AC 2010-1698: USING PROCESS FMEA IN AN AERONAUTICAL ENGINEERING TECHNOLOGY CAPSTONE COURSE

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Abstract

In the Aeronautical Engineering Technology program at Purdue University, undergraduate students gain experience in performance improvement in the capstone project courses. The performance improvement proposed and implemented by the students must also consider the impact on safety. Process Failure Modes and Effects Analysis (PFMEA) is one tool used in the aerospace industry to identify risks in products or processes, and to take action to mitigate or eliminate the risks. Using the SAE standard for PFMEA, students use a structured method to analyze the process steps and the associated risks. The capstone courses are a two-course senior capstone experience. In the first semester, the students prepare a proposal to redesign either a process or product for measurable, dramatic improvement. The projects affect real manufacturing and airport processes and products. In the second semester, students redesign and implement the improved process or product. The goal of the process redesign projects is typically to dramatically reduce process set-up time or process run time. Moreover, students must be made aware that process improvement must not decrease safety; rather the students must improve safety while improving other process performance measures. While there are many inclusions of product redesign in papers discussing capstone courses, this paper focuses on the use of PFMEA in capstone design, build, test and implement projects.

Constraints on time and resources are a reality for student projects. These constraints help prepare students for projects in their future careers. Using the PFMEA standard, students may concentrate improvement efforts on the high priority process steps. By considering process improvements that also include risk elimination or mitigation actions, the students improve the process performance and safety. Through this process, students have a greater understanding of process improvement techniques that lead to measureable improvements, and a greater understanding of the importance of using standards. This paper introduces PFMEA, presents the PFMEA method, and discusses PFMEA inclusion in senior aeronautical engineering technology courses.

Introduction

The Aeronautical Engineering Technology program at Purdue University is an ABET TAC accredited program. Undergraduate students take courses in aircraft sciences and systems, manufacturing processes, and general education topics prior to the senior year. The senior year has multiple capstone courses. This paper discusses the use of Process Failure Modes and Effects Analysis (PFMEA) in two capstone courses where students gain experience in proposing and conducting performance improvement projects.

The performance improvement projects proposed and implemented by the students must also consider the impact on safety. PFMEA is one tool used in the aerospace industry to identify risks in processes, and to take action to mitigate or eliminate the risks. Using the SAE standards for PFMEA, students use a structured method to analyze the process steps and the associated risks.

The process improvement projects are part of a two-course AET senior capstone experience. In the first semester, the students prepare a proposal to redesign either a process or product for measurable, dramatic improvement. The projects affect real manufacturing and airport processes and products. In the second semester, students redesign and implement the improved process or product. The goal of the process redesign projects is typically to dramatically reduce process set-up time or cycle time. Moreover, students must be made aware that process improvement must not decrease safety; rather the students must improve safety while improving other process performance measures. While there are many inclusions of product redesign in papers discussing capstone courses[1, 2], this paper focuses on the use of PFMEA in capstone design, build, test and implement projects for process improvement.

Student projects are constrained by the amount of time available to work on the projects, the resources available to improve the processes, and the necessity of the semester schedule. These constraints help prepare students for projects in their future careers where time, resources, and schedule seldom seem adequate. Using the PFMEA standards, students may concentrate improvement efforts on the high priority process steps. By considering process improvements that also include risk elimination or mitigation actions, the students improve the process performance and safety. As a result, students have a greater understanding of process improvement techniques that lead to measureable improvements, and a greater understanding of the importance of using standards. This paper introduces PFMEA, presents the PFMEA method, and discusses PFMEA inclusion in senior aeronautical engineering technology courses.

Process Failure Modes and Effects Analysis

Failure modes and effects analysis (FMEA) is a tool used in many industries such as automotive and aerospace, and by the military and NASA. FMEA standards have been established since the 1960's such as Mil-Std 1629A and SAE J1739 [3, 4]. There are also other standards for FMEA such as IEC 60812 and SAE ARP5580. There are two SAE standards: J1739 is for automotive, and ARP5580 is the aerospace recommended practice.

The SAE J1739 standard identifies the intended use of FMEA as a "before-the-event" way to reduce the probability of needing corrective action for failure modes after the process or product is implemented [4]. The FMEA is a continuous improvement tool that is useful three major applications: new designs or processes, changing existing designs or processes, and using existing designs or processes in new environments or applications [4]. In the J1739 standard, there are three major types of FMEA used to analyze risks: function, process, and machinery [4]. In Process FMEA (PFMEA), the analyst identifies and analyzes the risks associated with each step in the process. PFMEA is discussed in this paper as it relates to how it is implemented in senior level aeronautical engineering technology capstone courses at Purdue University. The SAE J1739 standard was selected over the ARP5580 due to the J1739 being immediate available and easy access for students in the university libraries which has the J1739 standard online. As the university library changes its online collections, the use of other standards such as the ARP5580 may be considered for adoption in the courses.

PFMEA Method

One approach to process FMEA is presented in SAE standard, SAE J1739 [4]. Figure 1 contains a form modified from SAE J1739. The process adapted for the AET courses is shown in Figure 2[6].

Process Step	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Causes of Failure	Occurrence	Current Controls	Detection	RPN	Recommended actions	Responsibility/ Date	Actions Taken	Severity	Occurrence	Detection	RPN
1	2	3	4	5	6	7	8	9	10	11	12				13

Figure 1. Process FMEA Form modified from SAE J1739 [4,6].

Analysis Focus	Questions
Current Process (on FMEA form)	1. What are the required steps in the process?
	2. What can go wrong (failure modes)?
	3. What are the effects when it goes wrong?
	4. How bad is it? (rating of severity S)
	5. What are the causes?
	6. How often does it happen? (rating of occurrence O)
	7. How is this cause prevented or detected?
	8. How good is this method at detecting and/or preventing the cause from happening? (rating of detection D)
	9. What is the risk priority number (RPN = SxOxD)?
Prioritization (answered off the form)	Which steps have the highest RPN?
	Which steps are the most severe? (highest S ratings)
Improved Process (on the FMEA form)	10. What product or process changes can be made? What special controls can be added?
	11. Who is going to make the changes happen? By when?
	12. What actions were taken?
	13. What are the new severity, occurrence, and detection ratings? What is the new RPN?

Figure 2. PFMEA Questions (adapted from Johnson &Ropp)[6]

In Figure 1, each column has a number that corresponds to the question being asked in Figure 2. Questions 1-8 and 10 are similar to those asked by SAE J1739[4]. To further explain the method, questions 9 and 11-13 are added [6]. The analyst answers the questions shown in figure 2 to fill in the form. The numbered questions in figure 2 correspond to the numbers shown inside the form in figure 1. As these answers may require specific expertise in multiple areas, the PFMEA process is usually conducted by teams.

Three separate areas of focus are needed to complete the PFMEA analysis: current process, prioritization, and improved process (see Figure 2) [6]. The current process is the focus in questions 1-9. After completing the entire form for questions 1-9 for the current process, the team analyzes the process and identifies the process steps to focus on first for improvements. These are the two questions in Figure 2 that do not appear on the form in Figure 1. Finally, the team focuses on improvements to be made to the process by answering questions 10-13. These three major areas of focus are best completed in three separate time periods. There should be no expectation that a team should address all of the questions in this analysis in one sitting.

As the team focuses on the current process, the team gains agreement on the boundary of the process (where it starts and stops) and focuses the efforts of the team and stakeholders. Failure modes are completed for each process step. Steps may have multiple failure modes and should be listed even if the failure has not yet occurred. The failures do not have to include extremely rare situations known as 'acts of God' [5]. The causes of each failure mode and any current devices, procedures or sensors in place to detect a failure are listed. Severity, occurrence and detection ratings are listed next. When beginning this process, it is recommended that the team start with the scales shown in the standard, then modify the language in the scale descriptions to better fit the needs of the team. SAE J1739 has defined scales from 1 (lowest) to 10 (highest) and a description for each level of severity, occurrence and detection. RPN is the risk priority number and is calculated by multiplying the ratings for severity, occurrence, and detection so that RPN = S x O x D.

After completing the current process portion of the form, the team begins to prioritize improvement efforts as shown in Figure 2 by answering two questions: a) Which steps have the highest RPN?, and b) Which steps are the most severe? The team must answer both questions because simply focusing on the highest RPNs, the team may miss risks. The team must address the highest RPNs and the highest severity steps (usually rated 9 or 10). This analysis requires that teams make decisions about which failure modes to address first. Most teams would prefer to address all of the failure modes, but limitations of time and resources may constrain the selection and completion of process improvements. This contraint requires the team to focus on the failure modes that will lead to the most impact on severity and RPN.

The team uses the current process information and the results of the analysis to develop ideas for process improvements. The team considers several process improvement alternatives before deciding on the plan to improve safety, shown by a reduced RPN. Specific recommendations are recorded on the form along with the responsible person and planned date of completion. During the improvement of the process, the team records the actual actions taken and recalculates the RPN. Process owner buy-in is critical to lasting process improvements. The process owner is the person who is responsible for the process after the team has completed the improvements. The team works with the process owner to implement the process changes. The process owner must ensure that personnel are trained in the new methods and understand why the improvements are necessary. In this manner, the process owner ensures that the process improvements remain in place.

PFMEA in Capstone Projects

PFMEA is used in AT497 Applied Research Project as one standard method to assess risk of alternate designs for processes. AT497 is a 3 semester credit hour course with 2 hours of lecture and 3 hours of lab each week, and is taught in the spring semester. In the previous fall semester, the students form teams and prepare project proposals in AT496 Applied Research Proposal, a one semester credit hour course. The project proposals follow an outline shown in Table 1.

Executive summary
Table of Contents (with a page-numbered outline)
- **I. Introduction**
- **II. Statement of the problem**
- **III. Significance of the problem**
- **IV. Goal of the project**
- **V. Definitions**
- **VI. Assumptions**
- **VII. Scope and Applicability**
- **VIII. Annotated Bibliography**
- **IX. Design Requirements**
- **X. Procedures**
- **XI. Time Action Plan for the Spring Semester**
- **XII. Anticipated Impact and Resources Required**

Appendix A: Cited Materials
Appendix B: Presentation Slides

Table 1. Outline of Project Proposal

In the ***X. Procedures*** section of the proposal, the teams identify the steps planned for the process improvement. The procedures for the capstone projects must be one of the Lean Six Sigma methodologies, either DMAIC or DMEDI[7]. Process improvement projects use the DMAIC methodology where Define, Measure, Analyze, Improve, Control are the five phases. In the D or Define phase, the teams identify the problem, potential impact and costs, team members, design requirements, and measures of impact. The initial PFMEA is conducted during the M or Measure phase of the Lean Six Sigma methodology. During the Analyze phase, teams use the PFMEA and the risk priority number to identify steps in the process that need to be addressed. During the I or Improve phase, the teams develop the new process and reassess the process using PFMEA to determine the new risk priority number. The C or Control phase, the teams transition the process to the process owner (usually a faculty member in charge of the lab or administrative area). In the project report due near the end of the spring semester, the students compare the before and after states of the process to measure the effect or impact of the process improvement. The projects have different potential impact measures, but one of the required measures is the difference in risk priority number. The teams present in the project reports the impact and the costs. The teams compare the hours and dollars budgeted for the project versus the actual hours and dollars spent.

The use of standards is emphasized by the instructor of AT497. All of the projects in the course must use a form of FMEA. The students may choose to use either an SAE standard or the FAA handbook method known as FMECA [6]. The teams identify the choice of method in the proposal in the ***X. Procedures*** section, in the description of the Measure phase effort. This paper focuses on the use of SAE standards for PFMEA.

One of the projects completed in spring 2009 involved a process improvement for the operation of a dynamometer in the engines laboratory. The team used SAE J1739 and the SOD scales provided in the standard. Another team used the standard in their project to improve a composite layup procedure. Below are two examples of partial PFMEA tables in figures 3 and 4.

Process Step	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Causes of Failure	Occurrence	Current Controls	Detection	RPN	Recommended actions	Responsibility/ Date	Actions Taken	Severity	Occurrence	Detection	RPN
Start dyno	Coolant reservoir depleted	Dyno overheats	9	Return pump malfunction	2	Training	9	324	Write a pre-run inspection checklist	JB / 4/7	Written checklist prepared	9	1	1	9
			9	Coolant not at required level prior to start	2	Training.	9	324	Mark the min. coolant level. Write a pre-run inspection checklist.	Evan / 4/15	Written checklist and visual procedures prepared	9	1	1	9
			9	Hole in coolant line	2	Training	4	72	Write a pre-run inspection checklist	Evan / 4/15	Written checklist prepared	9	1	1	9

Figure 3. Partial PFMEA for Dynamometer and Engine Test Stand Operation

Figure 3 shows the process step “start dyno”. This step is actually step 3 of the process steps listed in the complete PFMEA. This partial PFMEA is presented here to emphasize and illustrate the multiple causes of failure for one failure mode of one process step. The team analyzed the complete PFMEA and concentrated improvements on the highest RPNs and highest Severity ratings. Therefore, the team addressed all of the potential causes because each had a severity of 9, even though the third potential cause had a relatively low RPN. The action taken by the team was to prepare written and visual procedures that include pre-run inspection checklists and operational procedure. To address the coolant level, the team included on the checklist to ‘check the level of coolant in the coolant tank; add coolant if below 100 gallons’, and ‘inspect the coolant hoses used by the dyno for condition and security of attachment’. After implementing the improvements, the team estimated the RPN moved from 324 to 9 for two causes, and from 72 to 9 for the third cause.

Process Step	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Causes of Failure	Occurrence	Current Controls	Detection	RPN	Recommended actions	Responsibility/ Date	Actions Taken	Severity	Occurrence	Detection	RPN
Lay-up fiberglass	Resin sets too fast	Redo layup	6	bad mix	1	Training	4	24							
	Resin does not set	**Redo layup**	**6**	**bad mix**	**4**	**Training**	**4**	**96**	**Check Shelf life; follow written procedures**	**Terry / 4/10**	**Visual procedures prepared; added shelf life check to inventory procedures**	**6**	**1**	**1**	**6**
	Impurities in material	Rework to remove impurities	2	poor housekeeping	4	Training	4	32							
	Voids in material	Rework to fill voids	2	poor layup practices	4	Training	4	32							

Figure 4. Partial PFMEA for Composite Layup Procedure

Figure 4 shows the process step 'lay up fiberglass' from a highly detailed PFMEA prepared by a student team. The complete PFMEA shows multiple failure modes many of the over 40 process steps spanning several pages. Figure 4 shows four failure modes for a single step, taken from the complete PFMEA. This partial PFMEA illustrates the focus of the team on the highest RPNs. The team moved the RPN from 96 to 6 for one step in thre procedure by developing and implementing visual procedures, and by implementing a shelf life check to the inventory procedure.

In the project oral presentations and written reports, the teams demonstrate the use of PFMEA in the process improvement projects. In addition to other process measures, the teams must show the before and after analyses of the process. The use of PFMEA helps the team improve the safety of the process and the other process performance measures during the improvement projects. This course capstone project is the first time these students are exposed to the SAE standards for FMEA. The instructor introduces many standards in the course in order to improve the knowledge of students, increase the use of standards, and have students better understand the need for and the methods for lifelong learning.

Conclusion

Process Failure Modes and Effects Analysis (PFMEA) is one tool used in the process improvement projects in a two-course capstone series at Purdue University. Using the SAE J1739 standard for PFMEA, student teams use a structured method to analyze the process steps and the associated risks to improve safety of the process along with other process performance measures. The required use of a standard makes safety an explicit priority for improvement. The SAE J1739 standard provides a method of measuring the amount of improvement by comparing the RPN of the improved process to the current process. The projects change real manufacturing and airport processes and products in use at Purdue University airport. The goal of the process redesign projects is typically to dramatically reduce process set-up time or process run time. With the explicit use of PFMEA standards, students are made aware that process improvement must not decrease safety; rather the students must improve safety while improving other process performance measures. Using the PFMEA standard, students concentrate improvement efforts on the high priority process steps. Through this process, students have a greater understanding of process improvement techniques that lead to measureable improvements, and a greater understanding of the importance of using standards.

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