AN INTRODUCTION TO FAILURE MODE

AND EFFECTS ANALYSIS (FMEA)

by

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An Introduction to Failure Mode and Effects Analysis (FMEA)

Thesis directed by Professor Karen Kafadar

ABSTRACT

Failure Mode and Effects Analysis (FMEA) is a developmental tool used to identify failures and effects on systems, products or services. In addition to identifying failure modes and failure mode effects, FMEA provides for quantification and categorization of failure information in order to allocate and prioritize resources for risk abatement. The greatest impact of FMEA is in pre-production phases of new product or system development in order to provide for failure free systems and products during implementation. FMEA is a versatile tool that has many expressions and can be integrated with statistical and software tools to provide for a comprehensive view of risk.

This abstract accurately represents the content of the candidate’s thesis. I recommend its publication.

Signed __________________________
Karen Kafadar
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CHAPTER 1

INTRODUCTION

Current criteria for the success of consumer goods rely upon product introductions that are as failure free as possible. The costs associated with defective products from a liability or lost consumer standpoint can have dramatic impacts on a company. In a business environment that is becoming extremely competitive and global, the presence of failures in a system, product or service, can only serve to destabilize a company financially. Indeed, many companies have failed due to the inability of providing a product that is able to meet basic customer expectations and requirements.

The definition of failure is the inability of a system or product to meet a required function. Failures can be dramatic and sudden or subtle and gradual resulting in system or product degradation. Defective consumer products from common household appliances to much publicized automotive recalls have impacted from a few to millions of individuals. Not only product failure but even breakdowns in a service are potentially damaging. A misdiagnosed patient in a hospital as a result of a communication failure can be harmful to the patient and to the reputation of the hospital itself.

With increasing technological sophistication, the problem of finding and correcting failures is becoming more complex and at the same time increasingly imperative. The need for "first pass manufacturing", in which a product or service has been made failure free prior to widespread implementation, is critical. No longer are product recalls or field fixes feasible, desirable or cost effective. Figure 1.1 shows the cost associated with fixing problems as time progresses through a new product development cycle (7, p. 170) and Figure 1.2 compares U.S. vs Japanese company changes through a development cycle (7, p. 172). Changes made later in the design cycle are not only expensive but give away any competitive edge.

With increasing technological sophistication, requirements for failure free products are becoming more stringent, and for good reasons. For example, if a 0.1% failure level were allowed in the United States, the
Figure 1.1 Quality Lever

Figure 1.2 Change Comparison
following would occur (29, p. xxvi):

- Two unsafe landings at O’Hare Airport per day.
- 12 babies given to the wrong parents each day.
- 880,000 credit card magnetic strips with wrong information.
- 5,517,200 cases of flat soft drinks produced per year.
- Two million documents lost by the IRS each year.

Given the need for systems and products that are as failure free as possible, tools for identifying failures and correcting them are needed. It is the scope of this paper to discuss one such tool for identifying failures, their effects, causes, and how a failure analysis can provide guidance in the development of corrective action and risk abatement strategies.

**Failure Study Motivations**

The motivations for developing failure examination methods can best be developed through the following examples taken from the author’s experience in commercial manufacturing.

**Correct Solution, Wrong Problem?**

The first case involved the development of a statistical model to determine the risk associated with the implementation of an existing product that was modified in order to realize a cost savings. The risk was to be expressed through an anticipated nonconforming product rate that would be encountered once production of the "new" product began. The model itself was based as a linear combination of two independent variables in order to determine the probability that a certain predetermined threshold value (measured as a differential between two independent product components) for a certain failure mode would not be exceeded. Specifically, the model used was of the form

\[ E(a_1Y_1 + a_2Y_2) = a_1E(Y_1) + a_2E(Y_2) \]
\[ \sigma^2 (a_1 Y_1 + a_2 Y_2) = a_1^2 \sigma^2 (Y_1) + a_2^2 \sigma^2 (Y_2) \] when \( Y_1, Y_2 \) are independent.

The data for the model was obtained through limited scale experimentation using modified product components that were of interest. The study was planned carefully to minimize unnecessary variability and to insure that basic statistical assumptions were met through the use of randomized testing.

The subsequent data were exceptional in the sense of being symmetric and without large outlying values as interpreted through exploratory techniques such as histograms and boxplots. The appropriate parameters were plugged into the model and an estimate of the expected probability that a nonconforming product would occur was obtained. The probability, \( p \), of a nonconforming product, was rated against the manufacturing plant's output. The resultant rate was deemed to be inconsequential and therefore the risk of implementation was considered low. Thus a risk assessment based on an appropriate statistical technique was developed early in the design stages to provide confidence that costly process and product adjustments would not occur during implementation nor at any time during full production of the "new" product in question.

However, once implementation of the modified product was started, nonconforming product began to surface. At this point, the original model, the underlying assumptions, and data were examined. Nothing was found to be wrong with the development or interpretation of the model. In some ways, the model development was considered to be "textbook" ideal. If so why were problems appearing?

The answer was with the failure mode itself. The original risk assessment was developed for a certain type of failure mode. The failure mode that occurred during implementation was different. No consideration was given to alternate failure modes that could occur due to the modifications. As a result, resources were allocated to define the risk associated with only one particular failure mode, one which happened to be of lesser consequence. Consequently, problems with the actually observed failure mode had to be handled in a hasty fashion that resulted in increased interpersonal tensions and high testing cost.
I Need It Now and I Need It Perfect!

Another instance that motivated the need to find ways of looking at product failure involved the development of a new product. Specifically, a marketing team developed an idea for improving sales through an innovative product design feature. With new marketing projects, rapid implementation is often critical in order to be one step ahead of the competition. This rapid implementation or "fast track" approach places pressure on manufacturing and engineering to quickly develop and implement a new product. With new products, success relies heavily on immediate conformance to customer requirements. Failures of a new product can be devastating to the success of a marketing strategy.

Since the product implementation time line was critical, several issues arose which were not encountered previously. The first was determining the anticipated overall nonconforming product rate that might be encountered. The nonconforming rate on the existing product was measured in parts per 10 million i.e. \( p = 0.1 \). In order to determine what the new product would experience in terms of a nonconforming rate, the amount of product needed would be enormous. Large quantities of product would be required to satisfy the statistical power, given the small observed \( p \) value, if an accurate assessment of risk was desired. The ability to accurately assess if a true difference exists is problematic since manufacturing large quantities of a new product is a high risk and potentially high cost venture if problems are encountered. But a problem may not be detected if large quantities are not run. Hence, a circle exists that seems to have no opening. One way out of the circle is through forced failure testing, or accelerated testing, of certain design features in which the worst situation is evaluated in order to see if any immediate disasters occur as compared to control samples composed of current product manufactured under worst case conditions. This type of testing does assist in validating design integrity to some extent e.g. detection of catastrophes, but long term process capability, determined by the stability and low variability of product performance, is not easily addressed. Long term product capability, without producing large quantities of product, would have its assurance through understanding process failure modes and developing corrective action to minimize such failure modes as a result of process variability. Thus it was critical to concentrate on key process and design failure modes that would provide the most impact if not corrected. Since time was of the essence and resources were limited,
compounded with the need for "100% assurance", the question arose of how to best determine which failure modes were most critical in order to determine the proper focus of resources so that testing could be performed. How was this to be accomplished? This question prompted research into the topic of this paper.
CHAPTER 2

ORIGINS OF FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

Research into methods for identifying and classifying failure modes of a new product started with conversations with a co-worker about which other fields of manufacturing is the development of failure free products critical. The consensus was that the aerospace industry would be one such area where failure studies would fill a necessary and obvious need. Below are listed some examples from the aerospace sciences which illustrates this demand for failure studies:

- The 1979 crash of a DC-10 in Chicago was the result of large cracks in the engine mount as a result of severe and unanticipated maintenance procedures (19, p. 112)

- The Galileo space probe sent to explore Jupiter has suffered missions problems from a snared main antenna, a defective tape recorder and a faulty valve in the propellant pressurization system (5, p. 11)

- On June 3, 1980, the North American Air Defense Command (NORAD) reported that the U.S. was under missile attack. The alert was false and was attributed to a faulty computer circuit (14, p. 46).

- Cold temperatures embrittled the "O" rings on the space shuttle Challenger's solid fuel rockets resulting in tragic and complete mission failure (19, p. 5).

Further investigations into the history of failure identification studies in the aerospace industry led as far back to a lecture given by Wilbur Wright in September of 1901 to the Western Society of Engineers in which he stated (1, p. 86)

"The problems of land and water travel were solved in the 19th
century because it was possible to begin with small achievements and gradually work up to our present successes. The flying problem was left over to the 20th century, because in this case the art must be highly developed before any flight of any considerable duration at all can be obtained."

Wilbur Wright was expressing the need for a sophisticated approach to developing a new mode of transportation which could not rely on loosely connected trial and error experiments which had been successful in other fields. Indeed, the Wright brothers, bicycle mechanics that they were, pioneered aeronautical research, engineering and testing. The reasons for their careful up front work was most likely motivated by the same reasons that current manufacturing is confronted with in the development and implementation of a new product. The Wright brothers understood that they would be developing a "flying" machine that if failed, even once, could result in great bodily harm. Unfortunately this latter scenario did pan out for Orville Wright, who, on September 17, 1908, during a demonstration for the U.S. Army at Fort Meyer, suffered a crash landing because one of the propellers developed a longitudinal crack and failed. As a result, Orville Wright suffered injuries and his passenger, Lieutenant Thomas Selfridge, became the first powered airplane fatality (11, p. 230).

The Wright brothers' demonstration of a manned powered flying machine opened the flood gates for airplane development. Aircraft for military operations were utilized in World War I and the use of aircraft for mail delivery and transport soon followed. Increased use of airplanes resulted in increased air crashes (9, p. 1) and the need for increased reliability and safety levels for aircraft based on accident rates per hour of flying time. Airplanes were naturally becoming sleeker, faster and more complex than their wood and cloth ancestors. The natural consequence of this advance was increased hierarchies of interconnected components which could fail. In 1947, a paper was presented to the Institute of Aeronautical Sciences which stated (31, p. 11)

"Safety must be designed and built into airplanes just as are performance, stability, and structural integrity. A safety group must be just as important a part of a manufacturer's organization as a stress, aerodynamics, or a weights group."

The need for reliability and safety in systems was also recognized with rockets during World War II in Germany. The first series of 10 V-1
rockets (predecessor to the infamous V-2) either blew up on the launch pad or fell into the English Channel. Robert Lusser, a mathematician, was consulted on the problem of the V-1 rockets and developed a mathematical formalism to describe the reliability of a series system. Lusser determined that the old adage of "a chain is no stronger than its weakest link" was not applicable to a series system since it failed to account for random failure. Lusser developed the product law of series components, or that the reliability of a series system is equal to the product of the reliabilities of the individual components: \( R_s = R_1 R_2 R_3 \ldots R_n \)

Hence in a series system the reliability of the individual components must be much higher than the system reliability for satisfactory system performance. In the United States, efforts to improve reliability were focused on the extension of quality. Better designs, stronger materials, advanced inspection techniques, etc., were emphasized to extend the useful life of a part or an assembly. This philosophy was illustrated with General Motors Electro-Motive division which extended the useful life of traction motors used in locomotives from 250,000 miles to 1 million miles through the use of better materials and improved testing (9, p. 2).

During the Korean War in the 1950’s, the Department of Defense found that unreliable equipment required a tremendous amount of maintenance. Specifically, the cost to the Armed Services was $2 per year to maintain every $1 worth of electronic equipment (9, p. 2). As a result, the government found that it was wiser to design for reliability than it was to wait and repair equipment after failure. In the commercial arena, on the first anniversary of jetliner service, May 2, 1953, a de Havilland Comet disintegrated over India followed by two other Comet midair explosions during 1954. All explosions were the result of pressurization fatigue on the airplane’s cabin and were discovered through post mortem investigations of the wreckage (19, p. 176). This philosophy of "fly-fix-fly" was not applicable for high risk, high cost or high visibility systems. In the fly-fix-fly approach, improvements are based on examinations of failures in order to improve the next generation of a product or system. After-the-fact testing misses the mark in which potential failures cannot be tolerated as a finished product component.

Missile system development in the late 1950’s and early 1960’s also prompted new approaches for examining failures. The Minuteman intercontinental ballistic missile (ICBM) was one of the first to have a formal, disciplined system safety program (31, p. 11). Further prompting came from the Mercury and Gemini manned rocket programs that demanded success the first time. Disastrous accidents at four ICBM
missile/silo complexes in 1962 also resulted in increased safety awareness.

From this background, failure identification strategies originated. One early method was Failure Mode and Effects Analysis (FMEA) which emerged to identify failures in systems. FMEA is a simplified approach to systems reliability analysis (17, p. 559) and is utilized to identify a failure mode of a component, its cause, and the effect on the overall system. According to the "official" definition found in Military Standard 721C (MIL-STD-721C), a Failure Mode and Effects Analysis is (2, p. 3)

"A procedure by which each potential failure mode in a system is analyzed to determine the results or effects thereof on the system and to classify each potential failure mode according to its severity."

FMEA has evolved to include provisions for the development of corrective action strategies for the elimination of failures.

FMEA is utilized not only in highly visible and critical items such as aircraft, ballistic missile systems, oil refineries, nuclear power plants and satellites, but also in new consumer product introductions. For the same reasons, preventing large scale failures and increasing reliability before implementation of a design or system, FMEA has become so important in the commercial arena. "First pass manufacturing" is needed for any organization that requires a high level of quality and reliability at product introduction.
CHAPTER 3

FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

Tabular FMEA

How does a Failure Mode and Effects Analysis proceed? The basic development is through the use of a worksheet format consisting of several columns. This is appropriately called the tabular FMEA. An example of a general tabular FMEA is shown in Figure 3.1 (3, p. 14). The basic idea of the FMEA, as mentioned previously, is to characterize failures of a system or component, the causes of the failure and the effect of the failure on subsequent components or on the overall system. A FMEA is performed early in the design stages of a new product or system as a way of discovering failures so that necessary corrective action can be developed to reduce or eliminate failure modes. FMEA is used as a preventive action tool. FMEA is also a versatile tool that has expressions in maintainability analysis (MEA), logistical support analysis, safety analysis and damage analysis (DMEA). These alternate expressions were originally conceived for military applications but may be developed for commercial products. The level of sophistication and nature of a FMEA can be tailored to the situation at hand.

The general tabular FMEA expressed in Figure 3 consists of 9 key columns whose function can be defined as

<table>
<thead>
<tr>
<th>Column</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Component under consideration.</td>
</tr>
<tr>
<td>2</td>
<td>A concise statement of the function or intended purpose of the component.</td>
</tr>
<tr>
<td>3</td>
<td>The mode of failure of the component or the various ways in which failures are observed.</td>
</tr>
<tr>
<td>4</td>
<td>The cause of failure.</td>
</tr>
<tr>
<td>5</td>
<td>The effects of the failure on the next component and on the overall system.</td>
</tr>
<tr>
<td>Component</td>
<td>Function</td>
</tr>
<tr>
<td>-----------</td>
<td>----------</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.1 Tabular FMEA
The method of failure detection or discussion of how the failure may be detected.
Possible corrective action to reduce or eliminate the failure.
Effects of corrective action.
Remarks.

Columns 1 and 2 are used for identification and purpose of the part under study. The function of the component and its requirements is critical to guiding the development of the FMEA. Column 3 lists the failure modes and may consist of many modes for each specific component. The failure modes need to be based on the operating conditions at the time of failure since different situations may result in different failure modes. Column 4, the cause of failure, are possible reasons why the failure mode occurred. Column 5 describes the effects of failure on the next component and on the overall system. Column 6, the method of failure detection, is used in providing insight into what current controls will detect the failure mode prior to actual failure. Column 7, possible corrective action, and column 8, the effects of proposed corrective action, answer the question of how the failure modes will be addressed e.g. testing programs or control systems, and what effect did the corrective action have on the failure mode itself. Column 9, the "remarks" part of the worksheet, can be used to express specific concerns of the analyst during the analysis.

The tabular FMEA is a general method to brainstorm for failures of a system or component. The FMEA is started when some information is known of a system or component design and should start early in the design cycle since the goal is development of a product as free from failure as possible prior to full scale implementation. This goal applies not only to conceptually new products but also to existing ones which may be modified to new configurations. It is for this reason that FMEA is a living document and is considered complete only when a product, system or process is finalized with no anticipated future changes or modifications. Tabular FMEA is a very versatile tool that can be tailored to fit the analysis at hand and the level of indenture of a system or component. Tabular FMEA presents the results of a FMEA session in a logical and understandable format so that corrective action can be developed.
Failure Mode Effects and Criticality Analysis

Although the tabular FMEA is the cornerstone of a successful failure identification program, there are certain drawbacks. The process of performing a FMEA can be time intensive and generate large amounts of paperwork if the level of analysis is broad. The tabular FMEA also provides no quantifiable information on the severity of a failures’ effect on the overall system or on the likelihood of occurrence. The ability to grade a failure is crucial in determining resource allocation. For example, a faulty cigarette lighter on an automobile is far less severe to the operation of the vehicle and safety of the passengers than faulty brakes. The ability to characterize failures, in terms of their criticality and the frequency with which they occur, assures that the proper response with proper resources are allocated and that failure reduction activity is not haphazard or misdirected towards inconsequential items. A FMEA study can generate considerable amounts of failure modes, not all of which can be addressed in a timely or cost effect manner. For this reason, a relative basis to measure the importance of a failure mode on the overall success of a product or system is needed.

The introduction of criticality analysis (CA) as a complement to FMEA is a way to provide a ranking of failures. Criticality analysis was introduced by NASA prior to 1965 as a way to assure that hardware used in the space program was reliable (3, p. 17). To define (20, p. 102-1)

"The purpose of criticality analysis (CA) is to rank each potential failure mode identified in the FMEA Task 101, according to the combined influence of severity classification and its probability of occurrence based upon the best available data."

The failure analysis of FMEA and CA now becomes FMECA or Failure Mode Effects and Criticality Analysis. The "standard" for performing a Failure Mode, Effects and Criticality Analysis is developed in MIL-STD-1629A. Figure 3.2 represents Task 101 in MIL-STD-1629A which is a typical FMEA worksheet but now has a column for assessing the severity of a failure. The other columns of Task 101 are defined in detail in MIL-STD-1629A and are similar to the definitions provided previously for the tabular FMEA. Figure 3.3 represents a typical worksheet for Task 102, the criticality analysis, and includes, in addition to a severity column, specific parameters used to quantify the failure of a component. The probabilities in Task 102 when coupled with the
# Failure Mode and Effects Analysis

<table>
<thead>
<tr>
<th>Identification Number</th>
<th>Item/Function Identification (Nomenclature)</th>
<th>Function</th>
<th>Failure Modes and Causes</th>
<th>Mission Phase / Operational Mode</th>
<th>Failure Effects</th>
<th>Failure Detection Method</th>
<th>Compensating Provisions</th>
<th>Severity Class</th>
<th>Remarks</th>
</tr>
</thead>
</table>

![Table Image](image)

Figure 3.2 Failure Mode Effects Worksheet for Task 101 in MIL-STD-1629A
### Criticality Analysis

<table>
<thead>
<tr>
<th>No.</th>
<th>Item/Func. Identification (Nomenclature)</th>
<th>Function</th>
<th>Failure Modes and Causes</th>
<th>P/Mission Phase/Operational Mode</th>
<th>Severity Class</th>
<th>Failure Probability Failure Rate Date Source</th>
<th>Failure Effect Prob</th>
<th>Failure Mode Ratio</th>
<th>Failure Rate</th>
<th>Operating Time</th>
<th>Failure Mode Crit #</th>
<th>Item Crit #</th>
<th>Remarks</th>
</tr>
</thead>
</table>

**Equation:**

\[ C_m = B\alpha \lambda_p t \]

**Figure 3.3** Criticality Analysis for Task 102 in MIL-STD-1629A (Quantitative Method)
severity classification, aid in the development of a matrix illustrating how the various items under a failure study compare in terms of probability of occurrence and severity. The approaches used in the criticality analysis can be either quantitative or semi-quantitative.

Since both Task 101 and 102 have severity classification columns, a brief description of severity is in order. According to the MIL-STD-1629A, the value of severity classification is to provide a qualitative measure of the worst potential consequences resulting from a design error or item failure. Severity is classified below (20, p. 10):

<table>
<thead>
<tr>
<th>Category</th>
<th>Classification</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Catastrophic</td>
<td>A failure which may cause death or weapon system loss.</td>
</tr>
<tr>
<td>II</td>
<td>Critical</td>
<td>A failure which may cause severe injury, major property damage, or major system damage which will result in mission loss.</td>
</tr>
<tr>
<td>III</td>
<td>Marginal</td>
<td>A failure which may cause minor injury, minor property damage, or minor system damage which will result in delay or loss of availability or mission degradation.</td>
</tr>
<tr>
<td>IV</td>
<td>Minor</td>
<td>A failure not serious enough to cause injury, property damage, or system damage, but which will result in unscheduled maintenance or repair.</td>
</tr>
</tbody>
</table>

Although the above classification is directed primarily towards military applications, modifications can be made for use in product designs of consumer goods.
With the introduction of severity to the FMEA worksheet, items developed in a FMEA can be grouped in a logical manner. This categorization guides the allocation of resources for failure abatement strategies.

The key to criticality analysis is the ability to accurately quantify failure probabilities. However, this presents certain problems. In many instances what is known of an item’s failure probability may simply not be available and needs to be ascertained from engineering knowledge, historical evidence or best guess. In other cases the probabilities of failure may exist in handbooks, such as MIL-HDBK-217F, *Reliability Prediction of Electronic Equipment*, that provide failure rates for electronic equipment ranging from tubes and lasers to capacitors, resistors and lamps. These two types of situations will result in a criticality analysis performed in either a semi-quantitative or quantitative manner, respectively.

Figure 3.3 represents a criticality analysis worksheet in which failure probabilities can be assessed quantitatively e.g. obtaining certain parameter estimates for failure modes for an item under consideration. These parameters are located on the CA worksheet in Figure 3.3 and are defined explicitly in MIL-STD-1629A. The estimates are then used to calculate a failure mode criticality number, \( C_m \), where \( C_m = \beta \alpha \lambda_p t \) and the item criticality number, \( C_i = \sum (\beta \alpha \lambda_p t) \) from \( j = 1 \) to \( n \), in which \( n \) is the failure modes in the item that fall under a particular criticality classification and \( j \) is the last failure mode in the item under the criticality classification.

The above calculations are used when information pertaining to the various parameters is known. The quantitative method is considerably more complex than the qualitative method although it does provide for a more accurate analysis.

The qualitative method on the other hand is much simpler and more applicable when specific failure rate data are not available. Failure modes identified in the FMEA are assessed in terms of probability of occurrence and a scheme for grouping these probabilities is provided in MIL-STD-1629A. A summary of these classifications are as follows (20, p. 102-1):

<table>
<thead>
<tr>
<th>Level</th>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level A</td>
<td>Frequent</td>
<td>A high probability of occurrence during the operating time interval.</td>
</tr>
<tr>
<td>Level</td>
<td>Description</td>
<td>Probability of Occurrence</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>B</td>
<td>Reasonably Probable</td>
<td>A moderate probability of occurrence during the item operating time interval.</td>
</tr>
<tr>
<td>C</td>
<td>Occasional</td>
<td>An occasional probability of occurrence during item operating time interval.</td>
</tr>
<tr>
<td>D</td>
<td>Remote</td>
<td>An unlikely probability of occurrence during item operating time interval.</td>
</tr>
<tr>
<td>E</td>
<td>Extremely Unlikely</td>
<td>A failure whose probability of occurrence is essentially zero during item operating time interval.</td>
</tr>
</tbody>
</table>

MIL-STD-1629A provides specific failure values for the above definitions. However, the probabilities will vary depending upon the situation at hand. In other words, the above categories may be customized with different values and ranges of \( p \), the probability of failure, and need to be developed and agreed upon prior to the start of the FMEA.

Figure 3.4 shows how the criticality worksheet appears when the qualitative method is chosen.

Whether the analysis is quantitative or qualitative, the resultant analysis can be charted on a criticality matrix. An example of a criticality matrix is shown in Figure 3.5. The matrix is constructed by inserting item or failure mode classification numbers in matrix locations representing the severity classification and either the probability of occurrence or the criticality number, \( C_m \), for the item’s failure modes. The resultant chart indicates the corrective action priorities. Specifically, the diagonal line from the origin represents increasing criticality.

The criticality matrix provides a useful pictorial of failure modes and their overall relationship to an item or system in terms of what’s important regarding problem resolution.

MIL-STD-1629A provides a specific and methodical approach to constructing a FMEA and Criticality Analysis, resulting in the FMECA. MIL-STD-1629A can be modified easily to suit needs in commercial manufacturing or service environments. If the emphasis is on the simpler qualitative analysis, MIL-STD-1629A provides an effective brainstorming
**Criticality Analysis**

<table>
<thead>
<tr>
<th>Identification Number</th>
<th>Item/Functional Identification (Nomenclature)</th>
<th>Function</th>
<th>Failure Modes and Causes</th>
<th>Mission Phase / Operational Mode</th>
<th>Severity Class</th>
<th>Probability Level</th>
<th>Remarks</th>
</tr>
</thead>
</table>

Figure 3.4 Criticality Analysis for Task 102 in MIL-STD-1629A (Qualitative Method)
Figure 3.5 Criticality Matrix
(Quantitative and Qualitative y axis scales are both shown)
and prioritization tool that allows both experts and non-experts to participate in a failure study. Indeed, there are other FMEA approaches which are effective in determining failure modes and appropriate risk abatement strategies. Alternative approaches will be presented in the next section.
CHAPTER 4

FAILURE MODE AND EFFECTS ANALYSIS FOR MANUFACTURING

The methods and formats in Chapter 3 are fundamental examples of a FMEA. However, other formats exist which yield the same end result as the methods described above. One such format is shown in Figure 4.1, a FMEA worksheet taken from *Juran’s Quality Control Handbook* from the section titled "New Product Development" (6, p. 13.30). It is more general than the FMEA methods provided by MIL-STD-1629A and is representative of the type of FMEA worksheets currently in use in commercial arenas and those found in related literature.

The key element behind the FMEA worksheet in Figure 4.1 is the determination of a risk priority number or RPN. The RPN value is calculated by multiplying values obtained in the columns titled frequency of occurrence, degree of severity and chance of detection, here referred to as columns A, B and C, respectively. Note that the frequency of occurrence and degree of severity columns correspond to the probability of occurrence and severity columns in MIL-STD-1629A but now a column has been added to quantify the chance that a failure will be detected. The values for these columns are the numbers 1 to 10, scaled as follows:

<table>
<thead>
<tr>
<th>Column</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Frequency of Occurrence</td>
</tr>
<tr>
<td></td>
<td>1 = Rare occurrence</td>
</tr>
<tr>
<td></td>
<td>10 = Almost certain occurrence</td>
</tr>
<tr>
<td>B</td>
<td>Degree of Severity</td>
</tr>
<tr>
<td></td>
<td>1 = Insignificant loss to the user</td>
</tr>
<tr>
<td></td>
<td>10 = Product inoperative or major replacement cost or safety hazard.</td>
</tr>
<tr>
<td>Component</td>
<td>Mode of Failure</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------</td>
</tr>
</tbody>
</table>

Frequency of Occurrence:
1 = Rare occurrence
10 = Almost certain occurrence

Degree of Severity:
1 = Insignificant loss to the user
10 = Product inoperable or major replacement cost or safety hazard.

Degree of Detection:
1 = Certain detection before failure
10 = No detection possible before failure

Figure 4.1 FMEAC for New Product Development
C Chance of Detection

1 = Certain detection before failure
10 = No detection possible before failure

The subsequent RPN (RPN = A x B x C) is an integer between 1 (negligible risk) and 1000 (critical risk). This number is then utilized to prioritize corrective action.

The advantage of the worksheet in Figure 4.1 is its simplicity. The rating system is largely subjective in nature although historical information can be utilized to guide in number assignment. For example, if a certain item has a historically very low defect rate, the frequency of occurrence will be a 1 or 2. On the other hand, if no information is known of how a component may respond, the best guess of the FMEA team can be given on the 10 point scale. Further gradations of the numbering system can be developed. For example, in the above numbering scheme, values from 2 to 9 have not been defined. These intermediate values can be defined and based on specific process, product or mission requirements that the FMEA is addressing.

Another advantage of the FMEA worksheet in Figure 4.1 is the ability to sort the RPN number or columns A, B and C to find the "big ticket" items. For example, a FMEA team may decide to concentrate on the top 10% of highest RPN values, or concentrate on high severity items with low detectability and so on. Cutoff values for RPN numbers might be determined by the design team based on cost and resource factors e.g. RPN values of 50 or less might be considered noise whereas RPN values of 500 or more might require corrective action.

The last two columns of Figure 4.1 are important to the analysis. Once specific items have been targeted for corrective action, the action itself must be part of the FMEA. Hence the design action and design validation columns are included. The design validation refers to how the corrective action is verified. Once corrective action has been initiated, the RPN number may change and Figure 4.2 illustrates a FMEA worksheet in which the additional columns A’, B’ and C’ are utilized to calculate the new RPN.
<table>
<thead>
<tr>
<th>Component</th>
<th>Mode of Failure</th>
<th>Cause of Failure</th>
<th>Effect of Failure</th>
<th>A Frequency of Occurrence</th>
<th>B Degree of Severity</th>
<th>C Chance of Detection</th>
<th>Risk Priority Number</th>
<th>Design Action</th>
<th>Design Validation</th>
<th>A' Frequency</th>
<th>B' Severity</th>
<th>C' Detection</th>
<th>RPNI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Frequency of Occurrence:**
- 1 = Rare occurrence
- 10 = Almost certain occurrence

**Degree of Severity:**
- 1 = Insignificant loss to the user
- 10 = Product inoperable or major replacement cost or safety hazard

**Degree of Detection:**
- 1 = Certain detection before failure
- 10 = No detection possible before failure

---

**Figure 4.2 FMEAC for New Product Development with Corrective Action Columns**
Process and Design FMEA

To this point discussion has focused on general FMEA methods as applied to development of products or systems. Further refinements of the FMEA are into design FMEAs (DFMEA) and process FMEAs (PFMEA). The former focuses on the design of the product and the latter emphasizes consistent manufacture of the design. The DFMEA occurs first and then the PFMEA attempts to address issues related to manufacturing variability and product consistency. The difference between a DFMEA and PFMEA is often subtle; the following example illustrates the differences.

Suppose a series of recyclable rockets are built to study the upper atmosphere. The rockets are recyclable only if they return safely from their mission with little or no appreciable damage. Safe return depends in part upon the recovery system that consists of a parachute of a certain diameter. The diameter of the parachute was specified in the design stages to be 16 feet. A DFMEA resulted in a testing program that showed the risk to rocket safety and recoverability with a 16 foot parachute to be acceptable i.e. a "low" RPN. Next, a PFMEA on the process related to the production of the parachute was performed and revealed that the nominal value of parachute diameters of 16 feet is obtainable but the process variability is extremely high. Thus some parachutes may be smaller than 16 feet and some much larger than 16 feet; in either case, the product will fail to function as required. If the parachute is too small, the rocket will plummet to the ground; if too large, the rocket may be carried miles outside of the intended operating range. As a result, machine modifications are required to reduce the variability of the process insuring that the highest possible proportion of correct diameters are manufactured. Note that if the process had been stable (low variability) but the design was incorrect i.e. a mis-specified parachute size that is too larger or too small, then the problem would be with design.

A design FMEA is then used during design of a product, its component parts and any of the equipment necessary to manufacture the product. A process FMEA will be used in any process that can be mapped and that has associated and identifiable failure modes (7, p. 175). Both the DFMEA and PFMEA are able to use the same worksheet but it must be noted on the worksheet with a separate column whether the failure under consideration is a process or design issue. With the introduction of the PFMEA, the amount of paperwork will be considerably

27
increased requiring greater management.
CHAPTER 5

FAILURE MODE AND EFFECTS ANALYSIS AND
SOFTWARE DEVELOPMENT

Software development oftentimes requires that same basic
requirements of being failure free prior to introduction as do other
products. The criticality of software errors can be summed up in the
following examples:

- A software problem may have prevented a Patriot missile from
  tracking an Iraqi Scud missile that killed 28 Americans during the
  Gulf War (15, p. 62).

- The manned space capsule Gemini V missed its landing point by
  100 miles due to the guidance program ignoring the motion of the
  Earth around the sun (14, p. 49).

- A single incorrect character in the specification of a control
  program for an Atlas rocket carrying the first interplanetary
  spacecraft, Mariner I, caused the rocket to veer off course shortly
  after takeoff. Both the rocket and the spacecraft had to be
  destroyed (15, p. 63).

Software measures of performance can be expressed as defects per
1000 lines of code (KLOC), development time, modifications, re-writes,
etc. The same principles of FMEA, defining failures, causes and effects,
can be applied to software development. As with other products, a key
element in developing successful software is defining requirements
accurately. Accurate requirements drive design, planning and testing of
software.

How might a FMEA work with software development? Suppose
one is writing a structured program in PASCAL. Within the overall
program, there may be UNITS, or collections of constants, data types,
variables, functions and procedures. The unit may form a level of
indenture for the FMEA and individual components would be the
INTERFACE, CONST, TYPE, PROCEDURE and so on. Each of these in turn could be broken down further. For example, under a specific procedure, local declarations listed under the VAR section would be analyzed for potential failures e.g. declaring a variable as a INTEGER when indeed it needs to be a declared as an REAL. The key component of such an analysis is to understand the requirements and relationships to the overall program. As mentioned, requirements will provide the basis for the ability to correctly devise and carry out a plan of action in the development of the software. Testing will validate such actions and determine if more problem solving is warranted.

A key element to software development is through the use of metrics or measurements. Performance measurements such as reliability, efficiency, maintainability and cost are integral to software quality assurance. The era of undisciplined programming artists, or "hackers", must give way to a software development that is both disciplined and repeatable. FMEA methodology provides one tool to reach the objective of failure free software.
CHAPTER 6

STATISTICAL BASIS OF THE FMEA WORKSHEET

In development of the risk priority number, the question arises as to the statistical nature of the FMEA numbering system. Specifically, what distribution, if any, do the occurrence, severity and detection columns follow?

In the absence of known failure data, a generic rating system based a scale from 1 to 10 provides a way to grade failures. Such a scale can be viewed as being uniformly distributed i.e. described mathematically by the discrete density function

\[ f(x) = \frac{1}{n} \quad x = 1, 2, \ldots, n \]

with mean and variance

\[ E(X) = \frac{n + 1}{2} \quad , \quad V(X) = \frac{n^2 - 1}{12} \]

This implies that each gradation from 1 to 10 is equally likely to occur. Actual values used with the FMEA depend upon the knowledge of a FMEA team.

The uniform distribution provides a reasonable description of the rating system distribution in lieu of actual known failure data.

In addition to the column distributions, the calculation of the risk priority number, RPN, poses some interesting questions from a probability standpoint.

If RPN is considered to be a probability statement, the manipulations of columns A, B and C can be viewed in two ways. If each column is assumed to be statistically independent, then

\[ P(ABC) = P(A) P(B) P(C). \]

However, this may not be entirely accurate. If columns A, B and
C are somehow related, the use of conditional probabilities may be more appropriate. It is not unreasonable to imagine that provided that one event has occurred, the probability of the next event should be in accordance with the information provided in light of the first event. For example, if an item in a FMEA has a low probability of occurrence, the chance of detection may be low as well. This situation then follows the conditional probability form

\[ P(ABC) = P(A) \cdot P(B|A) \cdot P(C|AB) \]

where A, B and C are the columns defined previously. If failure data are accurately known, the above equation will provide for a more accurate model for the distribution of final RPN values than assuming (unrealistically) independence.
CHAPTER 7

FAILURE MODE AND EFFECTS ANALYSIS INTEGRATION

The value of a FMEA is to identify failure modes along with severity and probability of occurrence in order to rank key failures. Once this is done, development of corrective action is the next step. The value of corrective action is to aid in risk abatement.

Several corrective action strategies exist for both process and design issues. These strategies may be in the form of developing new manufacturing practices and procedures, modifying work habits, implementation of inspection routines, and so on. One specific tool which can be used as a corrective action strategy is statistics.

A diverse set of statistical techniques may used with a FMEA. These techniques are not limited to only corrective action but can be used during the construction of the FMEA to determine failure risks and probabilities or to provide an idea of how effective was the corrective action. In many instances, failure will be controlled by the ability to develop predictive models. Below are some techniques to accomplish such goals.

Surveys

Surveys are an investigative questioning technique. The primary function of surveys in the context of FMEA is to define customer requirements. The scope of a FMEA is determined by its ability to address failure modes in relation to certain conditions. As mentioned in the beginning of this paper, failure is defined as the inability of a product or system to meet a required function. The first step is the proper definition of what is needed from a product or service. Whether the customer is a consumer or the next process in a production line, absence of clear requirements may misdirect efforts needed to eliminate failure modes. Surveys, whether they are randomly mailed questionnaires to
consumers or interviews among different departments in a company, fill the need for developing clear requirements.

**Reliability Analysis**

Reliability is the determination of how likely a product or system will operate without failure for a stated period of time, t. The basic idea for the reliability of a component or system at time t is given by

\[ R(t) = P(T > t) \]

where T is a continuous random variable denoting time to failure and t is some specific time. Generally the distribution of T is modeled by a probability distribution such as the normal, exponential, gamma or Weibull.

Reliability models are useful in estimating the frequency of occurrence for a failure mode in a FMEA. Oftentimes, a new product is simply a modification of an older design from which data exist and can be used to predict the possible outcome for a modified product. Reliability models also may be used as a design action strategy to test different designs.

Reliability analysis is closely related to survival analysis. Both seek to identify factors which have an effect on the survival, over time, of a product, system or biological entity. For example, survival analysis can be used to model tool wear over time. Tooling failure in a stamping process, for example, leads to nonconforming product which may fail to meet a customer requirement. Both analyses utilize the hazard function given by

\[ h(t) = \frac{f(t)}{R(t)} \]

where f(t) is the probability density function of T (failure function) and R(t) is the probability of surviving to at least time t (reliability function). The hazard function is interpreted as the instantaneous failure rate i.e. the rate of failure at a given instant in time provided that the item has lasted until that time. Its shape describes situations in which a product may have a high failure rate directly after manufacture, such as an automobile during the "break in period". After a period of time, a hazard function
that remains constant is referred to as the "useful life" of the system. As the product ages, as with an automobile, breakdowns are more frequent and occur during the "wearout" period. Break in, useful life and wearout periods characterize the product in question. Each period may have different failure modes with differing probabilities and severities which must be taken into consideration in a FMEA under requirements. A graph of a generic hazard function is shown in Figure 7.1 (12, p. 10-5).

Linear Models

Linear models can take on forms such as those expressed as regression, analysis of variance and experimental design. The value of linear models is the ability to develop relationships between one or more independent variables and a response in order to provide insights into underlying mechanisms driving such relationships. Both regression and analysis of variance models can be utilized in experiments or with historical data. Multiple regression models follow the form

\[ Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_{p-1} X_{i,p-1} + \epsilon_i \]

where

\[ \beta_0, \beta_1, \ldots, \beta_{p-1} \text{ are parameters} \]

\[ X_{i1}, \ldots, X_{i,p-1} \text{ are known constants} \]

\[ \epsilon_i \text{ are independent } N(0, \sigma^2) \]

\[ i = 1, \ldots, n \]

and the multi-factor analysis of variance cell means model is

\[ Y_{ijk} = \mu_{ij} + \epsilon_{ijk} \]

where

\[ \mu_{ij} \text{ are parameters} \]

\[ \epsilon_{ijk} \text{ are independent } N(0, \sigma^2) \]

\[ i = 1, \ldots, a; j = 1, \ldots, b; k = 1, \ldots, n \]

Designed experiments, when done properly (randomization,
elimination of extraneous variation, etc.), can provide very useful analysis of experimental data. Designed experiments provide precise estimates and reliable models that can be used for optimization of a product or process. The predictive power aids in abating risk through identification of key factors and understanding their contribution and relationships to some output. Designed experiments also provide for developing products that are robust or insensitive to variations in a process or environment which certainly can play a role in risk abatement.

Exploratory Techniques

Perhaps one of the most widely utilized and powerful techniques that is available to an analyst are exploratory data techniques. Exploratory techniques differ from confirmatory studies in that the probabilistic assumptions underlying standard statistical tests are not the basis of analysis. This is not to say that exploratory and confirmatory techniques are diametrically opposed. Rather exploratory techniques are part of an iterative loop in which data first are explored for interesting patterns upon which confirmatory studies based on probabilistic models may be pursued. For example, exploratory techniques such as boxplots, scatterplots, robust regression, median polish, etc., provide for comparison and pattern identification. In many instances, exploratory techniques, coupled with process knowledge, can provide conclusive results of a data set without resorting to confirmatory techniques.

Statistical Process Control

Statistical process control, or SPC, encompasses a wide variety of graphical and statistical tools used to analyze, control, and improve a process or product. SPC is used extensively in quality applications.

One widely used SPC technique is the control chart. The value of a control chart is to track the performance of a process over time. More so, control charts are used to distinguish between natural variability versus special causes of variability. The ability to distinguish these two types of variation in a process form the basis of prevention. When a
process exhibits assignable causes of variability then action can be taken to correct the process to bring it back under control.

The value of SPC and control charts to FMEA is in corrective action. Control charts are used to detect situations that could pose a problem before they actually occur. The value of this cannot be underestimated if the purpose of FMEA is to develop a product that is known to be failure free before use.

Control charts are also a natural consequence of designed experiments discussed previously. If key factors of a product or process are identified through designed experimentation, the use of control charts assure that certain factor values are consistently manufactured in order to produce the optimum response as determined by the designed experiment. In many cases, experiments performed on a limited scale do not account for manufacturing variability. Implementing a new product on several different manufacturing processes is a risky endeavor if different components of variability are not taken into account. Control charts assist in tracking variability of different processes and provide the ability to detect special causes of variation. Control charts provide the means to compare variation between processes and pinpoint areas in need of variability reduction or control.
CHAPTER 8

FAILURE MODE AND EFFECTS ANALYSIS TERMINOLOGY

A remark on FMEA terminology is in order. In the previous discussion of Figures 4.1 and 4.2, the term FMEA was used in reference to the worksheets and to the action of performing a failure study. In some of the current literature on the topic of FMEA, Figures 4.1 and 4.2 are referred to as FMEA worksheets and the process as a FMEA and not necessarily a FMECA worksheet or analysis, although Juran’s Quality Control Handbook refers to them both as FMECA. Since Figures 4.1 and 4.2 are indicative of what has been noted in current literature on the topic and commonly referred to as FMEAs, the term FMEA will be used to describe the worksheet and analysis. Both the FMECA and FMEA provide essentially the same type of information but under slightly different formats and names.

FMEA Formats

Several different types of FMEA formats or worksheets have been discussed. Which format should one use?

In some cases a customer may require a supplier of a product or process to develop an FMEA according to a specific format; e.g. MIL-STD-1629A for Department of Defense contractors and SAMSO-STD-77-2, "Failure Modes and Effects Analysis for Satellites, Launch Vehicle, and Reentry Systems" for space vehicle contractors. Reference (21) is a manual on performing FMEA for suppliers to the Chrysler Corporation, Ford Motor Company and the General Motors Corporation. Learning industry specific FMEA formats can be accomplished through courses offered by a wide variety of organizations such as the American Society for Quality Control (ASQC).

In instances where an organization may wish to develop a FMEA without compliance to a specific format, one of the standard forms
presented in this paper can be utilized or custom formats developed. In either case, the formats must include a list of failure modes, their consequences and subsequent corrective action. The intent of performing a FMEA is to define failures so that appropriate failure abatement strategies can be developed early in the design stages before full scale implementation of a system or product. FMEA is not “rocket science”; the use of whatever format suits a specific need while maintaining the spirit of FMEA should be developed. Hybrid worksheets incorporating project schedules, FMEA results and testing programs are ways of using and extending the basic ideas of FMEA. Experimentation of formats is worthwhile to obtain the best method that is commensurate with a particular project. An example of an innovative failure strategy is provided in the appendix under case study B.

Software programs can be utilized to perform FMEA and manage the resultant analysis. Two such programs are Formuser by Engineered Work Systems, Inc., and FMEAPLUS by Ford Motor Company (both are registered trademarks) (29, p. 70). An excellent and quite suitable alternative is a spreadsheet program such as Microsoft Excel that provides the ability to sort the various columns. Of course software is not necessary to perform an FMEA but does make the task of compiling, updating and archiving FMEA results considerably easier. An example of a custom program is provided in the appendix under case study C.
CHAPTER 9

PERFORMING A SUCCESSFUL FAILURE MODE EFFECTS ANALYSIS

FMEA is generally developed using a "brainstorming" strategy. A FMEA is conducted through the following steps:

a) Define the system and the performance requirements.
b) Define assumptions and ground rules to be used in the analysis.
c) Develop a block diagram, flow chart or schematic of the subject under analysis.
d) Form a multi-disciplinary team and assign a group leader.
e) Initiate a FMEA brainstorming session.
f) Formalize the results of the FMEA in report form.
g) Develop corrective action strategies
h) Iterate the failure analysis.

The key component of a successful FMEA is the strategic use of a multi-disciplinary team. A FMEA must not be performed by one individual unless the scope of the problem is very limited. The use of a cross functional team allows for a richer and more comprehensive development of a FMEA and helps to insure that as many if not all failures of a system or product are identified. Along with a cross functional team is a block diagram, flow chart or schematic of the product or system under study. The scope of the failure study can be defined with these simple illustrative and informative devices and can provide a common ground for the team to develop the FMEA. As important as the block diagram and cross functional team are the system performance requirements. The multi-disciplinary team can assist in developing appropriate requirements that need to be met. Requirements can be developed from consumer complaints, historical product or system performance data or customer supplied requirements. Once the FMEA is completed, a review locates any deficiencies in the analysis. The final key item is to re-iterate the process once the corrective action items have been initiated.
FMEA is oftentimes an intense process for defining failures of a system or product. It is a time intensive project that may involve thousands of labor hours and generate large amounts of paperwork. It also depends upon good facilitation skills of the FMEA leader who must focus the FMEA group, have the ability to draw out the necessary information from the group and have a clear understanding of the system and performance requirements.
CHAPTER 10

LIMITATIONS OF FAILURE MODE AND EFFECTS ANALYSIS

Although FMEA provides a succinct methodology for examining failures and providing for corrective action, drawbacks of the method limit its usage. Common problems encountered in the failure effects analysis include the following (3, p. 85):

a) The analysis is time consuming and costly.
b) The analysis results and recommendations are often obtained too late in design to be easily incorporated.
c) Accurate failure data are difficult to obtain.
d) The level of detail necessary for a thorough, economical and effective analysis is difficult to define accurately.
e) The process of failure analysis is subject to inaccuracies.
f) Agreement of ratings for severity, detectability and occurrence may be problematic within a group environment.

Except for trivial cases, one can imagine the type of FMEA and the energy expenditure needed on a substantially complex endeavor such as designing an aircraft or complex automotive component. A certain amount of reduction in paperwork is achievable if a FMEA is performed on basic components and systems and if the scope of the FMEA is constrained. The lessons from one FMEA can be applied to other products or systems with similar qualities as well.

Another limitation of the FMEA is that the failure modes are assumed to be statistically independent; hence a FMEA may over-estimate system reliability (17, p. 559) (see chapter 6). However, the primary purpose of a FMEA is the identification of failures which may contribute the most to a system or product unreliability.

Apart from the technical aspects of FMEA, another element necessary and critical to efficiently and effectively develop a FMEA is facilitation skills. FMEA is not a mindless "fill in the blank" process but one of idea generation. The use of a multi-disciplinary team requires a group leader with excellent facilitation skills to keep the analysis moving,
motivate participants, maintain focus and resolve disagreements. The facilitator must also be familiar with FMEA development and its relation to a certain project in order to utilize the full benefit of the group.
CHAPTER 11

OTHER TECHNIQUES

Failure Mode and Effects Analysis is one technique for systematically identifying failures. Other techniques exist such as Fault Tree Analysis (FTA), a very useful failure development technique developed in 1961 by Bell Telephone Laboratories to evaluate the Minuteman Launch Control System. FTA begins with an ultimate failure effect of interest and a tree of failure causes is developed using Boolean logic. The analysis continues until only primary events are left. The tree is then analyzed using algebraic or graph theory principles. The FTA provides for a depiction of a particular failure and is developed consequent to a FMEA study.

Other techniques are Matrix FMEA (G.L. Barbour, 1977) which is based upon a matrix development of failures; Sneak Circuit Analysis (Boeing, 1967) used in determining failures of an electronic circuit, pneumatic, hydraulic and mechanical systems and programming logic; System State Phase Modelling (Tiger, 1969) which uses a logic diagram to investigate possible states of a system; Tabular Systems Reliability Analysis (Battelle Laboratories, 1971) which combines elements of fault tree analysis, Markov techniques and tabular FMEA into an integrated analysis; Event Sequence Analysis (Yellman, 1975) which traces the effects of system failures as a function of the order in which they occur; L.A.M technique (Reina and Squellati, 1980) which uses the physical properties of a system to evaluate the effects of failure; Approachability Analysis (Hitachi, 1981) which uses the concept of failures caused by improper relationships of parts and introduction of external components or errors into the system and finally, the Failure Combination Method (French Societe Nationale des Industries Aeronatiques et Spatiahs, 1981) which examines the effect of single, multiple and externally influenced failures on a system using an inductive approach.

Techniques for dealing with software and microcomputer applications also have been developed including software sneak analysis, integrated hardware/software analysis and integrated critical path analysis. The above alternate techniques were obtained from Reference
(3) which provides a succinct overview of the techniques along with references.
CHAPTER 12

THE FUTURE OF FAILURE MODE AND EFFECTS ANALYSIS

FMEA can be a costly and time consuming activity but, when used early in a design process, can recoup any up front expenditures by identifying and correcting failures at a point that is economically advantageous. FMEA also belongs to the disciplined. FMEA requires a commitment of time and energy from individuals participating in a FMEA and their ability to articulate their expertise. FMEA is a tool that allows the possibility of doing it right the first time versus fixing it a hundred times later at a much higher cost.

FMEA does not cure all the ills of a product or system. It does provide one way of listing and examining failures but is by no means the only method or one that should necessarily be used. FMEA is a continuous improvement tool that supplements and works with testing and quality programs to produce the best system or product possible.
APPENDIX A

CASE STUDY A

A FMEA OF A PHOENIX MODEL ROCKET RECOVERY SYSTEM

The discussion in this report has focused on the ideas underlying failure studies as expressed in the use of FMEA. This section will focus on a simple FMEA study to illustrate the principles.

Estes Industries of Penrose, Colorado, manufactures and sells model rocket kits. The rockets are of various sizes and complexity and are made from wood, cardboard and plastic. The rockets use solid fuel non-reusable engines of various sizes to propel the finished vehicles upwards of 1500 feet in some cases. The rockets have some type of recovery system; the most common consisting of a parachute that allows the rocket to return undamaged so it can be flown again (barring any losses to trees, power lines, lakes, etc).

One particular model kit is the Phoenix flying model rocket. The Phoenix is an air-to-air guided missile that is used on fighter aircraft as an offensive weapon against other aircraft. Unlike the real Phoenix, the 1/9 scale model consists of a recovery system that allows the rocket to be recovered after flight to be reused again.

The basic operation is rather simple. A disposable pre-manufactured solid rocket engine is installed in the tail section of the rocket. The engine is plugged with a nichrome wire which is connected to an ignition system powered by a series of batteries. The rocket is placed on a launch pad, a circular metal plate, and fittings (launch lugs) on the fuselage of the rocket are used to stabilize the rocket on the platform and during launch via a metal rod. The ignition of the engine is accomplished by pressing a button on the ignition system which is hand held from about 10 feet away that heats up the nichrome wire and ignites the propellant. The rocket lifts off and rapidly accelerates for a period of time. The thrust then "cuts out" and a coast stage is activated during which time the rocket glides to its highest altitude (the Phoenix is rated at a maximum altitude of about 1000 feet) while trailing smoke for
tracking by ground personnel. The coast stage then ignites an ejection charge that disengages the nose cone and separates the recovery system from the fuselage. The folded parachute is deployed slowing the vehicle for a gentle landing.

Estes rockets are well proven designs that are reliable and safe to operate, provided they are built correctly (a process parameter) and are used as intended. However, in the Phoenix rocket constructed specifically for this project, modifications to the recovery system were implemented. The recovery system consists of a parachute and shroud lines attached to the nose cone and an elastic line called the shock cord that is attached to the fuselage. The shock cord permits the absorption of ejection stresses and any residual acceleration to avoid damage to the recovery system attachment or the fuselage itself. Flame retardant paper "wadding" protects the recovery system from hot ejection gases. The wadding is placed between the engine and recovery system in the body of the rocket.

The standard recovery system uses a plastic parachute with narrow gauge shroud lines tied to the nose cone and shock cord. This design was improved with a nylon parachute, heavier shroud lines and the use of metal O-rings and two types of swivel hooks. The concept behind the modifications was to prevent problems with shroud and shock cord entanglements through the use of swivel hooks and melted parachutes through the use of other materials. Since the design resulted in a product modification with resultant unknown consequences, a FMEA was performed.

The first step was to develop a block diagram of the recovery system which is presented in Figure A.1 along with a statement of the requirements of the recovery system. The cross hatched blocks represent new features of the recovery system. The use and development of block diagrams or process flow diagrams cannot be understated. Any visual guides provide a common reference point for the FMEA team and often alleviate conflicts in interpretation of the system or product: a picture provides the proverbial thousand words. Block diagrams and process flow diagrams also are useful in further developments of testing programs and identification of key product or process parameters that may need to be evaluated or that cannot be controlled but need to be accounted for in a final analysis.

Once the block diagram was developed, a brainstorming session followed. In the case of the Phoenix, the author was the sole developer of the FMEA analysis. A correct approach would be a cross functional team but for the purposes of this report, a solitary analysis is sufficient.
Phoenix Recovery System

To provide for safe return (no damage or loss) under normal flight conditions.

Figure A.1 Phoenix Recovery System Block Diagram
to illustrate the concepts of FMEA.

The results of the failure study are provided on the attached FMEA sheets under Figures A.2, A.3 and A.4. Other forms such as the ones listed in the text could have been utilized with similar results.

The values for each component and failure were derived by best guess and developed on Figure A.2. Once again, if a cross functional team was utilized the values may be more representative or ‘true’. Nevertheless, for purposes of illustration, the subsequent values for columns A, B and C and the RPN value will suffice.

Sorting RPN values in Figure A.2 yields the results in figure A.3 with a RPN of 300 occurring with the nylon parachute. These results indicate that corrective action should begin with items surrounding the entanglement of the parachute with other components of the recovery system. The action proposed is to follow the manufacturer’s instructions on packing the parachute correctly with the shroud lines. Using this same category as an example, current packing of the parachute can be broken down into a design or process issue as illustrated in Figure A.5. In one case, packing of the parachute relates to the actual physical activity, while the other, the design side, asks the question if the manufacturer design for packing the parachute is correct. This same exercise could be done for each item on the FMEA. Doing so would double the amount of paperwork (at least) barring any further items added to the list for consideration under design or process parameters. In both cases validation of the design or process parameter might be performed with pre-flight testing using mock up rocket bodies or other methods of simulation.

At this point, other items could be considered with high RPN values, such as burned or flawed shroud lines. Alternatively the analysis can proceed with those items that may not have a relatively high RPN value, but very high severity values as shown in Figure A.4.

The FMEA for the Phoenix model rocket is based on the assumption that the rocket will operate under normal conditions. Normal operation in this case implies using a certain engine size and flying in favorable conditions (light wind, no precipitation, etc.). Altering the mission statement would affect the FMEA analysis. For example, if the mission were to fly in high winds, the importance of line or parachute entanglement would be of a higher order and the ability of the McMahon swivel hooks to rotate to keep the lines untangled would be of greater importance. Design issues surrounding parachute diameter would also be included since high winds and large parachutes can carry the rocket out of a desired operating range. Well defined requirements of the system are
### Phoenix Recovery System FMEA

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<th>Cause of Failure</th>
<th>Effect of Failure</th>
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<tr>
<td>Shroud Lines</td>
<td>Entanglement</td>
<td>Incorrect Pack</td>
<td>Reduced</td>
<td>4</td>
<td>5</td>
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<td>200</td>
<td>Pack per mfg, instructions</td>
</tr>
<tr>
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<td>No deployment</td>
<td>Incorrect Pack</td>
<td>Reduced</td>
<td>3</td>
<td>10</td>
<td>5</td>
<td>150</td>
<td>Pack per mfg, instructions</td>
</tr>
<tr>
<td>McMahon</td>
<td>Partial or No</td>
<td>Fouling</td>
<td>Tangled or</td>
<td>3</td>
<td>5</td>
<td>10</td>
<td>150</td>
<td>Clean/replace after flight</td>
</tr>
<tr>
<td>Swivel Hook</td>
<td>Rotation</td>
<td></td>
<td>twisted lines</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>McMahon</td>
<td>Partial or No</td>
<td>Fouling</td>
<td>Tangled or</td>
<td>3</td>
<td>5</td>
<td>10</td>
<td>150</td>
<td>Increase recovery wadding</td>
</tr>
<tr>
<td>Swivel Hook</td>
<td>Rotation</td>
<td></td>
<td>twisted lines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>McMahon</td>
<td>Partial or No</td>
<td>Mis-specified</td>
<td>Tangled or</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>125</td>
<td>Larger Hook</td>
</tr>
<tr>
<td>Swivel Hook</td>
<td>Rotation</td>
<td>swivel</td>
<td>twisted lines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shroud Lines</td>
<td>Breakage</td>
<td>Material Flaw</td>
<td>Reduced</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>Pre-flight inspection</td>
</tr>
<tr>
<td>Shroud Lines</td>
<td>Breakage</td>
<td>Burned</td>
<td>Reduced</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>Increase wadding</td>
</tr>
<tr>
<td>Shroud Lines</td>
<td>Breakage</td>
<td>Burned</td>
<td>Reduced</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>Flame retard line</td>
</tr>
<tr>
<td>Nylon</td>
<td>No deployment</td>
<td>Tight pack</td>
<td>Reduced</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>Pack per mfg, instructions</td>
</tr>
<tr>
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<td>No deployment</td>
<td>Burned</td>
<td>Reduced</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>100</td>
<td>Increase wadding</td>
</tr>
<tr>
<td>Nylon</td>
<td>Detachment</td>
<td>Line connector</td>
<td>Reduced</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>Inspect</td>
</tr>
<tr>
<td>Nylon</td>
<td>Detachment</td>
<td>Connector</td>
<td>Reduced</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>100</td>
<td>Inspect</td>
</tr>
<tr>
<td>O-ring</td>
<td>Breakage</td>
<td>Stress (overuse)</td>
<td>Component</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>100</td>
<td>Pre-flight inspection</td>
</tr>
<tr>
<td>O-ring</td>
<td>Breakage</td>
<td>Mis-specified</td>
<td>Component</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>100</td>
<td>Heavier gage page</td>
</tr>
<tr>
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<td>Broken Hooks</td>
<td>Stress (overuse)</td>
<td>Component</td>
<td>1</td>
<td>10</td>
<td>5</td>
<td>50</td>
<td>Inspection or replacement</td>
</tr>
<tr>
<td>McMahon</td>
<td>Broken Hooks</td>
<td>Mis-specified</td>
<td>Component</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>50</td>
<td>Heavier gage hook</td>
</tr>
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<td>Partial or No</td>
<td>Thermal</td>
<td>Tangled or</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>50</td>
<td>Increase Recovery wadding</td>
</tr>
<tr>
<td>Swivel Hook</td>
<td>Rotation</td>
<td>Expansion</td>
<td>twisted lines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hook with different properties</td>
</tr>
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<td>Partial or No</td>
<td>Thermal</td>
<td>Tangled or</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>50</td>
<td>Hook with different properties</td>
</tr>
<tr>
<td>Swivel Hook</td>
<td>Rotation</td>
<td>Expansion</td>
<td>twisted lines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shroud Lines</td>
<td>Breakage</td>
<td>Material Flaw</td>
<td>Reduced</td>
<td>2</td>
<td>10</td>
<td>2</td>
<td>40</td>
<td>Line replacement</td>
</tr>
<tr>
<td>Nylon</td>
<td>Ripped</td>
<td>Material Flaw</td>
<td>Reduced</td>
<td>1</td>
<td>7</td>
<td>5</td>
<td>35</td>
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</tr>
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<td>Ripped</td>
<td>Ground Entanglement</td>
<td>Reduced</td>
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<td>21</td>
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</tr>
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<td>Separation</td>
<td>Stress (overuse)</td>
<td>Component</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>Pre-flight inspection</td>
</tr>
<tr>
<td>O-ring</td>
<td>Separation</td>
<td>Mis-specified</td>
<td>Component</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>Heavier gage</td>
</tr>
<tr>
<td>Nose Cone</td>
<td>Broken Hooks</td>
<td>Stress (overuse)</td>
<td>Component</td>
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<td>2</td>
<td>3</td>
<td>9</td>
<td>Inspection of replacement</td>
</tr>
<tr>
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<td>Broken Hooks</td>
<td>Mis-specified</td>
<td>Component</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>9</td>
<td>Inspection of replacement</td>
</tr>
<tr>
<td>Nose Cone</td>
<td>Partial or No</td>
<td>High Coeff of</td>
<td>Component</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>Replace</td>
</tr>
<tr>
<td>Swivel Hook</td>
<td>Rotation</td>
<td>ball friction</td>
<td>Tangled or</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>Replace</td>
</tr>
<tr>
<td>McMahon</td>
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<td>High Coeff of</td>
<td>Tangled or</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>Replace</td>
</tr>
<tr>
<td>Swivel Hook</td>
<td>Rotation</td>
<td>ball friction</td>
<td>twisted lines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shroud Lines</td>
<td>Entanglement</td>
<td></td>
<td>Reduced</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>Change line page</td>
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<td>Swivel Hook</td>
<td>See McMahon</td>
<td>None</td>
<td>1</td>
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<td></td>
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Figure A.3 Sorted FMEA by RPN
<table>
<thead>
<tr>
<th>Component</th>
<th>Mode of Failure</th>
<th>Cause of Failure</th>
<th>Effect of Failure</th>
<th>Frequency</th>
<th>Severity</th>
<th>Detection</th>
<th>RPN</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nylon Parachute</td>
<td>No deployment</td>
<td></td>
<td>Reduced Recovery</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>300</td>
<td>Pack per msg.</td>
</tr>
<tr>
<td>Shroud Lines</td>
<td>Breakage</td>
<td>Material flaw</td>
<td>Reduced Recovery</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>150</td>
<td>Pre-flight inspection</td>
</tr>
<tr>
<td>Shroud Lines</td>
<td>Breakage</td>
<td>Burned</td>
<td>Reduced Recovery</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>Increase wadding</td>
</tr>
<tr>
<td>Shroud Lines</td>
<td>Breakage</td>
<td>Burned</td>
<td>Recovery</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>Flame retard line</td>
</tr>
<tr>
<td>Nylon Parachute</td>
<td>No deployment</td>
<td></td>
<td>Reduced Recovery</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>Pack per msg.</td>
</tr>
<tr>
<td>Shroud Lines</td>
<td>Breakage</td>
<td>Misspecified</td>
<td>Reduced Recovery</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>Increased wadding</td>
</tr>
<tr>
<td>O-ring</td>
<td>Breakage</td>
<td>Stress (overuse)</td>
<td>Reduced Recovery</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>100</td>
<td>Pre-flight inspection</td>
</tr>
<tr>
<td>O-ring</td>
<td>Breakage</td>
<td>Mis-specified</td>
<td>Component</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>100</td>
<td>Heavy gage</td>
</tr>
<tr>
<td>McMahon</td>
<td>Swivel hook</td>
<td>Broken hook</td>
<td>Stress (overuse)</td>
<td>1</td>
<td>10</td>
<td>5</td>
<td>50</td>
<td>Inspection or replacement</td>
</tr>
<tr>
<td>McMahon</td>
<td>Swivel hook</td>
<td>Broken hook</td>
<td>Component</td>
<td>1</td>
<td>10</td>
<td>5</td>
<td>50</td>
<td>Inspection or replacement</td>
</tr>
<tr>
<td>Shroud Lines</td>
<td>Breakage</td>
<td>Material flaw</td>
<td>Recovery</td>
<td>2</td>
<td>10</td>
<td>2</td>
<td>40</td>
<td>Line replacement</td>
</tr>
<tr>
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<td>Separation</td>
<td>Stress (overuse)</td>
<td>Component</td>
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<td>10</td>
<td>1</td>
<td>10</td>
<td>Pre-flight inspection</td>
</tr>
<tr>
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<td>Separation</td>
<td>Miss-specified</td>
<td>Component</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>Heavy gage</td>
</tr>
<tr>
<td>Nylon Parachute</td>
<td>Ripped</td>
<td>Material flaw</td>
<td>Reduced Recovery</td>
<td>1</td>
<td>7</td>
<td>5</td>
<td>55</td>
<td>Inspect</td>
</tr>
<tr>
<td>Shroud Lines</td>
<td>Entrainment</td>
<td></td>
<td>Reduced Recovery</td>
<td>3</td>
<td>7</td>
<td>1</td>
<td>21</td>
<td>Inspect</td>
</tr>
<tr>
<td>Swivel Hook</td>
<td>Partial or No Rotation</td>
<td>Foiling</td>
<td>Tangled or twisted lines</td>
<td>3</td>
<td>5</td>
<td>10</td>
<td>150</td>
<td>Clean replacement after flight</td>
</tr>
<tr>
<td>Swivel Hook</td>
<td>Partial or No Rotation</td>
<td>Foiling</td>
<td>Tangled or twisted lines</td>
<td>3</td>
<td>5</td>
<td>10</td>
<td>150</td>
<td>Increased recovery wadding</td>
</tr>
<tr>
<td>Swivel Hook</td>
<td>Partial or No Rotation</td>
<td>Mis-specified</td>
<td>Tangled or twisted lines</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>125</td>
<td>Larger hook</td>
</tr>
<tr>
<td>Swivel Hook</td>
<td>Partial or No Rotation</td>
<td>Thermal Expansion</td>
<td>Tangled or twisted lines</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>50</td>
<td>Increased recovery wadding</td>
</tr>
<tr>
<td>Swivel Hook</td>
<td>Partial or No Rotation</td>
<td>High Coef of ballet friction</td>
<td>Tangled or twisted lines</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>Lubricate</td>
</tr>
<tr>
<td>Swivel Hook</td>
<td>Partial or No Rotation</td>
<td>High Coef of ballet friction</td>
<td>Tangled or twisted lines</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>Replace</td>
</tr>
<tr>
<td>Shroud Lines</td>
<td>Incorrect line pack</td>
<td></td>
<td>Reduced Recovery</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>Change line pack</td>
</tr>
<tr>
<td>Nose Cone</td>
<td>Swivel Hook</td>
<td>Broken hook</td>
<td>Component</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>8</td>
<td>Inspection or replacement</td>
</tr>
<tr>
<td>Nose Cone</td>
<td>Swivel Hook</td>
<td>Missing specifications</td>
<td>Component</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>8</td>
<td>Heavier gage hook</td>
</tr>
</tbody>
</table>

Figure A.4 Sorted FMEA by Severity
## PHOENIX RECOVERY SYSTEM FMEA

<table>
<thead>
<tr>
<th>Component</th>
<th>Mode of Failure</th>
<th>Cause of Failure</th>
<th>Effect of Failure</th>
<th>Frequency of Occurrence</th>
<th>Degree of Severity</th>
<th>Chance of Detection</th>
<th>Risk Priority Number</th>
<th>Process or Design</th>
<th>Action</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nylon Parachute</td>
<td>No deployment</td>
<td>Entanglement</td>
<td>Reduced recoverability</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>300</td>
<td>P</td>
<td></td>
<td>Package per mfg. instructions</td>
</tr>
<tr>
<td>No deployment</td>
<td>Entanglement</td>
<td>Reduced recoverability</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>100</td>
<td>D</td>
<td>Redesign parachute pack</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure A.5** Phoenix Recovery System DFMEA and PFMEA
imperative prior to starting a FMEA.

The cursory analysis of the Phoenix recovery system yielded many failure modes. The values to determine the RPN numbers were not 'scientific' by any means. Nevertheless, the goal of targeting a failure mode in need of corrective action was met.
APPENDIX B

CASE STUDY B

STRATEGIC TEST DESIGN MATRIX

New product development at a beverage company\(^1\) in the form of packaging products (i.e. aluminum cans and lids) prompted the development of an approach to guarantee that new designs would provide customer required functionality at time of introduction into the marketplace. A system was developed to address consumer functionality requirements based upon the general premises of a classic FMEA but modified to address management expectations and requirements. A cross-functional team consisting of representatives from the disciplines of Quality Engineering, Quality Assurance and Research and Development developed a Strategic Design Matrix (STD) during the Spring of 1996. The STD matrix provides a "scorecard" to upper management on tracking and evaluating risk of new products during pre-production or development stages. The STD is driven by consumer requirements e.g. leaking container, loss of CO\(_2\), openability, etc., to better anticipate possible risks prior to introduction to the field.

The STD matrix is shown in figure B.1. The matrix consists of 12 columns which are largely self explanatory. The key feature of the STD which has made it successful is the success status column. This column is coded as green, yellow or red indicating no risk, potential risk and failure, respectively. The coding is determined by comparing test results against pre-determined success criteria. For example, a customer requirement is no container leakage. A possible test would be to ship test product with control product and evaluate the two samples. If leakage is found in the test sample and the success criteria states the absence of leakers, the success status column would be colored red along with a test reference number or name of the experimenter. On the other hand, if no

\(^1\) The company which developed the STD (with the author's assistance) asked not to be referred to by name in this paper.
### Strategic Test Design Matrix

<table>
<thead>
<tr>
<th>Qualification Phase</th>
<th>Consumer Issues (Failures)</th>
<th>Potential Cause(s)</th>
<th>Tests for Consumer Issues (Design or Process)</th>
<th>Packaging Location</th>
<th>Department (Individual Responsible)</th>
<th>Success Criteria</th>
<th>Success Status</th>
<th>Decision Date Based on Test Results</th>
<th>Risk Probability Given Test Results</th>
<th>Proceed to Next Phase Based on Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Passed**

**Warning (potential risk)**

**Failed (risk known)**

Figure B.1 Strategic Test Design Matrix
leakers are found but the sample size is small, the column may be colored yellow indicating caution since the small sample may not detect a problem with a potentially small defect rate (low statistical power). In this manner, management can quickly glance at the STD matrix and pinpoint areas of concern via the color coding. Specific points related to risk are explained under the risk probability given test results column and can be based on statistical information derived from a test, such as a "p" value for example. Decision date and proceed to next phase columns allow management to see how results are affecting project timelines.

The key to success in development of the STD matrix was through the use of a cross-functional team which not only brainstormed how the matrix should look like, but also to develop a list of the customer requirements and failure modes. The STD matrix is a new concept and work continues on its development. Specifically, the approach needs to be carried over into production phases of new designs in order to address possible failures caused by manufacturing variability. Failure modes and customer requirements at later production stages can be detailed through the use of a standard FMEA approach with critical elements subsequently transferred to the STD matrix along with testing requirements. Additional concerns with the STD matrix are with effectively communicating success status to a broader group of individuals that may be connected with a particular development project.
APPENDIX C

CASE STUDY C

FMEA COMPUTER IMPLEMENTATION

A wide variety of computer programs exist to accomplish the goals of a Failure Mode Effects Analysis. Specialized programs can be developed using a programming language and a compiler. One such program was developed using Borland’s Turbo PASCAL version 6.0.

The structured program developed is called "Failure Mode Effects Analysis", (executable file designation is FMEA.EXE) and is based on elements found in MIL-STD-1629A and the book Knowledge Based Management under the chapter "Failure Mode and Effects Analysis" (26, p. 132). Specifically, a system is defined and components of the system are listed with failure modes, causes, probabilities and severities. A risk priority number is defined as the product of a failure's occurrence and severity.

The program uses two base screens to develop the analysis. The first screen, Figure C.1 is used select for data entry, display, sorting and graphing routines. Selecting the graphing function brings up a second screen, Figure C.2, to graph elements of a FMEA data file in different formats. Sorting is accomplished through the screen shown in Figure C.3.

The program allows components of a system to be entered into a file along with failure mode, failure probability, failure effect, failure severity, failure cause and calculated component risk as shown in the in figure C.4. Each component entered is given an identification number. Currently no corrective action column is included in the software. The data that is entered provides a quick overview of risk for individual components when manipulated with the graphics option. The graphics option will allow the component identification numbers to be graphed on a criticality matrix as adopted from MIL-STD-1629A or to be broken down by failure probability, failure severity and overall risk and graphed as a stem and leaf type plots. Examples of each are shown in Figures C.5, C.6, C.7 and C.8, respectively, along with a listing of the actual data file.
[1] Input FMEA Data
[2] Display FMEA Table
[4] Sort FMEA Data
[5] QUIT THE PROGRAM

Figure C.1 FMEA Data Manipulation Options

Failure Mode Effects Graphing
---------------------------------

[6] Criticality Matrix
[7] Stem and Leaf of Occurrence
[8] Stem and Leaf of Severity
[9] Stem and Leaf of Risk
[10] QUIT ROUTINE

Figure C.2 FMEA Data Graphing Options

Failure Mode Effects Sorting
---------------------------------

[12] Sort on Severity
[13] Sort on Risk
[14] Sort on ID Number
[15] QUIT ROUTINE

Figure C.3. FMEA Sorting Options
### Failure Mode Effects Worksheet

<table>
<thead>
<tr>
<th>ID</th>
<th>Component</th>
<th>Failure Mode</th>
<th>Prob</th>
<th>Failure Effect</th>
<th>Severe</th>
<th>Failure Cause</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Engine</td>
<td>Misfires</td>
<td>2</td>
<td>Low mpg</td>
<td>2</td>
<td>Dirty injectors</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Cooling</td>
<td>Overheats</td>
<td>4</td>
<td>Engine damage</td>
<td>3</td>
<td>Poor flow</td>
<td>36</td>
</tr>
<tr>
<td>3</td>
<td>Exhaust</td>
<td>Leaks</td>
<td>2</td>
<td>CO emissions</td>
<td>10</td>
<td>Faulty joints</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>Trans</td>
<td>Slips</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PROB: 1 = Unlikely .. 10 = Certain  SEVERE: 1 = No Impact .. 10 = High Impact

---

Figure C.4  FMEA Data Entry Screen
Failure Mode Effects Summary

File: AUTO  System: Automobile  Date: 9/18/1996

<table>
<thead>
<tr>
<th>ID</th>
<th>Component</th>
<th>Failure Mode</th>
<th>Prob</th>
<th>Effect</th>
<th>Severe</th>
<th>Cause</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Engine</td>
<td>Misfires</td>
<td>2</td>
<td>Low mpg</td>
<td>2</td>
<td>Dirty injectors</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Cooling</td>
<td>Overheats</td>
<td>4</td>
<td>Engine</td>
<td>9</td>
<td>Poor flow</td>
<td>36</td>
</tr>
<tr>
<td>3</td>
<td>Exhaust</td>
<td>Leaks</td>
<td>2</td>
<td>CO emissions</td>
<td>10</td>
<td>Faulty joints</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>Trans</td>
<td>Slips</td>
<td>3</td>
<td>Low perform</td>
<td>6</td>
<td>Internal damage</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>Steering</td>
<td>Play</td>
<td>8</td>
<td>No control</td>
<td>10</td>
<td>Tie rods damaged</td>
<td>80</td>
</tr>
<tr>
<td>6</td>
<td>Tires</td>
<td>Rapid wear</td>
<td>3</td>
<td>High cost</td>
<td>3</td>
<td>Low pressure</td>
<td>9</td>
</tr>
<tr>
<td>7</td>
<td>Elect</td>
<td>Battery wear</td>
<td>2</td>
<td>High cost</td>
<td>3</td>
<td>Shorted wiring</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>Air Bag</td>
<td>No deployment</td>
<td>1</td>
<td>No safety</td>
<td>10</td>
<td>Defective bag</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>Brakes</td>
<td>Grab</td>
<td>8</td>
<td>No control</td>
<td>9</td>
<td>Binded linkage</td>
<td>72</td>
</tr>
<tr>
<td>10</td>
<td>Cruise</td>
<td>No operation</td>
<td>2</td>
<td>No speed control</td>
<td>5</td>
<td>Computer fault</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>Body</td>
<td>Leaks</td>
<td>5</td>
<td>Wet interior</td>
<td>2</td>
<td>Poor body fit</td>
<td>10</td>
</tr>
<tr>
<td>12</td>
<td>Fuel Pump</td>
<td>Low psi</td>
<td>5</td>
<td>Uneven run</td>
<td>7</td>
<td>Faulty valve</td>
<td>35</td>
</tr>
</tbody>
</table>

Figure C.5 Criticality Matrix of a FMEA Data Set (by ID)
### Stem and Leaf Matrix

**Occurrence**

```
10
  7
  3 5 12 9
8 1 4 2 11 5
```

Not Likely    Likely

### Failure Mode Effects Summary

<table>
<thead>
<tr>
<th>ID Component</th>
<th>Failure Mode</th>
<th>Prob</th>
<th>Failure Effect</th>
<th>Severe</th>
<th>Failure Cause</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 Brakes</td>
<td>Grab</td>
<td>8</td>
<td>No control</td>
<td>9</td>
<td>Binded linkage</td>
<td>72</td>
</tr>
<tr>
<td>5 Steering</td>
<td>Play</td>
<td>8</td>
<td>No control</td>
<td>10</td>
<td>Tie rods damaged</td>
<td>80</td>
</tr>
<tr>
<td>11 Body</td>
<td>Leaks</td>
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<td>Poor body fit</td>
<td>10</td>
</tr>
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<td>Faulty valve</td>
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</tr>
<tr>
<td>2 Cooling</td>
<td>Overheats</td>
<td>4</td>
<td>Engine damage</td>
<td>9</td>
<td>Poor flow</td>
<td>36</td>
</tr>
<tr>
<td>6 Tires</td>
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<td>High cost</td>
<td>3</td>
<td>Low pressure</td>
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</tr>
<tr>
<td>4 Trans</td>
<td>Slips</td>
<td>3</td>
<td>Low perform</td>
<td>6</td>
<td>Internal damage</td>
<td>18</td>
</tr>
<tr>
<td>3 Exhaust</td>
<td>Leaks</td>
<td>2</td>
<td>CO emissions</td>
<td>10</td>
<td>Faulty joints</td>
<td>20</td>
</tr>
<tr>
<td>1 Engine</td>
<td>Misfires</td>
<td>2</td>
<td>Low mpg</td>
<td>2</td>
<td>Dirty injectors</td>
<td>4</td>
</tr>
<tr>
<td>10 Cruise</td>
<td>No operation</td>
<td>2</td>
<td>No speed cntrl</td>
<td>5</td>
<td>Computer fault</td>
<td>10</td>
</tr>
<tr>
<td>7 Elect</td>
<td>Battery wear</td>
<td>2</td>
<td>High cost</td>
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<td>Shorted wiring</td>
<td>6</td>
</tr>
<tr>
<td>8 Air Bag</td>
<td>No deployment</td>
<td>1</td>
<td>No safety</td>
<td>10</td>
<td>Defective bag</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure C.6 Stem and Leaf Plot of FMEA Probabilities (by ID)
### Stem and Leaf Matrix

**Severity**

<table>
<thead>
<tr>
<th>Leaf</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

Not Severe | Severe

### Failure Mode Effects Summary

<table>
<thead>
<tr>
<th>ID Component</th>
<th>Failure Mode</th>
<th>Prob</th>
<th>Failure Effect</th>
<th>Severe</th>
<th>Failure Cause</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 Air Bag</td>
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<tr>
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<td>36</td>
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<td>5</td>
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<td>3</td>
<td>Low pressure</td>
<td>9</td>
</tr>
<tr>
<td>7 Elect</td>
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<td>2</td>
<td>Dirty injectors</td>
<td>4</td>
</tr>
<tr>
<td>11 Body</td>
<td>Leaks</td>
<td>5</td>
<td>Wet interior</td>
<td>2</td>
<td>Poor body fit</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure C.7  Stem and Leaf Plot of FMEA Severities (by ID)
### Stem and Leaf Matrix

**Risk**

```
11
7  10
6  8  12
1  4  3  2
```

1-9 10-19 20-29 30-39 40-49 50-59 60-69 70-79 80-89 90-100

Low Risk  High Risk

---

### Failure Mode Effects Summary

<table>
<thead>
<tr>
<th>ID Component</th>
<th>Failure Mode</th>
<th>Prob</th>
<th>Failure Effect</th>
<th>Severe</th>
<th>Failure Cause</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Steering</td>
<td>Play</td>
<td>8</td>
<td>No control</td>
<td>10</td>
<td>Tie rods damaged</td>
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<tr>
<td>9 Brakes</td>
<td>Grab</td>
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<td>2 Cooling</td>
<td>Overheats</td>
<td>4</td>
<td>Engine damage</td>
<td>9</td>
<td>Poor flow</td>
<td>36</td>
</tr>
<tr>
<td>12 Fuel Pump</td>
<td>Low psi</td>
<td>5</td>
<td>Uneven run</td>
<td>7</td>
<td>Faulty valve</td>
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</tr>
<tr>
<td>3 Exhaust</td>
<td>Leaks</td>
<td>2</td>
<td>CO emissions</td>
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<td>Faulty joints</td>
<td>20</td>
</tr>
<tr>
<td>4 Trans</td>
<td>Slips</td>
<td>3</td>
<td>Low perform</td>
<td>6</td>
<td>Internal damage</td>
<td>18</td>
</tr>
<tr>
<td>8 Air Bag</td>
<td>No deployment</td>
<td>1</td>
<td>No safety</td>
<td>10</td>
<td>Defective bag</td>
<td>10</td>
</tr>
<tr>
<td>11 Body</td>
<td>Leaks</td>
<td>5</td>
<td>Wet interior</td>
<td>2</td>
<td>Poor body fit</td>
<td>10</td>
</tr>
<tr>
<td>10 Cruise</td>
<td>No operation</td>
<td>2</td>
<td>No speed cntrl</td>
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<td>Rapid wear</td>
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<td>3</td>
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<td>Shorted wiring</td>
<td>6</td>
</tr>
<tr>
<td>1 Engine</td>
<td>Misfires</td>
<td>2</td>
<td>Low mpg</td>
<td>2</td>
<td>Dirty injectors</td>
<td>4</td>
</tr>
</tbody>
</table>

---

Figure C.8 Stem and Leaf Plot of FMEA Risk (by ID)
used.

The program provides the mechanism to quickly determine high risk items in a system. The basis behind the analysis relies on standard methods of developing a FMEA such as determining correct requirements and operating phases for a system and determination of the level of detail needed.

A summary of program elements is provided in the following matrix:

<table>
<thead>
<tr>
<th>Program Elements for FMEA.EXE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Program (PAS)</strong></td>
</tr>
<tr>
<td>FMEA</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>FMEADATA (Unit)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>FMEAMAT (Unit)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>FMEASORT (Unit)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

The source code for the software is listed on the following pages and includes all the Pascal components used to gather, sort and display
data starting with the main program driver. The sorting routine was based on work developed by Professor Zenas Hartvigson for PASCAL programming coursework at the University of Colorado at Denver (8). A degree of editing was necessary in order to properly format the source code to the report but the overall program is unchanged from the actual working version.
PROGRAM Fmea;
{
    PROSPECTUS

This program driver was developed to utilize various program components to act as a vehicle in performing a Failure Mode Effects Analysis. Specifically, the units called are

FmeaMat      Graphing of FMEA data
FmeaSort     Routine for sorting FMEA data files
FmeaData     Unit for allowing a user to build a FMEA file

The FMEA format is a modification of the one outlined under MIL-STD-1629A and the book Knowledge Based Management by Schmidt, Klemmele and Berdine (Air Academy Press, 1996) in order to provide a fundamental way in which to quickly determine critical failure modes in a system or process.

AUTHOR

}

USES
    Crt,
    FmeaMat,     {Graphing of FMEA data}
    FmeaSort,    {Sorts the FMEA data}
    FmeaData;    {The record manager unit for FMEA data}

{**************************************************************************}
PROCEDURE LocateFile (VAR Routine,InFile: STRING);

{Prompt the user for the location of the file he/she wishes to process...}

VAR
    Key,    {Part of pause and data entry routines...}
    Answer : CHAR;
BEGIN

ClrScr;
Answer := 'N';
WHILE Answer <> 'Y' DO
BEGIN
  TEXTCOLOR(WHITE);
  Gotoxy(02,08);
  WRITE(OUTPUT,' Please Input The Path And Filename of the file to be
        ,Routine);
  Gotoxy(04,10);
  TEXTCOLOR(Yellow);
  WRITE(OUTPUT, ' ->       <---');
  Gotoxy(29,10);
  READLN(INPUT,InFile);
  TEXTCOLOR(WHITE);
REPEAT
  Gotoxy(50,12);
  WRITE(OUTPUT,' ');
  Gotoxy(02,12);
  WRITE(OUTPUT,' Your drive\directory\ filename selection is ');
  Gotoxy(55,12);
  TEXTCOLOR(White);
  WRITE(OUTPUT,InFile);
  TEXTCOLOR(WHITE);
  Gotoxy(02,13);
  WRITE(OUTPUT,' Is this correct (Y/N)?');
  Gotoxy(32,13);
  Answer := ReadKey;
  Answer := UPCASE(Answer);
UNTIL (Answer = 'Y') OR (Answer = 'N');
WRITELN(OUTPUT);
END;
TEXTCOLOR(LightGray);
END; {End of procedure LocateFile}

{**************************MAIN PROGRAM DRIVER**************************}

VAR
  Endit : BOOLEAN;  {Part of looping controls}
  Choice,
  Continue,
  Key  : CHAR; {Used in user selections}

70
GraphFile,  
RoutineType,  
DataFile : STRING;         {Tracking of filenames and analysis types} 

BEGIN  
    Edit := TRUE;          {Variable initialization}  
    Choice := '';  
    Key := '';  
    RoutineType := '';  

{Main menu with choices and input prompts}  
TEXTBACKGROUND(BLUE);  
REPEAT 
    REPEAT 
        ClrScr;  
        TEXTBACKGROUND(BLUE);  
        TEXTCOLOR(White);  
        Gotoxy(20,3);  
        WRITE(OUTPUT,'R E C O R D M A N A G E R');  
        Gotoxy(20,4);  
        WRITE(OUTPUT,'--------------------------------');  
        TEXTCOLOR(Yellow);  
        Gotoxy(30,9);  
        DELAY(150);  
        WRITE(OUTPUT,'[I] Input FMEA Data');  
        Gotoxy(30,11);  
        DELAY(150);  
        WRITE(OUTPUT,'[D] Display FMEA Table');  
        Gotoxy(30,13);  
        DELAY(150);  
        WRITE(OUTPUT,'[G] Graphical Display');  
        Gotoxy(30,15);  
        DELAY(150);  
        WRITE(OUTPUT,'[S] Sort FMEA Data');  
        Gotoxy(30,17);  
        DELAY(150);  
        WRITE(OUTPUT,'[Q] QUIT THE PROGRAM');  
        choice := UPCASE(ReadKey);  
        {Read what key has been pressed - convert to caps}  
    UNTIL (Choice = 'D') OR (Choice = 'S') OR (Choice = 'I') OR  
        (Choice = 'G') OR (Choice = 'Q');  

71
ClrScr;
CASE Choice OF  {Choices for the program}

'I'  : BEGIN  {Input data}
    ClrScr;
    RoutineType := 'INPUT';
    LocateFile(RoutineType,DataFile);
    AddRecord(RoutineType,DataFile);
END;

'D'  : BEGIN  {Display a data file}
    ClrScr;
    RoutineType := 'DISPLAYED';
    LocateFile(RoutineType,DataFile);
    Display(DataFile);
END;

'S'  : BEGIN  {Sort a data file}
    RoutineType := 'SORTED';
    LocateFile(RoutineType,DataFile);
    Sort(DataFile);
END;

'G'  : BEGIN  {Graphing a data file}
    RoutineType := 'CHARTED';
    LocateFile(RoutineType,DataFile);
    GraphSelect(DataFile);
END;

'Q'  : BEGIN
    Edit := FALSE;
END;
UNTIL Edit <> TRUE;  {End of choices}
END.  {End of program driver}
UNIT FmeaData;

{This unit is utilized for data entry and display}

INTERFACE

TYPE

MasterRecord = RECORD
  System,  {The type of system to be studied}
  Mission,  {The purpose and operating range of the system}
  Component,  {The components that make up the system}
  Failure,  {The failure of a specific component}
  Cause,  {What caused the failure to happen}
  Effect   : STRING [25];   {The effect system failure}
  ID,   {A numeric assigned to the component}
  FMEADay,  {The day on which the FMEA was performed}
  FMEAMonth,  {The month of the FMEA}
  FMEAYear,  {The year on which the FMEA was performed}
  Occurrence,  {The liklihood of the failure}
  Severity,  {The severity of the failure}
  Risk     : INTEGER   {The combined risk number of occurrence and severity}
END;

MasterRecordFile = FILE OF MasterRecord;

PROCEDURE AddRecord (VAR Operation,DataSource : STRING);
PROCEDURE Display (DataSource : STRING);
PROCEDURE Sort (DataSource : STRING);

{***************************************************************************************}
IMPLEMENTATION

USES
  Graph,   {Pascal Graphics Unit}
  Dos,     {Dos unit }
  BGI_Driv,    { all the BGI drivers }

73
BGI_Font, { all the BGI fonts }
Crt, { CRT device unit }
FmeaSort; { The sorting unit for the FMEA data sets }

CONST
  GraphMode : INTEGER = 0; { Initialize graphics to appropriate graph mode }
{**********************************************************************************}
PROCEDURE AddRecord (VAR Operation, DataSource : STRING); { This procedure is utilized to develop a data file used in the FMEA study }

VAR
  key     : CHAR;  { Used in pausing }
  F_Mission,
  F_System,
  F_Component,
  F_Failure,
  F_Effect,
  F_Cause  : STRING [25];
  MstrFile : MasterRecordFile;
  MstrInfo : MasterRecord;
  TDay,
  TMonth,
  TYear,
  F_Id,
  I,
  yCount,
  F_Occurrence,
  F_Severity,
  F_Risk   : INTEGER;
  Finished : BOOLEAN; { Used to terminate data entry }

BEGIN
  yCount := 8;
  F_ID := 1;
  F_Component := ' ';
BEGIN
{ Screen formatting and data entry }
  ClrScr;
  TEXTCOLOR(White);
  Gotoxy(23, 2);
WRITE(OUTPUT, 'Failure Mode Effects Worksheet');
Gotoxy(30,3);
WRITE(OUTPUT, 'File Information');
Gotoxy(29,7);
WRITE(OUTPUT, 'System : '); READLN(INPUT,F_System);
Gotoxy(29,9);
WRITE(OUTPUT, 'Mission : '); READLN(INPUT,F_Mission);
REPEAT
  Gotoxy(45,11);
  ClrEOL;
  Gotoxy(25,11);
  WRITE(OUTPUT, ' Month (1..12) = '); 
  Gotoxy(45,11);
  TEXTCOLOR(White);
  READLN(INPUT,TMonth);
UNTIL (TMonth > = 1) AND (TMonth <= 12);
REPEAT
  Gotoxy(45,12);
  ClrEOL;
  Gotoxy(25,12);
  WRITE(OUTPUT, ' Date (1..31) = '); 
  Gotoxy(45,12);
  TEXTCOLOR(White);
  READLN(INPUT,TDay);
UNTIL (TDay > = 1) AND (TDay <= 31);
REPEAT
  Gotoxy(45,13);
  ClrEOL;
  Gotoxy(25,13);
  WRITE(OUTPUT, 'Year (1996..2100) = '); 
  Gotoxy(45,13);
  READLN(INPUT,TYear);
UNTIL (TYear >= 1996) AND (TYear <= 2100);
Gotoxy(25,24);
WRITE(OUTPUT, 'Press Any Key To Continue');
END;
ASSIGN(MstrFile,DataSource);
REWRITE(MstrFile);
REPEAT
IF ((yCount = 23) OR (yCount = 8)) THEN
BEGIN
ClrScr;
yCount := 8;
TEXTBACKGROUND(BLUE);
TEXTCOLOR(White);
Gotoxy(23,2);
WRITE(OUTPUT,'Failure Mode Effects Worksheet');
Gotoxy(23,3);
WRITE(OUTPUT,'--------------------------');
Gotoxy(1,6);
WRITE(OUTPUT,'ID');
Gotoxy(4,6);
WRITE(OUTPUT,'Component');
Gotoxy(17,5);
WRITE(OUTPUT,'Failure');
Gotoxy(17,6);
WRITE(OUTPUT,' Mode ');
Gotoxy(30,6);
WRITE(OUTPUT,'Prob');
Gotoxy(38,5);
WRITE(OUTPUT,'Failure');
Gotoxy(38,6);
WRITE(OUTPUT,'Effect');
Gotoxy(50,6);
WRITE(OUTPUT,'Severe');
Gotoxy(62,5);
WRITE(OUTPUT,'Failure');
Gotoxy(62,6);
WRITE(OUTPUT,' Cause');
Gotoxy(75,6);
WRITE(OUTPUT,'Risk');
Gotoxy(1,7);
WRITE(OUTPUT,'---------------------------------');
TEXTCOLOR( Yellow);
Gotoxy(2,24);
WRITE(OUTPUT,'PROB: 1 = Unlikely .. 10 = Certain SEVERE: 1 =
No Impact .. 10 = High Impact');
END;
TEXTCOLOR(LightCyan);
Gotoxy(1,yCount);
WRITE(OUTPUT,F_ID);
Gotoxy(4,yCount);
READLN(INPUT,F_Component);
IF F_Component <> '***' THEN  {Termination of data entry}
   BEGIN
      Gotoxy(15,yCount);
      READLN(INPUT,F_Failure);
      REPEAT
         Gotoxy(31,yCount);
         CrEOL;
         READLN(INPUT,F_Occurrence);
      UNTIL (F_Occurrence >= 1) AND (F_Occurrence <= 10);
      Gotoxy(37,yCount);
      READLN(INPUT,F_Effect);
      REPEAT
         Gotoxy(52,yCount);
         CrEOL;
         READLN(INPUT,F_Severity);
      UNTIL (F_Severity >= 1) AND (F_Severity <= 10);
      Gotoxy(58,yCount);
      READLN(INPUT,F_Cause);
      F_Risk := F_Occurrence*F_Severity;
      Gotoxy(76,yCount);
      WRITE(OUTPUT,F_Risk);
      yCount := yCount + 1;
      ASSIGN(MstrFile,DataSource);
      RESET(MstrFile);
      SEEK(MstrFile,FILESIZE(MstrFile));  {Appending of the file}
      MstrInfo.System := F_System;
      MstrInfo.ID := F_Id;
      MstrInfo.Component := F_Component;
      MstrInfo.Failure := F_Failure;
      MstrInfo.Occurrence := F_Occurrence;
      MstrInfo.Effect := F_Effect;
      MstrInfo.Cause := F_Cause;
      MstrInfo.Severity := F_Severity;
      MstrInfo.Risk := F_Risk;
      MstrInfo.FMEADay := TDay;
      MstrInfo.FMEAMonth := TMonth;
      MstrInfo.FMEAYear := TYear;
WRITE(MstrFile,MstrInfo);
F_Id := F_Id + 1;
CLOSE (MstrFile);
END;
UNTIL (F_Component = '*');
END; {End of procedure AddRecord}
{**********************************************************************}
PROCEDURE Display (DataToDisplay : STRING);
{Procedure display opens a FMEA data file and displays the contents to
screen}

VAR
TempFile : MasterRecordFile; {The FMEA file...}
ContinueChoice,
Key : CHAR; {Part of pause}
Rec : MasterRecord; {The record structure}
RecordNumber,
Counter,
RecordNo,
yCount,
I : INTEGER;

BEGIN
RecordNo := 0; {Variable initialization}
RecordNumber := 0;
Counter := 1;
yCount := 9;
Counter := 0;
ASSIGN (TempFile, DataToDisplay); {Assigning the file to be opened}
RESET (TempFile);
REPEAT
SEEK (TempFile, RecordNo);
READ (TempFile, Rec);
IF ((yCount = 23) or (yCount = 9)) THEN
BEGIN
ClrScr;
yCount := 9; {Screen formatting}
TEXTBACKGROUND(BLUE);
TEXTCOLOR(White);
Gotoxy(23,1);
WRITE(OUTPUT, 'Failure Mode Effects Summary');

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Gotoxy(23,2);
WRITE(OUTPUT,'----------------------------------');
Gotoxy(10,4);
WRITE(OUTPUT,'File : ',DataToDisplay);
Gotoxy(30,4);
WRITE(OUTPUT,'System : ',Rec.System);
Gotoxy(55,4);
WRITE(OUTPUT,'Date:',Rec.FMEAMonth,'/',
       Rec.FMEADay,'/',Rec.FMEAYear);
Gotoxy(1,7);
WRITE(OUTPUT,'ID');
Gotoxy(4,7);
WRITE(OUTPUT,'Component');
Gotoxy(17,6);
WRITE(OUTPUT,'Failure');
Gotoxy(17,7);
WRITE(OUTPUT,' Mode ');
Gotoxy(30,7);
WRITE(OUTPUT,'Prob');
Gotoxy(38,6);
WRITE(OUTPUT,'Failure');
Gotoxy(38,7);
WRITE(OUTPUT,'Effect');
Gotoxy(50,7);
WRITE(OUTPUT,'Severe');
Gotoxy(62,6);
WRITE(OUTPUT,'Failure');
Gotoxy(62,7);
WRITE(OUTPUT,'Cause');
Gotoxy(75,7);
WRITE(OUTPUT,'Risk');
Gotoxy(1,8);
WRITE(OUTPUT,'----------------------------------');
TEXTCOLOR(Yellow);
END; {End of formatting}
BEGIN {Beginning of data file reading and display}
WITH Rec DO
BEGIN
   TEXTCOLOR(LightCyan);
   Gotoxy(1,yCount);
   WRITE(OUTPUT,ID:2);
Gotoxy(4,yCount);
WRITE(OUTPUT,Component);
Gotoxy(15,yCount);
WRITE(OUTPUT,Failure);
Gotoxy(31,yCount);
WRITE(OUTPUT,Occurrence);
Gotoxy(37,yCount);
WRITE(OUTPUT,Effect);
Gotoxy(52,yCount);
WRITE(OUTPUT,Severity);
Gotoxy(58,yCount);
WRITE(OUTPUT,Cause);
Gotoxy(76,yCount);
WRITE(OUTPUT,Risk);
RecordNo := RecordNo + 1;
yCount := yCount + 1;
END;
END;
IF yCount = 23 THEN
  key := Readkey;
UNTIL EOF(TempFile);
CLOSE(TempFile);
key := ReadFile;
END;{End of procedure Display}
{*******************************************************************************
PROCEDURE Sort (DataToSort : STRING);
{Procedure Sort prompts the user to sort an FMEA file on various columns}
{Calls on the unit FMEASort}

VAR
  Choice, {Variables for screen formatting and prompts}
  TypeSort,
  key : CHAR;
  EndRoutine : BOOLEAN;
  I : INTEGER;

BEGIN
  EndRoutine := TRUE;
  REPEAT
    REPEAT

ClrScr;
TEXTBACKGROUND(BLUE);
TEXTCOLOR(White);
Gotoxy(23,3);
WRITE(OUTPUT,'Failure Mode Effects Sorting');
Gotoxy(23,4);
WRITE(OUTPUT,'------------------------------');
Gotoxy(23,7);
WRITE(OUTPUT,'[P] Sort on Probability');
Gotoxy(23,9);
WRITE(OUTPUT,'[S] Sort on Severity');
Gotoxy(23,11);
WRITE(OUTPUT,'[R] Sort on Risk');
Gotoxy(23,13);
WRITE(OUTPUT,'[L] Sort on ID Number');
Gotoxy(23,15);
WRITE(OUTPUT,'[Q] QUIT ROUTINE');
choice:=UPCASE(ReadKey); {Read what key has been pressed}
UNTIL (Choice = 'P') OR (Choice = 'S') OR (Choice = 'R')
  OR (Choice = 'I') OR (Choice = 'Q');

CASE Choice OF
  'P' : BEGIN   {Sort on failure occurrence}
    ClrScr;
    gotoxy(25,12);
    TextColor(Yellow);
    WRITE(OUTPUT,'Sorting ','DataToSort,' on Probability');
    QuickSort(DataToSort,Prob_Less_Than);
    FOR I := 1 TO 15 DO
      BEGIN
        Gotoxy(25 + I,14);
        WRITE(OUTPUT,'.');
        DELAY(100);
      END;
    Gotoxy(25,16);
    WRITE(OUTPUT,'Press Any Key To Continue');
    key := Readkey;
  END;
  'S' : BEGIN   {Sort on failure severity}
    ClrScr;
    gotoxy(25,12);
TextColor(Yellow);
WRITE(OUTPUT,'Sorting ',DataToSort, ' on Severity');
QuickSort(DataToSort,Severe_Less_Then);
FOR I := 1 TO 15 DO
    BEGIN
        Gotoxy(25 +I,14);
        WRITE(OUTPUT,' .');
        DELAY(100);
    END;
Gotoxy(25,16);
WRITE(OUTPUT,'Press Any Key To Continue');
key := Readkey;
END;

'R' : BEGIN    {Sort on combined risk value}
   ClrScr;
gotoxy(25,12);
TextColor(Yellow);
WRITE(OUTPUT,'Sorting ',DataToSort, ' on Risk');
QuickSort(DataToSort,Risk_Less_Then);
FOR I := 1 TO 15 DO
    BEGIN
        Gotoxy(25 +I,14);
        WRITE(OUTPUT,' .');
        DELAY(100);
    END;
Gotoxy(25,16);
WRITE(OUTPUT,'Press Any Key To Continue');
key := Readkey;
END;

'I' : BEGIN    {Sort on component ID}
   ClrScr;
gotoxy(25,12);
TextColor(Yellow);
WRITE(OUTPUT,'Sorting ',DataToSort, ' on ID Number');
QuickSort(DataToSort,ID_Less_Then);
FOR I := 1 TO 15 DO
    BEGIN
        Gotoxy(25 +I,14);
        WRITE(OUTPUT,' .');
        DELAY(100);
    END;
Gotoxy(25,16);
WRITE(OUTPUT,'Press Any Key To Continue');
key := Readkey;
END;

'Q' : BEGIN
   EndRoutine := FALSE;
END;

END;
UNTIL EndRoutine <> TRUE;
END; {End of procedure Sort}
{**************************}
BEGIN
END.
UNIT FmeaMat;
{This unit is used for graphing of failure mode data obtained in FmeaData}

INTERFACE
TYPE
  MasterRecord = RECORD  {Defining the record}
    System,  {The type of system to be studied}
    Mission, {The purpose and operating range of the system}
    Component, {The components that make up the system}
    Failure, {The failure of a specific component}
    Cause,   {What caused the failure to happen}
    Effect  : STRING [25]; {The effect system failure}
    ID,      {A numeric assigned to the component}
    FMEADay, {The day on which the FMEA was performed}
    FMEAMonth, {The month of the FMEA}
    FMEAYear, {The year on which the FMEA was performed}
    Occurrence, {The likelihood of the failure}
    Severity, {The severity of the failure}
    Risk     : INTEGER {The combined risk number of occurrence and severity}
  END;

  MasterRecordFile = FILE OF MasterRecord;

PROCEDURE GraphDisplay (DataFile : STRING; Routine : CHAR);
PROCEDURE GraphSelect (VAR DataFile : STRING);

IMPLEMENTATION

USES
  Graph,   {Pascal Graphics Unit}
  Dos,     {Dos unit}
  BGIDriv, {all the BGI drivers}
  BGIFont, {all the BGI fonts}
  FmeaSort, {Sort routine for FMEA data}
  Crt;     {CRT device unit}

CONST
  GraphMode : INTEGER = 0;   {Initialize graphics to appropriate
graph mode

{********************************************************************}
PROCEDURE GraphSelect (VAR DataFile : STRING);
{Screen displays to prompt the user for a graphing selection}

VAR
  Choice,           {Variables used in screen formatting and prompts}
  TypeSort,
  GraphRoutine,
  key            : CHAR;
  EndRoutine    : BOOLEAN;
  I             : INTEGER;

BEGIN
  EndRoutine := TRUE;
  REPEAT
    REPEAT
      {Screen formatting and options}
      ClrScr;
      TEXTBACKGROUND(BLUE);
      TEXTCOLOR(White);
      Gotoxy(23,3);
      WRITE(OUTPUT,'Failure Mode Effects Graphing');
      Gotoxy(23,4);
      WRITE(OUTPUT,'------------------');
      Gotoxy(23,7);
      WRITE(OUTPUT,'[C] Criticality Matrix');
      Gotoxy(23,9);
      WRITE(OUTPUT,'[O] Stem and Leaf of Occurrence');
      Gotoxy(23,11);
      WRITE(OUTPUT,'[S] Stem and Leaf of Severity');
      Gotoxy(23,13);
      WRITE(OUTPUT,'[R] Stem and Leaf of Risk');
      Gotoxy(23,15);
      WRITE(OUTPUT,'[Q] QUIT ROUTINE');
      choice:=UPCASE(ReadKey);  {Read what key has been pressed - convert to caps}
      UNTIL (Choice = 'C') OR (Choice = 'O') OR (Choice = 'S')
          OR (Choice = 'R') OR (Choice = 'Q');

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CASE Choice OF
  'C' : BEGIN  {Criticality graph}
    GraphRoutine := 'C';
    GraphDisplay (DataFile, GraphRoutine);
  END;
  'O' : BEGIN   {Stem and Leaf of failure occurrence}
    GraphRoutine := 'O';
    GraphDisplay (DataFile, GraphRoutine);
  END;
  'S' : BEGIN   {Stem and Leaf of failure severity}
    GraphRoutine := 'S';
    GraphDisplay (DataFile, GraphRoutine);
  END;
  'R' : BEGIN   {Stem and Leaf of combined risk measure}
    GraphRoutine := 'R';
    GraphDisplay (DataFile, GraphRoutine);
  END;
  'Q' : BEGIN   {Quit the routine}
    EndRoutine := FALSE;
  END;
END;
UNTIL EndRoutine <> TRUE;
END;  {End of procedure GraphSelect}
{*******************************************************************************}
PROCEDURE GraphDisplay (DataFile: STRING; Routine : CHAR);
{Procedure to display failure data in different modes}

VAR
  TempFile     : MasterRecordFile;
  Key          : CHAR;
  Rec          : MasterRecord;

  I,          {Variables for screen formatting and display}
  J,
  K,
  L,
  Occ,
  Sev,
  R,
  y1,y2,y3,y4,y5,y6,y7,y8,y9,y10,
  x1,x2,x3,x4,x5,x6,x7,x8,x9,x10,
BEGIN
ClrScr; \{Variable initialization\}
xCount := 11;
RecordNo := 0;
I := 0;
Index := 0;
Spacer := 0;
yCount := 1;
pCount := 10;
y1 := 18;
y2 := 18;
y3 := 18;
y4 := 18;
y5 := 18;
y6 := 18;
y7 := 18;
y8 := 18;
y9 := 18;
y10 := 18;
CASE Routine OF
  \textquoteleft C\textquoteright : \{Criticality\}
  BEGIN
  ClrScr; \{Formatting the criticality matrix\}
  \{Matrix\}
  FOR Spacer := 1 TO 2 DO
  BEGIN
  FOR I := 11 TO 65 DO
  BEGIN
  Gotoxy(I,yCount);
  WRITE(OUTPUT,\textquoteleft-\textquoteright);
  END;
  FOR I := 1 TO 12 DO
BEGIN
  Gotoxy(xCount,yCount);
  WRITE(OUTPUT, '+');
  xCount := xCount + 5;
END;
  xCount := 11;
  yCount := 23;
END;
FOR Spacer := 2 TO 22 DO
BEGIN
  Gotoxy(11,Spacer);
  WRITE(OUTPUT, '|');
  Gotoxy(66,Spacer);
  WRITE(OUTPUT, '|');
END;
  yCount := 3;
FOR I := 1 TO 10 DO
BEGIN
  Gotoxy(11,yCount);
  WRITE(OUTPUT, '+');
  Gotoxy(8,yCount);
  WRITE(OUTPUT,pCount);
  Gotoxy(66,yCount);
  WRITE(OUTPUT, '+');
  pCount := pCount - 1;
  yCount := yCount + 2;
END;
  xCount := 16;
FOR J := 1 TO 10 DO
BEGIN
  Gotoxy(xCount,24);
  WRITE(OUTPUT,J);
  xCount := xCount + 5;
END;
  Gotoxy(3,7);
  WRITE(OUTPUT,'P');
  Gotoxy(3,8);
  WRITE(OUTPUT,'r');
  Gotoxy(3,9);
  WRITE(OUTPUT,'o');
  Gotoxy(3,10);
WRITE(OUTPUT, 'b');
Gotoxy(3,11);
WRITE(OUTPUT, 'a');
Gotoxy(3,12);
WRITE(OUTPUT, 'b');
Gotoxy(3,13);
WRITE(OUTPUT, 'i');
Gotoxy(3,14);
WRITE(OUTPUT, 'l');
Gotoxy(3,15);
WRITE(OUTPUT, 'i');
Gotoxy(3,16);
WRITE(OUTPUT, 't');
Gotoxy(3,17);
WRITE(OUTPUT, 'y');
Gotoxy(69,2);
WRITE(OUTPUT, 'Criticality');
Gotoxy(69,3);
WRITE(OUTPUT, 'Matrix');
Gotoxy(35,25);
WRITE(OUTPUT, 'Severity');
QuickSort(DataFile, ID_Less_Than); {Sorting on ID}
ASSIGN (TempFile, DataFile); {Assigning the data file}
RESET(TempFile);
SEEK (TempFile, 1);
READ (TempFile, Rec);
Gotoxy(69,6);
WRITE(OUTPUT, 'File');
Gotoxy(69,7);
WRITE(OUTPUT, '----------');
Gotoxy(69,8);
WRITE(OUTPUT, Datafile);
Gotoxy(69,11);
WRITE(OUTPUT, 'System');
Gotoxy(69,12);
WRITE(OUTPUT, '----------');
Gotoxy(69,13);
WRITE(OUTPUT, Rec.System);
Gotoxy(69,16);
WRITE(OUTPUT, 'Date');
Gotoxy(69,17);
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WRITE(OUTPUT,’--------’);
Gotoxy(69,18);
WRITE(OUTPUT,Rec.FMEAMonth,’/’,
    Rec.FMEADay,’/’ ,Rec.FMEAYear);
yCount := 23;
xCount := 11;
RESET (TempFile);
REPEAT  {Display all ID numbers on the matrix}
    SEEK (TempFile, RecordNo);
    READ (TempFile, Rec);
    WITH Rec DO
        BEGIN
            Occ := Occurrence;
            Sev := Severity;
            xCount := xCount + (5*Sev);
            yCount := yCount-(2*Occurrence);
            Gotoxy(xCount,yCount);
            WRITE(OUTPUT,ID);
            RecordNo := RecordNo + 1;
            yCount := 23;
            xCount := 11;
        END;
    UNTIL EOF(TempFile);
CLOSE(TempFile);
key := Readkey;
END;  {End of display for all ID numbers}
‘O’,‘S’,‘R’ : BEGIN
    {Stem and Leaf}  Gotoxy(30,5);
    {Plots}  WRITE(OUTPUT,’Stem and Leaf Matrix’);
CASE Routine OF
    ‘O’ : BEGIN  {Failure occurrence display}
        Gotoxy(16,19);
        WRITE(OUTPUT,’+----+----+----+----+----+
            +----+----+----+----+’);
        Gotoxy(16,20);
        WRITE(OUTPUT,’1 2 3 4 5
            6 7 8 9 10’);
        Gotoxy(36,7);
        WRITE(OUTPUT,’Occurrence’);
        Gotoxy(13,22);
        WRITE(OUTPUT,’Not Likely’);
Gotoxy(60,22);
WRITE(OUTPUT,'Likely');
END;
'S' : BEGIN    {Failure severity display}
  Gotoxy(16,19);
  WRITE(OUTPUT, '+-----+-----+-----+-----+-----+'  
             '+-----+-----+-----+-----+' );
  Gotoxy(16,20);
  WRITE(OUTPUT,'1 2 3 4 5  
             6 7 8 9 10');
  Gotoxy(36,7);
  WRITE(OUTPUT,'Severity');
  Gotoxy(13,22);
  WRITE(OUTPUT,'Not Severe');
  Gotoxy(60,22);
  WRITE(OUTPUT,'Severe');
END;
'R' : BEGIN    {Combined risk number display}
  Gotoxy(6,19);
  WRITE(OUTPUT, '+-----+-----+-----+-----+'  
             '+-----+-----+-----+-----+' );
  Gotoxy(6,20);
  WRITE(OUTPUT,' 1-9 10-19 20-29 30-39  
             40-49 50-59 60-69 70-79  
             80-89 90-100');
  Gotoxy(36,7);
  WRITE(OUTPUT,' Risk');
  Gotoxy(6,22);
  WRITE(OUTPUT,'Low Risk');
  Gotoxy(69,22);
  WRITE(OUTPUT,'High Risk');
END;
END;    {End of graphical screen formatting}
QuickSort(DFile,ID_Less_Then);    {Sort on ID numbers}
ASSIGN (TempFile, DFile);
RESET (TempFile);
REPEAT
  SEEK (TempFile, RecordNo);
  READ (TempFile, Rec);
  Gotoxy(10,2);
WRITE(OUTPUT, 'File: .DataFile);
Gotoxy(30,2);
WRITE(OUTPUT, 'System: .Rec.System);
Gotoxy(55,2);
WRITE(OUTPUT, 'Date: .Rec.FMEAMonth,/.','
           Rec.FMEADay,/.',Rec.FMEAYear);
WITH Rec DO
BEGIN
CASE Routine OF
 'O' : BEGIN {Display component ID occ}
Occ := Rec.Occurrence;
CASE Occ OF
1 : BEGIN
   x1 := 15;
   Gotoxy(x1,y1);
   WRITE(OUTPUT,ID:2);
   y1 := y1 - 1;
END;
2 : BEGIN
   x2 := 20;
   Gotoxy(x2,y2);
   WRITE(OUTPUT,ID:2);
   y2 := y2 - 1;
END;
3 : BEGIN
   x3 := 25;
   Gotoxy(x3,y3);
   WRITE(OUTPUT,ID:2);
   y3 := y3 - 1;
END;
4 : BEGIN
   x4 := 30;
   Gotoxy(x4,y4);
   WRITE(OUTPUT,ID:2);
   y4 := y4 - 1;
END;
5 : BEGIN
   x5 := 35;
   Gotoxy(x5,y5);
   WRITE(OUTPUT,ID:2);
   y5 := y5 - 1;
END

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6 : BEGIN
   \texttt{x6 := 40;}
   \texttt{Gotoxy(x6,y6);}
   \texttt{WRITE(OUTPUT,ID:2);}
   \texttt{y6 := y6 - 1;}
END;

7 : BEGIN
   \texttt{x7 := 45;}
   \texttt{Gotoxy(x7,y7);}
   \texttt{WRITE(OUTPUT,ID:2);}
   \texttt{y7 := y7 - 1;}
END;

8 : BEGIN
   \texttt{x8 := 50;}
   \texttt{Gotoxy(x8,y8);}
   \texttt{WRITE(OUTPUT,ID:2);}
   \texttt{y8 := y8 - 1;}
END;

9 : BEGIN
   \texttt{x9 := 55;}
   \texttt{Gotoxy(x9,y9);}
   \texttt{WRITE(OUTPUT,ID:2);}
   \texttt{y9 := y9 - 1;}
END;

10 : BEGIN
    \texttt{x10 := 60;}
    \texttt{Gotoxy(x10,y10);}
    \texttt{WRITE(OUTPUT,ID:2);}
    \texttt{y10 := y10 - 1;}
END;

END;

\texttt{\textsc{'S'} : BEGIN \{Display component ID by sev\}}
  \begin{align*}
  \texttt{Sev := Rec.Sequential;} \\
  \texttt{CASE Sev OF} \\
  \texttt{1 : BEGIN} \\
  \texttt{x1 := 15;} \\
  \texttt{Gotoxy(x1,y1);}
  \end{align*}
  \texttt{WRITE(OUTPUT,ID:2);}'
\texttt{y1 := y1 - 1;}

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END;
2 : BEGIN
x2 := 20;
Gotoxy(x2,y2);
WRITE(OUTPUT,ID:2);
y2 := y2 - 1;
END;
3 : BEGIN
x3 := 25;
Gotoxy(x3,y3);
WRITE(OUTPUT,ID:2);
y3 := y3 - 1;
END;
4 : BEGIN
x4 := 30;
Gotoxy(x4,y4);
WRITE(OUTPUT,ID:2);
y4 := y4 - 1;
END;
5 : BEGIN
x5 := 35;
Gotoxy(x5,y5);
WRITE(OUTPUT,ID:2);
y5 := y5 - 1;
END;
6 : BEGIN
x6 := 40;
Gotoxy(x6,y6);
WRITE(OUTPUT,ID:2);
y6 := y6 - 1;
END;
7 : BEGIN
x7 := 45;
Gotoxy(x7,y7);
WRITE(OUTPUT,ID:2);
y7 := y7 - 1;
END;
8 : BEGIN
x8 := 50;
Gotoxy(x8,y8);
WRITE(OUTPUT,ID:2);
y8 := y8 - 1;
END;

9 : BEGIN
  x9 := 55;
  Gotoxy(x9,y9);
  WRITE(OUTPUT,ID:2);
  y9 := y9 - 1;
END;

10 : BEGIN
  x10 := 60;
  Gotoxy(x10,y10);
  WRITE(OUTPUT,ID:2);
  y10 := y10 - 1;
END;

END;

R : = Rec.Risk;
CASE R OF
  1..9 : BEGIN
    x1 := 9;
    Gotoxy(x1,y1);
    WRITE(OUTPUT,ID:2);
    y1 := y1 - 1;
END;

10..19 : BEGIN
  x2 := 16;
  Gotoxy(x2,y2);
  WRITE(OUTPUT,ID:2);
  y2 := y2 - 1;
END;

20..29 : BEGIN
  x3 := 23;
  Gotoxy(x3,y3);
  WRITE(OUTPUT,ID:2);
  y3 := y3 - 1;
END;

30..39 : BEGIN
  x4 := 30;
  Gotoxy(x4,y4);

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WRITE(OUTPUT,ID:2);  
y4 := y4 - 1;
END;

40..49 : BEGIN
  x5 := 37;
  Gotoxy(x5,y5);
  WRITE(OUTPUT,ID:2);
  y5 := y5 - 1;
END;

50..59 : BEGIN
  x6 := 44;
  Gotoxy(x6,y6);
  WRITE(OUTPUT,ID:2);
  y6 := y6 - 1;
END;

60..69 : BEGIN
  x7 := 51;
  Gotoxy(x7,y7);
  WRITE(OUTPUT,ID:2);
  y7 := y7 - 1;
END;

70..79 : BEGIN
  x8 := 58;
  Gotoxy(x8,y8);
  WRITE(OUTPUT,ID:2);
  y8 := y8 - 1;
END;

80..89 : BEGIN
  x9 := 65;
  Gotoxy(x9,y9);
  WRITE(OUTPUT,ID:2);
  y9 := y9 - 1;
END;

90..100 : BEGIN
  x10 := 72;
  Gotoxy(x10,y10);
  WRITE(OUTPUT,ID:2);
  y10 := y10 - 1;
END;

END;
END;

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END;
RecordNo := RecordNo + 1; {Step through the file}
END;
UNTIL EOF(TempFile);
CLOSE(TempFile);
key := Readkey;
END; {End of displays for O, C and R}
END; {End of case for general categories}
END; {End of procedure GraphDisplay}
{*******************************************************************************
{*******************************************************************************
VAR
  GraphDriver, Error : Integer;
  Key : CHAR;

{ The following section was added in to combine the Pascal
graphics with the main executable. It is the modified BGILINK
program that was provided with the Pascal 6.0 software and was
modified specifically for this program initialization section.
}
BEGIN {Initialization section}

{ Register all the drivers }
IF RegisterBGlDriver(@CGADriverProc) < 0 THEN
BEGIN
  Writeln('CGA', ': ', GraphErrorMsg(GraphResult));
  Halt(1);
END;
IF RegisterBGlDriver(@EGA/VDriverProc) < 0 THEN
BEGIN
  Writeln('EGA/VGA', ': ', GraphErrorMsg(GraphResult));
  Halt(1);
END;
IF RegisterBGlDriver(@HercDriverProc) < 0 THEN
BEGIN
  Writeln('Herc', ': ', GraphErrorMsg(GraphResult));
  Halt(1);
END;
IF RegisterBGlDriver(@ATTDriverProc) < 0 THEN
BEGIN

Write('AT&T', ': ', GraphErrorMsg(GraphResult));
Halt(1);
END;

IF RegisterBGI(@PC3270DriverProc) < 0 THEN
BEGIN
Write('PC 3270', ': ', GraphErrorMsg(GraphResult));
Halt(1);
END;

{ Register all the fonts }
IF RegisterBGI(@GothicFontProc) < 0 THEN
BEGIN
Write('Gothic', ': ', GraphErrorMsg(GraphResult));
Halt(1);
END;

IF RegisterBGI(@SansSerifFontProc) < 0 THEN
BEGIN
Write('SansSerif', ': ', GraphErrorMsg(GraphResult));
Halt(1);
END;

IF RegisterBGI(@SmallFontProc) < 0 THEN
BEGIN
Write('Small', ': ', GraphErrorMsg(GraphResult));
Halt(1);
END;

IF RegisterBGI(@TriplexFontProc) < 0 THEN
BEGIN
Write('Triplex', ': ', GraphErrorMsg(GraphResult));
Halt(1);
END;

GraphDriver := Detect;                { autodetect the hardware }
InitGraph(GraphDriver, GraphMode, ''); { activate graphics }
IF GraphResult <> grOk THEN            { any errors? }
BEGIN
Write('Graphics init error: ', GraphErrorMsg(GraphDriver));
Halt(1);
END;
CloseGraph;
GraphDriver := Detect;                { autodetect the hardware }

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InitGraph(GraphDriver, GraphMode, ''); { activate graphics }
IF GraphResult <> grok then    { any errors? }
BEGIN
  Writeln('Graphics init error: '; GraphErrorMsg(GraphDriver));
  Halt(1);
END;

{Display of program name and software identification}
SetGraphMode(GraphMode);    { Set graph mode to current device }
SetColor(White);
SetLineStyle(SolidLn,0,Thickness);
SetFillStyle(SolidFill,LightGray);
Rectangle(125,70,475,420);
FloodFill(145,80,White);
SetTextStyle(TriplexFont, HorizDir, 4);
SetColor(GetBkColor);
OutTextXY(200,140,'Failure Mode');
OutTextXY(174,175,'Effects Analysis');
SetTextStyle(SansSerifFont, HorizDir, 1);
SetColor(Blue);
OutTextXY(185,300,'Press Any Key To Proceed');
OutTextXY(186,300,'Press Any Key To Proceed');
SetTextStyle(DefaultFont, HorizDir, 1);
OutTextXY(175,400,'TonyG Software Explorations 1996');
key: = ReadKey;
RestoreCrtMode;    { Restore the screen to original configuration }
END. { End of initialization }
UNIT FmeaSort;
{R,-S-}
{
    PROSPECTUS
    This unit will accept a file of a certain type and sort it by
failure occurrence, failure severity, overall failure risk or
component ID.

ALGORITHM

A file of MasterRecord is read into the unit.

The file is sorted according to rules in the various functions
using the QUICKSORT algorithm.

See each function or procedure for more detailed description of
how they work.

AUTHOR

Originally written by Zenas Hartsvigson for Math 5260 at the
University of Colorado at Denver in the laboratory and course
handbook (1992) and accompanying software. Modified for the
failure mode effects program called FMEA.PAS by Tony Gojanovic.
Modified source code for this unit written and compiled with
Boreland Turbo Pascal Version 6.0 and CSE editor. Modified
Summer 1996. Comments with a ZH are credited to Zenas
Hartsvigson.

}{*******************************************************}
INTERFACE

TYPE
    MasterRecord = RECORD    {Defining the record}
        System,     {The type of system to be studied}
        Mission,    {The purpose and operating range of the system}
        Component,  {The components that make up the system}
        Failure,    {The failure of a specific component}
}
Cause, {What caused the failure to happen}
Effect : STRING [25]; {The effect system failure}
ID, {A numeric assigned to the component}
FMEADay, {The day of the FMEA}
FMEAMonth, {The month of the FMEA}
FMEAYear, {The year on which the FMEA was performed}
Occurrence, {The likelihood of the failure}
Severity, {The severity of the failure}
Risk : INTEGER {The combined risk number of occurrence and severity}

END;

MasterRecordFile = FILE OF MasterRecord;

File_Name_Type = STRING;

{General procedure/function type for use in quick-sorter operation ZH}
Order_Type = FUNCTION (rec_1, rec_2: MasterRecord): BOOLEAN;

{The main operations that will sort the file}
FUNCTION Prob_Less_Than (rec_1, rec_2: MasterRecord): BOOLEAN;
FUNCTION Severe_Less_Than (rec_1, rec_2: MasterRecord): BOOLEAN;
FUNCTION Risk_Less_Than (rec_1, rec_2: MasterRecord): BOOLEAN;
FUNCTION ID_Less_Than (rec_1, rec_2: MasterRecord): BOOLEAN;
PROCEDURE QuickSort(VAR file_name: File_Name_Type;
                       Less_Than: Order_Type);

{***********************************************************************************}
IMPLEMENTATION

USES
    Crt;

{***********************************************************************************}
FUNCTION Prob_Less_Than (rec_1, rec_2: MasterRecord): BOOLEAN;
{
    This operation will order two records, rec_1 and rec_2 in terms of given probabilities. Depending on position, the function will be given a BOOLEAN value to be used in the main sorting routine.
}
BEGIN
  IF
    rec_1.occurrence + rec_1.occurrence > rec_2.occurrence + rec_2.occurrence
  THEN
    Prob_Less_Than := TRUE
  ELSE
    Prob_Less_Than := FALSE;
  END;

FUNCTION Severe_Less_Than (rec_1, rec_2: MasterRecord): BOOLEAN;
{
  This operation will order two records, rec_1 and rec_2 in terms of
  severity values. Depending on position, the function will
  be given a BOOLEAN value to be used in the main sorting routine.
}
BEGIN
  IF
    rec_1.severity + rec_1.severity > rec_2.severity + rec_2.severity
  THEN
    Severe_Less_Than := TRUE
  ELSE
    Severe_Less_Than := FALSE;
  END;

FUNCTION Risk_Less_Than (rec_1, rec_2: MasterRecord): BOOLEAN;
{
  This operation will order two records, rec_1 and rec_2 in terms of
  calculated risk values. Depending on position, the function will
  be given a BOOLEAN value to be used in the main sorting routine.
}
BEGIN
  IF
    rec_1.risk + rec_1.risk > rec_2.risk + rec_2.risk
  THEN
    Risk_Less_Than := TRUE
  ELSE
    Risk_Less_Than := FALSE;
  END;
}
FUNCTION ID_Less_Than (rec_1, rec_2: MasterRecord): BOOLEAN;
{
    This operation will order two records, rec_1 and rec_2 in terms of
    component ID values. Depending on position, the function will
    be given a BOOLEAN value to be used in the main sorting routine.
}
BEGIN
    IF
        rec_1.id + rec_1.id < rec_2.id + rec_2.id
    THEN
        Id_Less_Than := TRUE
    ELSE
        Id_Less_Than := FALSE;
    END;
{/*********************************************************************/
PROCEDURE QuickSort(VAR file_name: File_Name_Type;
                      Less_Than: Order_Type);

{ QUICKSORT sorts elements in the array, a, with indices between
{ LO and HI (both inclusive). Note that the QUICKSORT proce-
{ dure provides only an "interface" to the program. The actual
{ processing takes place in the SORT procedure, which executes
{ itself recursively. (ZH) }

VAR
    data_file : MasterRecordFile;
{/*************************************************************************/
PROCEDURE Sort(left, right: INTEGER);
{
    Sort selects one record as an anchor in the data file between
    the left-index and right-index values. It reorganizes all of the
    records in the disk file starting with the record at the left-index
    and going to the record at the right-index so that those records
    "less than" the anchor are on the left-side of the anchor
    and all other records are on the right-side. It should be observed
    that the anchor will be moved to the right or left as needed to
    accommodate locating the smaller items to its left and the bigger
    items to its right. When the items have been moved, the left-side
    and the right-side are not ordered. These "sides" are passed
    recursively to sort by giving the indices of the ends of each

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"side." A side of length 1 is sorted. (ZH)

\}

VAR
\i, \ j: INTEGER; \{indices (ZH)\}
partition_anchor,
i_th_rec,
j_th_rec: MasterRecord;

BEGIN
\i := left;
\ j := right;

{capture the partition_anchor record, which is
 selected to be middle record in the disk file (ZH)}
Seek (data_file, (left + right) DIV 2);
READ (data_file, partition_anchor);

REPEAT
{read in i_th record from the disk file (ZH)}
Seek (data_file, i);
READ (data_file, i_th_rec);

{read data file from left-to-right until a record is found
 that is not Less_Than the partition_anchor record (ZH)}
WHILE Less_Than (i_th_rec, partition_anchor) DO
BEGIN
\ i := \ i + 1;
Seek (data_file, i);
READ (data_file, i_th_rec);
END;

{read in the j_th record from the disk file (ZH)}
Seek (data_file, j);
READ (data_file, j_th_rec);

{read data file from right-to-left until a record is found
 that is equal or Less_Than the partition_anchor record (ZH)}
WHILE Less_Than (partition_anchor, j_th_rec) DO
BEGIN

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j := j - 1;
Seek (data_file, j);
READ (data_file, j_th_rec);
END;

IF (i <= j) THEN
BEGIN
{swap the i_th and j_th disk file records (ZH)}
Seek (data_file, i);
WRITE (data_file, j_th_rec);
Seek (data_file, j);
WRITE (data_file, i_th_rec);
{move index for left pointer to the right and
move index for right pointer to the left (ZHI)}
i := i + 1;
j := j - 1;
END;
UNTIL i > j;

IF left < j THEN
{Recursively pass left-side to Sort (ZH)}
Sort(left,j);

IF i < right THEN
{Recursively pass right-side to Sort (ZH)}
Sort(i,right);
END;
{*******************************************************************************
BEGIN {quicksort - assign and open files, sort the records, close the
file};
Assign (data_file, file_name);
Reset (data_file);
sort(0,FileSize(data_file) - 1);
Close (data_file);
END;
*******************************************************************************
END {End of Program Unit Sort}.}
BIBLIOGRAPHY


