2021 ASEE ANNUAL CONFERENCE
Virtual Meeting | July 26–29, 2021 | Pacific Daylight Time
Paper ID #33418

Using SAE Resources in FMEA in an Aeronautical Engineering Technology Junior-Level Logistics Course

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Abstract

SAE standards are widely used in the aerospace industry. The use of standards in classroom settings introduces students to industry standards that reinforce the importance of standards and lifelong learning. Undergraduate students gain experience in system cost and risk improvement in a design support analysis course. A semester-long project forces the students to evaluate a design for impacts to cost and safety. Failure Modes and Effects Analysis (FMEA) is one tool used in the aerospace industry to identify risks in products or processes and to act to mitigate or eliminate the risks. Using the SAE ARP5580 standard and SAE's Reliability Program Handbook TAHB009A for FMEA, students use a structured method to analyze and identify potential failure modes while evaluating an aerospace design.

While there are many inclusions of product redesign in papers discussing capstone design courses, this paper focuses on the use of FMEA in a Design Support Analysis course in an Aeronautical Engineering Technology program at a junior level. The course includes lectures, videos, quizzes, and the final project. The goal of the final project is to dramatically reduce life cycle costs through maintenance reductions, a priori failure identification and analysis, and subsequent reliability and maintainability improvements. This paper introduces the FMEA process as described in SAE ARP5580, presents the FMEA method as completed in the course, and discusses FMEA changes that could be incorporated to improvements to the course.

Keywords: standards, FMEA, logistics, engineering technology

Introduction

The use of standards in the aerospace industry is widespread. Standards are used for wide ranging purposes such as heat treatment of forgings or glass cleaner. Standards are also used for processes such as reliability tasks, including a Failure Modes and Effects Analysis (FMEA). A FMEA is used throughout the product design schedule and is a tool, that if effectively employed provides great reward to the design by reducing failures and decreasing life cycle costs.

Just as engineering technology students in preparation for a career in aerospace should learn how to use other tools like an ohm meters, torque wrenches, and CAD programs, they should also understand how to use process tools. Many aeronautical engineering technology students find themselves in careers where they are tasked with the analysis of a system before the design is completed. Tools such as cause and effect fault trees, FRACAS, life cycle cost calculation. One process tool that is often used in industry is the FMEA.

There are many standards which describe the process for developing a FMEA. The US Military once used MIL-STD-785, but it was cancelled in 1988. Now they have GEIASTD0009. Numerous website and organizations such as Six Sigma include processes for completing a FMEA.

To prepare students for careers in quality and reliability, it is important for them to learn about FMEA. Traditionally students have been introduced to FMEA at the capstone or senior level. This paper introduces junior level students to the FMEA process, as described in SAE ARP5580, presents the FMEA method as completed in the course, and discusses FMEA changes that could be incorporated to improvements and greater alignment to the standard to the course.

FMEA in Engineering and Engineering Technology Courses

The literature on the use of FMEA as a component of capstone or senior design courses in engineering and engineering technology programs typically describes the use of the tool in the educational environment and the expected student outcome. These papers were selected to demonstrate the variety of applications across engineering and engineering technology disciplines.

A four-course sequence of Design for X (DFx) is part of a mechanical engineering curriculum where the fourth course is a senior course in Advanced Design Methodologies that has a FMEA component [1]. The student teams are exposed to FMEA in lectures and use FMEA in design project assignments. The students analyze their design in terms of a severity-occurrence-detectability score, demonstrate understanding of the implications, and make changes to the design as needed. Their pedagogical approach seeks to combine DFx and FMEA so that students learn theory and gain from hands-on applications. "The learning outcome for students is a method that they can systematically identify and correct potential product or process deficiencies before they occur" [1, p 29].

Process FMEA is used in the aeronautical engineering technology two-course series of capstone design. The course used FMEA standard SAE J1739 over the SAE ARP5580 due to the availability of J1739 to the students by accessing the university libraries' collections [2]. A series of process FMEA questions were developed and used to guide students through the critical thinking needed at each step of the form [2], [3]. Because baseline process design FMEA and improved process design FMEA analyses were required, the capstone project focused students' attention on improving process performance and that must include improving safety [2].

A three-course sequence in capstone design in mechanical engineering seeks to integrate product design and development with project management. There is an engineering design methods course taken in the junior year, and a two-semester capstone sequence in the senior year [4]. The engineering design methods course has FMEA analysis as one of the course topics and deliverables in the risk, reliability, and failure assessment area [4]. One of the course learning outcomes is the student's perception of the importance and proficiency of using failure analysis tools.

A single-semester senior system design course in a mechanical engineering technology program includes FMEA in Phase 3 Detail Design of the six-phase product development process used in the course [5]. The FMEA was used to evaluate safety and revise the product designed in the course. Students were able to identify possible failures and actual failures that occurred during the design course and include these in their FMEA [5].

In a single-semester, senior level, aerospace systems engineering course in an aerospace engineering program, FMEA is required during the design, build, fly project [6]. The course is spread over 44 meetings, punctuated by a series of 13 technical interchange meetings (TIM) and three design reviews before culminating in a performance acceptance demonstration and final briefing [6]. FMEA is a deliverable in draft form for the third TIM, and a final FMEA is a deliverable in the ninth TIM.

FMEA Process by ARP5580

SAE International's Aerospace Standard Aerospace Recommended Practice 5580 (ARP5580), *Recommended Failure Modes and Effects Analysis (FMEA) Practices for Non-Automobile Applications* (SAE, 2020) identifies and describes a process for developing a FMEA. The process begins with gathering experiential data and requirements. If the design is new then the next step is to postulate failure modes. If there is existing data, then that data is accessed. Regardless of which data is used, the next step is to complete a failure latency analysis, or a fault tree. Finally, the FMEA is documented and reported.

The process for developing a FMEA in ARP5580 begins with identifying when the FMEA is to be developed and what type of FMEA is to be completed. During system design there are multiple types of FMEA to be completed at different points of the development schedule. During the conceptual design the effort is focused on planning. Moving into the preliminary stage a functional analysis is completed. During the detailed design and development stage both an interface analysis and detailed analysis or an update to the functional analysis is completed. A verify analysis is completed along the design verification and validation stage. Finally, a field analysis is completed while the product is in use and being supported.

Where there is not a perfect one to one match, based on the requirements of the course, the best option for a FMEA for the students to complete is the functional analysis. The purpose of a functional FMEA is to reduce design uncertainty through the assessment of the functionality of the system [7]. The functional FMEA analyses the functions of an item, not the components [7]. The functional FMEA begins with a functional diagram. To analyze the system, each function is failed one at a time and documented on worksheets. The worksheet format is shown in figure 1.

Version Date:
Analyst:
End Item/Process Identifier:
Subsystem/Subprocess Identifier:

Modeled End Item						**Failure Mode**										
Item/Function/ Action Name	Item/Function/ Action Identifier	Failure Mode	Failure Mode Idenifier	Failure Mode Probability	Fault Equivalence Identifier	Operating Mode	Operating Mode Identifier	Local Effect(s)	Next-level Effect(s)	End-level Effect(s)	Severity	Compensating Provision(s)	Detecting Monitor	Detection Method	Remarks

Figure 1. Functional FMEA Worksheet format [7]

FMEA Process in AET Course

The junior level course provides students with the concepts, processes, and tools regarding the review and analysis of system designs. The students learn the elements of logistics and the effect of design on the maintainability, reliability, and supportability of a system. Student outcomes for the course are related to design related logistics items such as reliability, maintainability, availability, and system failure identification. Students are expected upon completion of the course to determine Mean Time Between Failure (MTBF), identify top cost and reliability drivers, calculate system availability, calculate life cycle costs, and identify potential failure modes of a system.

Students accomplish these goals through the completion of a thirteen-week project. The students work in teams of four or five students, depending on the class size. The goal of the project is for the students to identify a flight training aircraft to be used for the Paper Airplane Flight School. The students are provided documents with the ground rules for the project, reporting requirements, design and operating requirements, and the project rubric in the form of Contract Line Items (CLINs).

The first activity the students complete is a project schedule. The schedule is established at the beginning of the semester. While there is a mid-semester status review where the students present what they have completed in their projects till that point, there is no requirement for what must be completed at that point. There are no interim deliverables for the course. Once they establish the schedule, they are not allowed to change it. If they run late, which they often do, they are only allowed to report the delay, not re-baseline. There is no penalty for delays in the schedule. On a weekly basis they present a short status of the program. This is similar to a common industry process for reporting program status. The one-page slide includes “Accomplishments”, “Next Steps”, “Issues”, and the program schedule.

Once the students complete the schedule, they proceed through steps to complete a simplified logistical design analysis and evaluation of a design choice beginning with a need analysis, house of quality, life cycle costs, and failure mode identification. This paper focuses on the failure mode activity of the project.

In the AET course, students do develop a functional diagram, however, it is not used as the sole source of data to pull from for the FMEA worksheet. Students develop a cause-and-effect diagram. Specifically, a fishbone or Ishikawa diagram. Students complete the fishbone diagram one of two different ways. One way is to analyze the system based on failures, see figure 2 for an example. Other students do complete the fishbone by function, see figure 3.

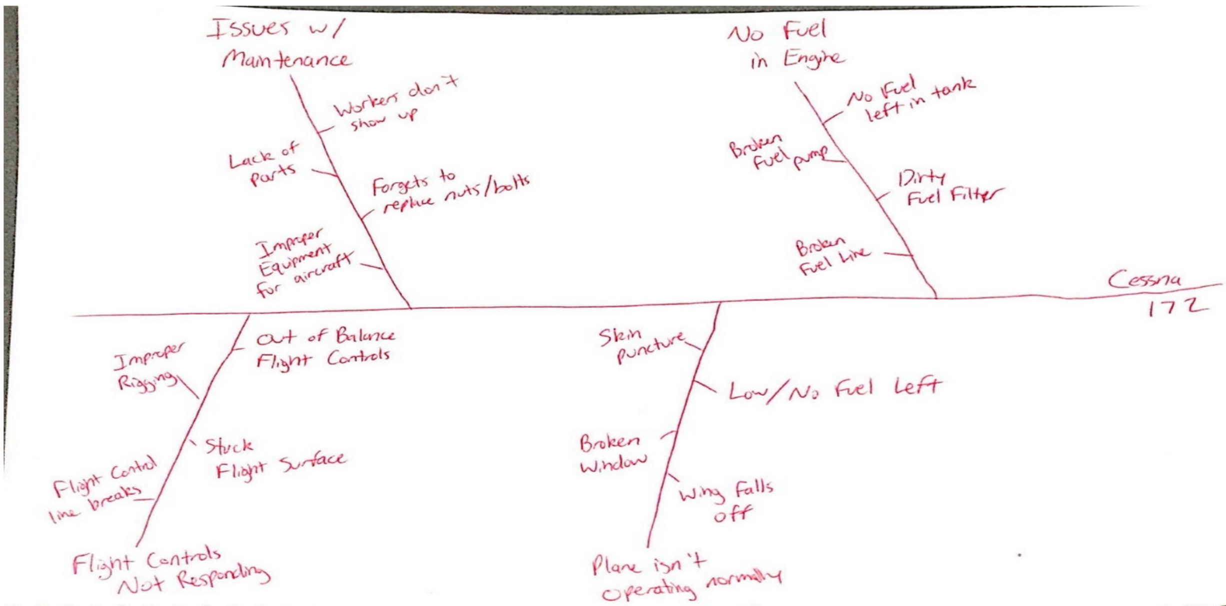

Figure 2. Student example of fishbone diagram by failure.

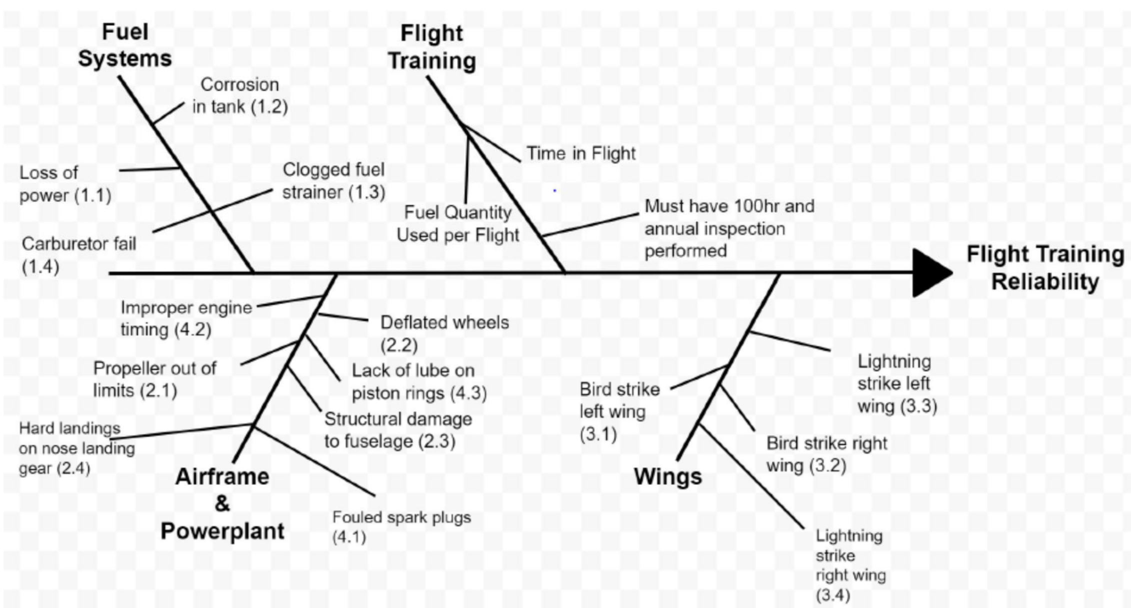

Figure 3. Student example of fishbone diagram by function.

In order to simplify the process, students use these diagrams to begin development of their FMEAs. Students build the FMEA based on how the decisions and diagrams develop organically. Students are provided examples of how to build both the diagram and FMEA, but limited direction on how to build them. Students are allowed and encouraged to ask questions of the instructor, of course. Student examples of FMEAs based on failure (figure 4) and function (figure 5).

Reference Number	Process Description	Failure Mode	Cause of Failure	Effect of Failure	Likelihood of Occurrence	Severity (How Critical)	Likelihood of Detection	RPN
1	All Screens Operating Displaying Correct Data	Avionics failure						
1.1			Bad Wiring	No Data Displayed	2	8	3	48
1.2			Excess Vibration		3	5	10	150
1.3			Improper Connection		4	2	10	80
1.4			Out of Calibration	Incorrect Data Displayed	5	9	1	45
2	Flaps Move Up and Down	Flaps Not Extending						
2.1			Flap Tracks Dirty	Flaps Jam / Limited Travel	5	10	10	500
2.2			Faulty Actuator	Flaps Do Not Operate	4	10	4	160
2.3			Bad Wiring		2	10	1	20
2.4			Bad Switch		3	10	3	90
3	Engine Operates Within Manufacturers Specifications	Engine Not Operating Properly						
3.1			Fuel System Contaminated	Engine Runs Poorly / Excessive Vibrations	2	9	2	36
3.2			Plugs Fouled		6	9	6	324
3.3			Mags Not Timed		3	7	5	105
3.4			Valves Worn		2	3	2	12
4	Fuel System Runs With Good Pressure	Fuel System Leaks						
4.1			Boost Pump Gasket Failure	Decrease In Range	3	3	10	90
4.2			Welds Cracked On Tank		1	10	8	80
4.3			Loose Fuel Fittings		6	9	9	486
4.4			Worn O-rings		7	6	8	336

Figure 4. Student example of FMEA by failure

Reference Number	Process Description	Failure Mode	Cause Failure	Effect of Failure	Likelihood of Occurance (1: unlikely, 10: likely)	Severity (1: not critical, 10: severe)	Likelihood of Detection (1: detectable, 10: undetectable)	RPN		Sorted Cause Failure	Sorted RPN
1.1	Functional Flight	Structural	Fatigue Cracks	Loss of Structural Integrity	5	8	5	200		Corrosion (Structural)	700
			Corrosion	Loss of Structural Integrity	10	10	7	700		Corrosion (Powerplant)	630
			Improper Fastener Insallation	Fastener faliure, Smoking rivets, Oversized holes, overly bucked rivets, over-torquing	8	7	4	224		Corrosion (Fuel System)	441
1.2	Functional Flight	Powerplant	Detonation	Vibration, severe engine damage loss of power	5	6	3	90		Improper Fastener Installation	224
			Corrosion	Loss of Structural Integrity	10	9	7	630		Fatigue Cracks	200
			Clogged Oil Filter	no circulation of oil, engine over temp.,	4	6	3	72		Pre-Ignition	100
			Pre-Ignition	Vibration, severe engine damage, loss of power	2	10	5	100		Detonation	90
1.3	Functional Flight	Landing Gear	Leakages	loss of braking force, hydraulic fluid spills and pools in the plane, toxic fluids on components under leaks	3	10	2	60		Hydraulic Blockage	81
			Brake Failure	Tire failure, likely crash if plane cannot slow down, flat spots on tire, overstressed thrust reversers,	3	10	1	30		Clogged Oil Filter	72
			Hydraulic Blockage	Loss of Function, Dangerous Landing Conditions	3	9	3	81		Leakages	60
			Incomplete Deployment	Dangerous Landing Conditions, super scratched fuselage, landing gear through the bottom of the fuselage	1	10	1	10		Fuel Leak	60
1.4	Functional Flight	Fuel System	Fuel Leakage	Loss of power, engine fire	3	10	2	60		Carburator Failure/Fuel Injection Failure	60
			Corrosion	Loss of Structural Integrity	7	9	7	441		Clogged Filter	36
			Clogged Filter	starves the engine for fuel, loss of power, FOD damage in engine	6	3	2	36		Brake Failure	30
			Carburator Failure/Fuel Injection Failure	a rich or weak fuel air mixture, loss of power, over-powered	2	10	3	60		Incomplete Deployment	10

Figure 5. Student example of FMEA by system

The students then take that information and use it to create the basis of a simple Failure Modes and Effects Analysis (FMEA). The FMEA in the course is a modified and simplified combination of a FMECA from MIL-STD-1629A and a process FMEA from SAE's Reliability Program Handbook. The analysis worksheet headings for the FMEA are shown below in Figure 6.

Reference number	Process description	Failure mode	Cause of failure	Effect of failure	Likelihood of occurrence *1 good 10 bad*	Severity (How critical) *1 good 10 bad*	Likelihood of detection *1 good 10 bad*	RPN

Figure 6. FMEA worksheet headings used in this class.

Once students complete their FMEA, they have the opportunity as part of extra credit for the program to identify a modification or redesign of a system based on the findings from the FMEA.

Students will report findings from the FMEA and calculate the Risk Priority Number (RPN). Students report RPN findings using a ranked bar graph. The next step of the process requires the identification and creation of a maintenance, repair, or inspection task determined by the findings of the FMEA.

Next Steps

The course as currently structured does not follow the process laid out by ARP5580. While the incorporation of FMEA can be tailored to each situation, and processes are recommendations, not prescriptive. There are areas where more alignment with the standard is desirable.

The first step for better alignment with the standard is to provide greater visibility of the uses of standards, SAE ARP5580 specifically, and its process. Students need to understand where the process comes from, who should be using it, and how the standard is applied in different situations.

Another improvement is to modify the worksheet to better align with the standard. There is value in teaching the students what a Risk Priority Number (RPN) is and how it can be used. However, the RPN is not part of the functional FMEA worksheet as described in ARP5580. Any modification made to the worksheet used in class to align more with ARP5580 format will still include the calculation of the RPN.

Consistency in the scoring of the RPN elements is needed. Currently, students choose their own scale for scoring. Groups may have different criteria and this leads to scores that are not consistent between groups. Standards that identify criteria for numeric scores can be given to students for incorporation into the process (e.g. SAE J1739 [8]). This may reduce the inconsistencies between groups in scoring. For example, ARP5580 has a metric for scoring severity. Though the criteria do not include a numeric value for RPN calculation, it is easy enough to assign a numeric value. The three levels in SAE ARP5580 are critical, essential and non-essential. Critical are the functions "for which the occurrence of any failure, condition, or design error would prevent the continued safe flight and landing of the aircraft" [7]. Essential are the functions "for which the occurrence of any failure, condition, or design error would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions" [7]. Non-essential are the functions "for which failures or design errors could not significantly degrade aircraft capability or crew ability" [7].

Conclusion

The paper discussed the execution of FMEA in a junior level engineering technology design course. The existing process, developed over many years, aligns mostly with SAE ARP5580; however, there are areas where the course can easily incorporate additional information and direction from the standards. SAE, International has developed a relatively simple-to-understand process for the development of a FMEA. By reviewing, at a simplistic level, a FMEA at the junior level, this better prepares the students for greater depth of use in their capstone courses.

References

[1] A. Asgari, C. Yang, and B. F. Rolfe, "Modern enhancements in teaching design theories to mechanical engineering students", *Australasian Journal of Engineering Education*, Vol. 18, No. 1, pp. 25-34, 2012.

[2] M. Johnson, *Using Process FMEA in an Aeronautical Engineering Technology Capstone Course*: 2010 Annual Conference & Exposition, Louisville, Kentucky. 10.18260/1-2—16670. [Online]. Available: https://peer.asee.org/16670.

[3] M. E. Johnson and T. D. Ropp, "Safety and Process Improvement using PFMEA in Aviation Courses and Laboratories," *ATEC Journal*, vol. 31, no. 2, pp. 10-17, 2009.

[4] S. K. McConomy, R. Soman, N. Gupta, and C. Shih, 2018, *Continued Development of an Integrated Capstone Design Curriculum:* 2018 ASEE Annual Conference & Exposition, June 23, 2018, Salt Lake City, Utah. 10.18260/1-2—30222.

[5] A. Xiao, R. Alba, O. Yasar, A. Zhang, and G. B. Gailani, *Senior Design Case Study: Application of System Engineering Concepts in the Design of a Router*: 2019 ASEE Annual Conference & Exposition, June 2019, Tampa, Florida. 10.18260/1-2—33258.

[6] M. C. Hatfield and D. Thorsen, *UAS Aerospace Projects as a Catalyst for Interdisciplinary Engineering:* 2019 ASEE Annual Conference & Exposition, June 2019, Tampa, Florida. 10.18260/1-2—33467.

[7] *SAE Recommended Failure Modes and Effects Analysis (FMEA) Practices for Non-Automobile Applications*, SAE Standard ARP5580, 2020.

[8] *SAE Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA)*, SAE J1739, 2009.