Final Vehicle Development Components
   a. Stage 6: Develop and Test Models
   b. Stage 7: Make the Decision
   c. Stage 8: Communicate and Specify
   d. Stage 9: Implement and Commercialize
7. Competition
   a. Stage 10: Perform Post Implementation and Review Assessment
8. Final Design Presentation

Halfway through the project at the end of Stage 5, each team presents a preliminary design presentation to the class, detailing the contents of the design stages to date and their performance predictions. The final five stages are completed in the second half of the project's lifespan, and include building prototypes, selecting final designs, collecting vehicle test data, participating in a competition and making a final design presentation.

In Spring 2012, the 5 x 5 risk matrix was incorporated into ME101 and designed as an assignment that students have to use throughout the duration of the project. The 5 x 5 matrix assignment was accompanied by a lecture discussing the importance of risk management and a description of the MxN technique for identifying and classifying risk as part of a design build project. The first step to building the 5x5 risk matrix is to identify risks and translate them into risk statements. The students identify risks based on the specific goals they set in Stage 2 of the 10 stage design process, but explore any additional risks they feel are relevant. For instance, a team may have set a goal in Stage 2 that their mousetrap vehicle not travel more than three feet off course in either direction by the time it has reached a complete stop. The team would then translate this risk of traveling off course into a risk statement, which identifies the reason(s) their vehicle may travel off course. For example, "Poor wheel alignment may cause our vehicle to travel off course by more than 3 feet." With each risk statement, the students assign a likelihood and consequence value from 1 – 5, with 5 being the most likely to occur, and 5 being the most devastating consequences. Each statement is subjectively rated according to the student best estimation of the likelihood of an event occurring and the consequences should the unfavorable event occur. The risk statement number is then plotted on the 5 x 5 Risk Matrix so the students can communicate visually where the risk falls for that particular statement. Next, the teams create RM statements for each risk statement. They would attempt to decrease the overall risk of an unfavorable event occurring by lowering the likelihood, consequences, or both, of each statement. The students could mitigate the risk of traveling off course by stating that they have developed and tested a self-steering system for their vehicle, which keeps it on course. After writing RM statements for each risk statement, the students plot the risks on the matrix a second time to communicate visually how they have affected the risk of each statement.

Students turn in each section of Stage 5, including the 5 x 5 Matrix, a week before their preliminary design presentation. Each team's work is critiqued and suggestions are made before the presentation to allow time for changes. The 5 x 5 risk matrix is then included in the final design presentation that each team makes in Stage 8. After presenting, the instructor, student assistants and industry evaluators in the audience are given time to ask questions and critique the presentation and give students feedback in relation to their current progress.

III. EVALUATION RESULTS

Two sets of assessment data were collected to evaluate how well RM was added to the course and the ability of students to apply RM concepts in the project. The first set of data comes from a self-report survey and the second from the assessment of the Final Design Presentations by an industry evaluator.

III.A. Self-Report Survey

A self-report survey was designed and distributed to fourteen students in the course to obtain their perceptions of their comprehension of risk management techniques and to identify areas for making changes to improve the course in the future. Figure 2 shows percentages of the students' agreement/disagreement ratings of the survey's forced-response questions. For questions 1-5, at least 72% of the students agreed or strongly agreed that the instruction of the 5x5 matrix was easy to grasp and it is a useful tool for identifying risks and developing risk mitigation strategies. In comparison, question 6 received a lower rating where 34% of the students disagreed that writing risk statements is an easy task for them. However, as indicated in questions 7-11, it is encouraging to see that the students thought the matrix helped their team consider design changes and it played an important role in contributing to their success in the project. Importantly, 72% of the students felt that they could teach the matrix to other students and would use it in future design projects.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1. The instructions included in the design packet and lecture for completing the 5x5 matrix were clear and easy to understand.	0%	0%	17%	50%	33%
2. The 5x5 matrix had a clear purpose in the design process.	0%	0%	17%	67%	17%
3. The 5x5 matrix was a valuable tool in the design process.	0%	0%	22%	61%	17%
4. I found it easy to assign a numerical value to the likelihood of an undesirable event occurring using the 5x5 matrix.	0%	0%	6%	78%	17%
5. I found it easy to assign a numerical value to the consequences of an undesirable event occurring using the 5x5 matrix.	0%	0%	6%	78%	17%
6. I found it easy to come up with risk statements using the 5x5 matrix.	0%	6%	28%	56%	11%
7. The 5x5 matrix helped me see where our design was at risk of failure.	0%	0%	11%	67%	22%
8. The 5x5 matrix helped our team develop mitigation strategies to reduce risk of an undesirable event occurring.	0%	0%	11%	67%	22%
9. The 5x5 matrix led our team to consider design changes we would have otherwise not considered.	0%	6%	22%	50%	22%
10. The 5x5 matrix did not help our team at all.	33%	61%	6%	0%	0%
11. The 5x5 matrix contributed to the success of our project.	0%	0%	22%	67%	11%
12. I would be able to teach the 5x5 risk mitigation technique to a fellow student.	0%	6%	22%	50%	22%
13. I would use the 5x5 matrix in future design projects.	0%	0%	17%	50%	33%

Figure 2 – Self-Report Survey

III.B. Final Design Presentation Assessment and Future Improvement

William Munsch, a program manager at PWR, attended the project Final Design Presentations where Risk Management was included, and asked students questions related to their understanding of Risk Management and performed an assessment of the presentations after the event. The objective of the evaluation was to determine if the students grasped the basic concepts and terminology of Risk Management, and to determine if an appropriate level of application capability had been demonstrated for a first opportunity introduction course. It is not expected that students would be able to execute the process at a professional level, when they had only been exposed to Risk Management for the first time. Rather, an appropriate level of capability for first-time exposure would be grasp of the basic terminology along with an ability to converse using those terms, a basic understanding of the relationship of Consequence verses Likelihood on the 5 x 5 matrix, and a demonstrated ability to identify a risk followed by mitigation plans that would be expected to improve the risk posture.

Five project groups provided presentations about the design, fabrication, testing, and competition of their mousetrap race car. All five teams incorporated Risk Management into their projects. They completed brainstorm activities to identify risks and establish the 5 x 5 matrix, and developed mitigation plans and completed an after mitigation 5 x 5 matrix.

All five teams demonstrated the basic concepts in their presentations. Their risk statements were universally simplistic. A typical example from one presentation showing an appropriate level of understanding is, “Poor wheel alignment: Run off course.” The basic concept of a potential condition and a resulting consequence is demonstrated. An example from another team shows that they were not able articulate the relationship of condition leading to consequence; “Friction may be very high.” Being able to communicate this cause-effect relationship at a very basic level would be considered satisfactory in this project.

All teams recognized technical risks and attempted to provide mitigation plans. None of the teams recognized schedule or cost as risks to success, even though several articulated those issues during the presentations. Since this activity was actually a project that includes schedules, deadlines and team collaboration elements, the recognition of risks beyond basic technical performance would be expected.

Mitigation plans were universally one line per risk, however they were appropriately aimed at either reducing the likelihood or designing out the issue, hence the consequence. This is probably appropriate for this level of the curriculum. Most teams were able to demonstrate the appropriate movement of the risk on the 5 x 5 matrix relative to the type of mitigation they chose to implement. That is a common misconception, even at a professional level, so gaining that level of capability at an introductory level course is encouraging. Higher level courses would be expected to add the concept that a Mitigation Plan is truly a plan with multiple steps and can include complementary or fallback activities.

One team was able to recognize more risks as they worked the project and added them to their documentation along with mitigation plans. This is important, since it shows that they recognized Risk Management as a living part of the project, rather than just an event. Most teams were able to effectively respond to questions, although in a few cases they confused the concepts. One concept that was not clear from all the presentations was whether the final state 5 x 5 matrix represented a predicted state or an actual achieved assessment. Students at this level should be able articulate which they are showing. Higher level courses would be expected to include burn down plans and actual achieved results.

Overall, for a first attempt at incorporating the Risk Management process into an introductory engineering course, the results are very positive. The students demonstrated a working knowledge of the basic concepts and for the most part, were able to articulate those concepts correctly. Several results were identified that represent improvement opportunities for the next course, as well as expectations for higher level courses.

IV. DISCUSSION AND FUTURE DEVELOPMENT

The survey and Final Design Presentation results are in good agreement, and consistent in several aspects. First, they suggest that the students are able to: 1) identify the risks in a design-build project; 2) write simple risk statements that describe the likelihood of the undesirable risk/event occurring and the severity of the consequences should the undesirable risk/event occur; 3) research, implement and document mitigation steps to reduce the risks throughout the different phases of the project; and 4) discuss how the implemented mitigation steps affected each risk statement. Second, they both point out a common difficulty that students have in writing effective risk statements, which involves providing clarity and descriptive information regarding the condition present and the associate risk event. It is expected that students will get better at this with more practice writing cause-effect statements. It is also evident that the students possess a satisfactory level of proficiency and confidence in approaching risk mitigation as evidenced in their commanding use of the terminology and desire to teach the matrix to other students and use it in future projects.

To build on this and integrate RM method into the curriculum, a feasible path would be to introduce and teach RM in the department's design stem courses (ME101, ME186 Mechanical Design, ME286 Design for Manufacturing, ME386 Computer Aided Design and Analysis, and ME486 Senior Design) that span from freshman, sophomore, junior, to senior levels. The guiding principles for integration could include: 1) having at least three iterations of introducing and teaching RM between freshman and senior year; 2) increasing the levels of sophistication of risks and including all three types of risks (i.e., cost, schedule, and technical); 3) increasing the duration for risk monitoring to one year by ME486 Senior Design course; 4) involving multiple sub-system teams in a project in working together on common risks and developing interrelated and comprehensive risk mitigation strategies; 5) providing workshops to enhance faculty competence in teaching RM and share best practices; and 6) developing assessment tools and procedures for each design stem course.

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Biographical Information

Dr. Nhut Ho is a Mechanical Engineering professor at California State University, Northridge. He received his MS and Ph.D. from MIT. His current research focuses on systems engineering, design and evaluation of advanced automation tools, human factors engineering, product development, and higher education reform models. He is the leader in promoting CDIO in Vietnam, where he has engaged that nation in the curriculum reform effort and serves as CDIO Chief Advisor for Vietnam National University – Ho Chi Minh City and translated the CDIO book into Vietnamese.

Austin Davis is a Mechanical Engineering student at California State University, Northridge. He received his BS in Business from San Diego State University in 2007, and is currently pursuing a MS in Mechanical Engineering. He works as a Teacher's Assistant for the Mechanical Engineering 101 course and has helped in integrating risk management techniques into the introductory course at CSUN while aiding first year students with design build projects.

William Munsch graduated from San Diego State University in 1988 with a BS in Aerospace Engineering and from California State University Northridge in 1994 with a MS in Mechanical Engineering. He has worked at Rocketdyne for over 23 years in numerous engineering and program leadership roles on major propulsion programs. Some of the programs include MA-3, MA-5, MA-5A, RS-27, X-33, Integrated Powerhead Demonstration, RS-84, J-2X, RS-68 and THAAD. William has an extensive background in Risk Management on these various programs as IPT Leader, Program Chief Engineer and currently as Program Manager for THAAD. He is also active in the Industry Advisory Board for California State University Northridge Mechanical Engineering department.

Corresponding author

Dr. Nhut Ho
California State University, Northridge
18111 Nordhoff Street,
Northridge, CA 91324, USA
1-818-677-2187
nhuttho@csun.edu