CHAPTER 1
WHY DO WE NEED FMEAs?

What is an FMEA?

How many times have we heard an engineer say `we should have known that this would happen?`. Probably too often. But this is not acceptable in engineering, especially with the resulting on-cost. Even the most complex designs have aspects which are similar to other components, such as the tolerancing or machining required. Very few situations arise that are unique; most are adaptations.

If experience allows us to reasonably estimate likely problems, we should use this to plan ways of overcoming them. However, one person's experiences may not be enough (see chapter 2). Typically, all work is checked and this mechanism, it is hoped, will predict any future problems. This does use the assumption that the checker does not require checking. In reality they do, but how many re-checks would be required to ensure success? The simple answer is that you can never have enough checkers to guarantee no problems.

Although FMEAs are not designed to check, they are designed to detect errors. Early detection offers many advantages:

- It is much cheaper to modify a drawing than to re-manufacture;
- Large changes that are re-planned early do not have to delay the overall timing;
- Eliminating failures saves money;
- Why spend time and effort producing items that are likely to cause problems?

This list is not exhaustive and no attempt has been made to discuss the effect of potentially unsatisfied customers: the reason why many companies have gone into liquidation. Any technique that offers the ability to remove problems has to be positive, and the FMEA is one such technique.

History

Post war developments in the aerospace industry, particularly in jet engines, offered new and exciting designs that would outperform all previous types. Coupled with the cold war, the race to have the superior air force resulted in an expansion of these industries. Unlike previous aircraft of the second world war, the technology required enormous budgets to develop and test.

Initially, the cost was of no concern: the need for an air force equipped with such planes was paramount. As technology developed in the 1950s, newer generations of aircraft were subsequently planned. The estimates to fund these increased out of all proportion. Naturally, questions were asked, but only when the funding to overcome previously identified mistakes were discussed was any action considered.
Closer investigation revealed that on numerous occasions, the experience gained was not carried forward and mistakes were being repeatedly made. On large investments, especially research, this can run into seven figure values. Naturally, this had to be stopped - or reduced dramatically. Reliability engineering was a science in its infancy whose aims were to achieve improvements by quantitative and qualitative approaches. Using mathematical models it is possible to determine the probability of a failure, but this requires statistical evidence to support the data. Where no such data exists other methods are necessary. FMEA is one such technique.

FMEAs were designed to be a team effort where the experience of the team would evaluate new work with a view to preventing previous mistakes occurring again. It was never assumed to be the panacea to all situations. However, what started out as an initial attempt to reduce mistakes soon enabled predictions of other unforeseen problems. Developing the technique to expand upon this facet required a more structured approach.

It was found that dealing with the design and manufacturing aspects together encompassed too many areas. The separation of the FMEA teams into Design and Process allowed for a fuller analysis of the situation. The necessary experts in each team utilised the skill and ability that previously limited the full potential.

Design FMEA covers:

- All new designs of components;
- Carry over components used in new situations;
- Modified components.

The first point is clear and the reasons behind it are self-explanatory. The next two items introduce a new facet. FMEAs do not have to be limited only to new designs; advantages can be gained from modified and alternative usage. If the environment changes for a new situation this could raise other potential failure modes. Moreover, small modifications can drastically reduce the reliability of the design. It is not sufficient to assume otherwise. In practice, all designs should have a corresponding FMEA: if they are done retrospectively there is little reason to assume anything will result. Only where changes occur does any ability exist to implement a FMEA. This is also a good starting position. By the nature of design updates and changes, following this pattern will eventually produce a Design FMEA for everything.

Process FMEA covers:

- All new processes;
- Process modifications.

Again, the first point justifies itself. Likewise, any changes to the process and the equipment are where other potential failure modes can occur. Implementation of FMEAs on new production lines is structured. By starting with the design changes it will also ensure a successful implementation of all necessary processes.
The advent of automation in the American car companies also introduced costing concerns similar to that of the aerospace industries of the 1950s. Although FMEAs were considered a useful tool, the car industry only began to use it in the early 1970s. Until that time it was generally limited to aerospace/military applications. With the car companies having commercial power over numerous sub-suppliers it was natural they too became involved. As with most quality systems it was not for another decade that the European car companies followed suit. This was through direct intervention from America, and was also an attempt to match incoming Japanese cars. Quality was synonymous with the Japanese product range; this had to be matched.

Within Europe, sub-suppliers were positively encouraged to follow with various levels of success. Even limited success results in some improvements. Whether FMEAs expanded in use from the pressure of the car industries is not clear. The development of Total Quality Management (TQM) probably played its part too. In this system, FMEAs are a foundation in the path to total quality. As the world continuously strives for improvement for marketing advantage, the use of FMEAs has been supported too. There is no one single reason for using either the design or process route; the more reasons there are, the greater its choice of success. Benefits for industry are:

- A mandatory requirement for company quality standards;
- Improvement of product quality;
- Improvement of customer satisfaction;
- Process improvement;
- Reliability improvement;
- Design improvement;
- Product liability;
- Safety improvements;
- Reduction in the recall values.

Whichever reason, or combination of reasons, the overall effect and benefits must improve cost and quality.

FMEAs in Other Companies

The aerospace and car industries, although large, do not account for the majority of the engineering sector. Indeed, their influence is not as strong as they would believe. Many other industries require similar, if not higher standards. Electronics, and in particular, the domestic market demand very high levels of quality and product reliability. Numerous companies in this sector have had major problems because they failed to identify this need. Nowadays, the electronics industry has become the greatest user of FMEAs and is expected to remain so in
the future. Nevertheless, they are not the only industry. Table 1.1 shows the use, by industry, for FMEAs:

<table>
<thead>
<tr>
<th>Industry</th>
<th>Use (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronics</td>
<td>38%</td>
</tr>
<tr>
<td>Motor</td>
<td>31%</td>
</tr>
<tr>
<td>Aerospace</td>
<td>16%</td>
</tr>
<tr>
<td>Construction</td>
<td>6%</td>
</tr>
<tr>
<td>Mining</td>
<td>3%</td>
</tr>
<tr>
<td>Other</td>
<td>6%</td>
</tr>
</tbody>
</table>

Table 1.1 Industries using FMEAs (1992)

Usage in so many varying applications places a different emphasis on each approach. What is significant to one industry may be of no use to another. Nevertheless, the basic use does not change. It is the collection of data and the ways they are understood that differs. This can also vary in a company. Table 1.2 shows what supporting evidence is used in justifying FMEAs, and the decisions made:

<table>
<thead>
<tr>
<th>Technique</th>
<th>Use (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process flow chart</td>
<td>35%</td>
</tr>
<tr>
<td>TAGUCHI</td>
<td>11%</td>
</tr>
<tr>
<td>PARETO</td>
<td>10%</td>
</tr>
<tr>
<td>SPC</td>
<td>8%</td>
</tr>
<tr>
<td>Concern action-reports</td>
<td>8%</td>
</tr>
<tr>
<td>Control charts</td>
<td>7%</td>
</tr>
<tr>
<td>Warranty analysis</td>
<td>6%</td>
</tr>
<tr>
<td>Other</td>
<td>15%</td>
</tr>
</tbody>
</table>

Table 1.2 Techniques used with FMEAs

**Customer**

For whatever reason an FMEA is undertaken and, regardless of the required benefits, satisfying the customer must be the number one goal. This person or company will have their own expectations and determining exactly what they are can be impossible. However, defining the product or service as quality can clarify the end result.

Quality in its simplest form is defined as `Fitness for Purpose'. This definition is acceptable for non-technical people, but for engineers it is open and unclear. Numerous people have attempted to define quality and what it means with a sharp snappy statement, again with little or no success. It is important to define what quality is before subjective assumptions about customer satisfaction are dealt with. Our definition is:

The quality of a product or service must relate to customers' requirements and expectations at a cost that is realistic. It is expected that the suppliers of products and services will ensure dimensional control, reduce variations and aim for never-ending improvements.

This is rather lengthy, but uses quality in terms of several aspects. First, not everything is a product, it can be a service. This is currently highly relevant where an everincreasing percentage of the population works in service-related industries.
Secondly, it should meet what is required of it. This is where mistakes are made. It is possible to buy a man’s suit for less than £100, or far in excess of this cost if it is handmade. Both perform an adequate role. However, the cheaper one is unlikely to have the same appearance as the other. Nor should it. Someone who pays £100 for a suit does not expect the same product as the handmade suit. They should both be satisfied that they have a product that represents value. Prestige value is not the same as quality.

Finally, how many times have we bought something which is good apart from one minor irritation - only to find that when it is replaced, the fault has not been eliminated? If we identify the concern, so should the provider. This forms what is defined as never-ending improvements. The provider of the product or service must strive to achieve this. Reducing process variation and maintaining dimensional control is good engineering practice. Anything else is not likely to be acceptable.

Adopting this model as a quality expectation for a customer will assist in the various stages of an FMEA. A customer does not only have to be the end user, i.e. someone who buys it. It can be numerous other people, even those in the same organisation. Or the production operator at the next operation. All of these people depend upon previous functions being carried out correctly.

Whoever is chosen, their concerns, respect and views must be allowed for. In all cases, the situation that allows the worst scenario should be adopted. Here, it can be evaluated by the whole team to put it in context of all others. Nevertheless, as in all qualitative work, some degree of reality should be applied. This can be highlighted by two examples.

First, the manufacturer of double glazing. If, when a customer wishes to replace their patio door and they sell the item as second-hand, no allowance for the re-fitting would be necessary. Who would expect a guarantee on such an item? It is sold for one application and one fitting. Any concerns that might arise from its subsequent use should not have a detrimental effect on the company. No one would really expect to blame the company.

Secondly, consider a passenger-carrying aircraft. At all times while it is in service there is a minimum airworthiness standard that must be maintained. No matter how many times it is sold, it should be able to fly safely.

Here, the argument of the customer is clear; one should allow for subsequent users, the other should not. Where there are no clear distinctions, the team will have to decide by drawing upon the potential situations that may occur for that item. One should always remember that a quality product and satisfied customer are paramount.

Why Continue with FMEAs?

If a FMEA is to fail at an early stage, it is usually prior to the completion of a draft document. Typical reasons range from ‘I have not got the time’ to ‘what is the point?’.

An FMEA, in both the short and long term, will save a company money regardless of the headaches and efforts to achieve it. These savings will be direct (less scrap) and indirect (customer returns). If it achieves nothing else it is worthwhile.
Long term use of FMEAs evaluates the situation in full production. Here; it is easy to be complacent and to concentrate efforts on new projects. However where never-ending improvements are required, as in TQM, it also meets this stipulation. Tackling long established concerns is not reactive, but pro-active. It relates back to the initial description of quality where customers expect never-ending improvements. What better way is there for a customer to recommend a product by describing it as ‘even better than before’?

As BS5750 has become recognised as the norm for a company, TQM will be in the future. Although it is a philosophy, it requires the use of FMEAs for combining many aspects of a company. It is also the simplest way to show through documentation that never-ending improvements are made and expected to be made in the future. The planned revision to BS5750 is believed to stipulate the requirements of never-ending improvements. If this is true, their use will be seen as a way of life, as control charts are nowadays.

It can be shown schematically in figure 1.1 that the key to the whole system is the rudder (FMEA). Regardless of what else that occurs, the rudder will direct the path; without one, the direction is unknown.
CHAPTER 2
SETTING UP AN FMEA TEAM

What is Teamwork?

Everyone in industry is a team member; not everyone is aware of it! If you are working on a production line the subsequent operator will depend on you doing your work. Likewise, you will depend upon them successfully, doing their work. Without all the operations the product cannot be sold. Hence, no profit and no wages. If this production team does not work together the result is no production. This is an extreme, and the lack of results is obvious. Designing or planning for production is important too. However, if stages are missed or not correctly done they too will affect the outcome, albeit much later.

If the planning team consists of six engineers who all have functions, they will all be interlinked. It will only take one to do a bad job for the whole planning exercise to suffer. Like the phrase ‘a weak link in a chain’, a team that has a weak link will also fail.

Teamwork can be described, for FMEAs, as a group of people who all have actions and responsibilities to perform with an end result in view. A little ‘wordy’ but if people do not react to the end result it may never be reached.

Why Teamwork?

FMEAs (problem solving) concentrate on predicting what can go wrong and to decide if it is a problem. To establish exactly what can go wrong is not easy at the best of times; with time constraints it can become impossible. A designer may have no idea why a dimension might not be maintained. The production engineer cannot know what design features are critical to the function. Therefore, by using people with different backgrounds and skills the scope of knowledge is increased. However, you cannot keep increasing the number. Eventually a saturation point will be reached, where any increase will have a detrimental effect - too many people trying to say too much!

Who to Select and Why

Working on the point that too many will be just as bad as too few, what is the exact size of an FMEA team? There is no single answer; often the number changes from meeting to meeting. It may become necessary to have a specialist attend for discussion of a single aspect, or the answer could be obtained by a team member outside the meeting. In any case, this will depend on the circumstances at any one time.

Generally, there are several people who are found on most teams. These are usually representatives of individual departments that make up most of the project work, and they include:

- A designer (one who is actively involved in both the design and detail);
- A planner (an engineer dealing with the process and procurement tasks);
- Production (those who will use it);
- Quality (usually a Statistical Process Control (SPC) expert);
- Purchase (especially if large investment results)

These representatives are paramount to cover the basic aspects of even relatively small concerns. They do not form an exhaustive list. Indeed, any fewer would be unlikely to have success. Additional representatives might come from other company locations. Larger companies usually have several sites. The planners may have very little knowledge or experience of production preferences in a factory that is several hundred miles away. Likewise one production representative may not reflect the style for that site. In many cases, it may be necessary to have two such persons; any more would not be recommended.

Multinationals that invest large amounts of money to buy equipment encourage their vendors to participate. It may seem strange to have machine tool suppliers actively involved, but they can have a profound influence. Even small changes to designs have an effect. If that results in a modification on a specialised machine tool bed the cost could be astronomical. The delay in machine delivery can further delay a programme.

Suppliers of components can also have a pro-active role to play. Again, changes can result in on-costs and delays. If the design requires reliability testing or government certification, this can result in lengthy delays. On the positive side, they may have suggestions that lead to cost savings and smoother timing. It is not unrealistic to expect this; simultaneous engineering depends on all parties being truthful. Suppliers that show positive attitudes are also likely to gain repeat or new orders.

Not all companies have the industrial muscle to ensure that outside companies participate; it is even harder when the order values are small. Nevertheless, this option should be fully explored and progressive companies are likely to become involved in other ways for support.

It has been known that the Personnel Department join the team when changes to working practices are likely. In these instances, they may be there to find out information for later use. But there are likely to be instances when apparently unrelated people are useful. This will, of course, depend upon the individual situation. Overall, the team can combine numerous people to support the application necessary, but if the number increases to beyond eight, difficulties can easily arise.
Although the document is a team effort, one member must write it. No one individual would have the expertise to write it alone. Depending upon the FMEA (Design or Production) the first draft is usually the responsibility of a designer or manufacturing engineer. They would be familiar with most of the fundamental and detailed aspects of the design or process.

The draft would consist of a breakdown of the design/process for other information to be added, i.e. current controls. No attempt should be made to add the numbers or potential failure modes. This would lead the others too much, and further investigation could easily be ignored.

Actions that might become necessary do affect the timing of a project, and are in many instances obligatory. If these are identified at a late stage in the programme, delays will be inevitable. To minimise this it is important to start the procedure at the beginning of any programme. Any departure from this timing will waste the potential changes that may occur.

At any meeting a chair/scribe is always required; FMEAs are no different. The draft author often takes this responsibility, although it is not a problem if someone else does provided they are relatively familiar with the task.

**How Often to Meet?**

An FMEA is a live document; it should always reflect the present situation and the changes recorded. In no situation should it be revised just to show what has changed. All change must first pass through the team.

When starting on the task there is a lot of work that must take place; administration
accounts for a large part. Weekly meetings enable the draft to be transformed into a useful document. Once this situation is agreed, longer time spans are typical. This enables actions to be followed through and minimises the time a meeting takes.

The more complex the design or process is, the longer it will take, reflecting not size but detail. Once a steady state is reached, the time between meetings can increase. Typical designs/processes that have been in production for a while only need to meet yearly, unless there are changes planned. Concentrating the effort at the start should eliminate the requirement of the majority of concerns. This enables efforts to be directed to concerns that arise in other important stages of the programme.

**A Typical Meeting**

FMEAs are not unlike other problem-solving techniques, i.e. brainstorming, Taguchi and Value Engineering. There are basic rules that must be followed by all team members. Otherwise, a leader might force the issues to their way of thinking.

The four basic rules are:

I) All parts delivered are 100% correct to the drawing;

II) Each team member is equally important;

III) Sub-suppliers are our partners;

IV) The goal is for never-ending improvements.

All of these must be followed; it is not a case of pick what you believe is the most important. Like any good system, without its rules it will not work successfully, and FMEAs are no exception. The rules were derived through experience and improvements to the technique.

**Rules**

When discussing the potential failure modes (see chapter 3) there are situations where numerous failure modes can be apparent. If the scenario is further complicated by 'out of specifications' on delivered parts the system can become unmanageable. That is not to say they should be ignored. They too should be covered by their own quality system.

A team may comprise people who are at different levels in the organisation. Some may wish to improve their relative influence on the meeting purely because they are the only manager present. This is not acceptable. It is probable that anyone may identify a concern, or a suitable solution. It may require a fresh approach rather than a repeat of previous experiences.

Sub-suppliers can have a useful input and they too will be interested in eliminating concerns. Rejects cost everyone money and they can assist at all stages. It can forge future links and a company is no longer a voice at the end of a telephone.

The whole idea of FMEAs is to improve a design or process, but will the first improvement be the perfect solution? The simple answer is NO. There is no reason why the same analysis
cannot eliminate more concerns. Eventually a situation will be reached when no more practical improvements are possible without large scale investment. In this instance other questions have to be asked.

FMEA meetings are not short, nor should they be. However, the time each one takes can reflect how members of the team work together and how positively they tackle each concern. Obviously, the initial ones are usually the longest. There is a finite time of how long each can last. It is better not to carry over to the next day but to re-arrange in the near future.

**When Teams do not Work**

No matter how a team is selected, there can always be personality clashes between two or more individuals. These must be resolved, whether by talking it through outside the meeting or through management intervention. Any friction in the team will discourage a positive attitude. Likewise, if a member of the team is replaced for any reason (promotion etc) the new member must be accepted.

There are no rules on who to include or exclude; no method exists to guarantee this. But as in any selection, errors need to be refined.
CHAPTER 3
WORKING THROUGH THE FORM

Starting

The start in developing an FMEA is perhaps the hardest part. It can be very hard to build up the dedication to complete what can be a long task. Nevertheless, the start will naturally lay down the foundation for the whole task. Any attempt to reduce the detail at any stage, especially the start, is likely to continue. Therefore, it is worth putting that little bit more effort in initially.

Whether it is a design or process FMEA, it is best to rough it out on the draft document (see appendix). Once the FMEA team have reviewed this draft it can be transferred to the final document (see appendix). By adopting this approach it prevents any attempt to fill in the other sections, which should be tackled at a much later stage. When the various stages are taken out of order, many of the potential benefits are lost. Although it is tempting to rush, never attempt this, otherwise the process will become a paper exercise and you end up by matching the document to the design or process you expect.

Form Filling

There are several columns on the document, each having a required description. The headings correspond to the actions reviewed or to be taken. All the following descriptions adopt a standard approach for both the design and process FMEA. Individual descriptions will concentrate on each where appropriate.

Part/Process Description

The first column on the left band side is an administration one. Descriptions on the first page will highlight the main design component or the process part or production line. These either direct the attention to a specific section when developing the FMEA or to enable a reference point when using the document at a later stage.

Part Function/Process Layout

Here a more detailed description is necessary. A design might be a support bracket, while a process one could be the assembly of the bracket. Large designs can be very difficult to sectionalise, particularly when features are performing a dual function. Indeed, an existing feature may be hard to justify. In such a situation this may indicate the feature is superfluous. Probably the feature is not understood or it is there to hold/join/divide other more important features.

Process functions can be more easily sectionalised. This may vary from part to part, i.e. a small function that an operator performs in the whole cycle of a machine. There is no need to adopt the same approach throughout. Often where certain parts contain more actions or problems, sub-dividing these further is not a problem. It is left up to the discretion of the first drafter and finally the team.

Potential Failure Mode
Of all the tasks to perform in the FMEA this is by far the hardest. Any failure mode that is missed could be the one that causes the largest concern. This is where the advantage of the teamwork comes in. A team (of several members) has a greater chance of identifying it.

A process is no easier than a design FMEA; both require a degree of lateral, thinking and the ability to comprehend all realistic situations. Use the assumptions discussed in chapter 2 to remove the situations that cannot realistically be discussed or solved. Likewise, concerns with bought-in parts are out of the control of the team; other avenues exist to solve these situations.

Before trying to review what can be a complex process it is worth analysing a relatively simple process. See figure 3.1. This is a simple bracket which has to be bolted to a component; there is no washer and the bracket is symmetrical. Also, we can assume the tolerance on the orientation is +/-25°:

**Bracket**

![Bracket assembly](image)

**Figure 3.1 Bracket assembly**

There are several potential failure modes; try to establish what these could be prior to reading our descriptions of them. Each classifies something that could go wrong.

**Loose**

This is the most obvious one: we have all experienced problems because of loose bolts. The description could have been classified as not to the correct torque or no torque (only partly engaged in the threaded hole). It would be, in our opinion, not
worth making this division because the resultant effects would be the same.

Too tight

In many respects, this is the opposite of loose, but it cannot be classified under the same heading. What could go wrong because of this would be completely different. A bracket of a softer material (plastic) could fracture under the loads from an excessively high torque.

Stripped thread

There are several reasons why a stripped thread occurs, but the results are still the same: the torque value will not be maintained and sooner or later the bracket will become loose. Moreover, the component with the stripped thread will be scrap. Even if it can be repaired this is an unnecessary cost to the production.

Damaged head

Damaged heads result from inefficiencies in the tightening system, e.g. too large a socket, design torque too high. This failure mode can be rectified and repeats will not occur. Likewise, a damaged head can prevent service, and produce items that cannot be repaired.

Wrong bolt

Yes, this can occur. Admittedly a bolt that is too large will never fit into the hole. There are many different types of threads (coarse, fine, square etc). Similar diameters may overlap in certain situations, especially where an operator has several threaded components that may be fitted to numerous variations in design.

Missing bolt

In this particular instance, it would be obvious - the bracket could not be assembled. But what if that bracket was not noted as missing? Where numerous bolts are used to secure a component it is easy to miss one. How many times have you repaired something, and at the end there are several components left?

Missing bracket

A missing bracket may result from problems similar to those mentioned above. Even large components can still be missed. Automatic assembly machines are prone to this. They cannot always detect if the gripper has failed to engage or drop the part while moving.

Bracket incorrect

It could be upside down or not square to the orientation required. For this application there is a
large tolerance, although in certain positions the bracket hole could not be engaged by an item that may have to pass through the other hole.

All of these potential failure modes are realistic and have occurred in numerous situations, and are likely to occur many times in the future. There are no reasons to justify these mistakes and most people could identify all of them by looking at this assembly. Nevertheless, there are assemblies that cannot be visually checked and require a thorough investigation with specialised equipment.

Where does this fit in for a design? Well, it is not that different and follows the same lateral thinking approach as that for a process FMEA. Figure 3.2 shows a section through a component which has an M12 tapped hole above a water jacket. For this application we can assume the water jacket is for a cooling function, as in a cylinder head on a car:

![M12 hole](image)

**Figure 3.2 A cross section through a cylinder head**

The tapped hole is conventional: it consists of a spot face, pilot hole and threaded section. Potential failure modes may occur in normal use, while some may only occur when the design is used in unrecommended environments: rain, beat, no maintenance or unconventional uses. This latter group may be ignored if it is so decided; improvements to these will upgrade the overall potential of the design. The former should be considered as paramount under all instances.

For this design there can be many potential failure modes, but without specifying exactly what the boundary constraints are they cannot be detected. Anyway, consider the tapped hole of M12:
Too shallow

A small reduction in the depth of the tapped hole will have no noticeable effect. Carry on decreasing the depth and eventually it will be too shallow for the bolt (it will bottom out): a common design error.

Too deep

Again, if it is only slightly deeper than required, there will be no real concern. However, as the depth increases there will come a point when problems can arise.

(I) If the tapped hole is several mm deeper, there will come a point where problems can arise. Assuming that the main material is cast iron, the water jacket will assist in the oxidisation of the surface. Oxidised materials, especially thin sections, are weak. Even if the depth of the hole is 5mm from the water jacket, prolonged use could result in a failure.

(II) A tapped hole that protrudes into the water jacket can have the same failure mode as that in (I). A thread does not form a good water seal. Both of these modes would allow water seepage. On this design, you cannot predict what damage this might cause, but whatever this is, such a leakage is undesirable in all situations.

Design and process potential failure modes can be too numerous to mention; each will ultimately depend on the exact application. There are, in our experience, particular ones that repeat frequently, but whether this is because mistakes are repeatedly made, or because they are not described properly is not known. These should not be taken as exhaustive, more a guide to start and build on for individual situations.

Typically, design FMEAs are harder to describe. Failure modes for one design can be unique, and unlikely to be repeated on others. Where designs are produced to meet a specification these can be used to start. Modifications that are required to overcome a design error are also likely to guide the engineer to possible failure mode.

Process failure modes are easier to determine because the mistakes (or potential ones) made by an operator indicate clearly where a concern can arise. Careful analysis and examination of these points must be made if the whole task is to be utilised to the full. Below are listed the generally common ones. However, it must be stated that potential failure modes are assumed to happen under standard conditions. This is only fair: no one could justify a short fall in a design of a calculator if it was dropped in water. Likewise, if a crane failed when lifting an article that exceeded its design weight.

Where process failure modes cause concern is when potential problems to other operators are assumed to be of a greater concern than those to the customer. This is not to say they are not, but the person who buys the product can soon become dissatisfied when trivial things cause undue problems.
Design

Brittle  Buckling  Collapsed  Corrosion
Cracked  Deformed  Fatigue  Fractured
Friction  Harshness  High-stress  Jammed
Noise    Overheating  Peel Force  Soft
Sticking Vibration  Vacuum  Worn

Comments of 'weak and poor design' are not suitable. Potential failure modes should be limited to physical occurrences which may be likely under normal operating conditions. The list states failure modes that can usually be calculated through mechanical analysis. This may be sufficient; further experimental investigations may have to be undertaken for the final solution.

Process

Bent    Blistered  Brittle  Broken
Buckled Corroded  Cracked  Damaged
Deformed Dented  Distorted  Dropped
Friction Leaking  Loose  Jammed
Melted   Misaligned  Misassemble  Missing
Porous  Rough  Shorted  Smashed
Tight    Warped  Worn  Wrinkled

Process FMEAs should avoid the use of phrases such as `not right', `not working' or `bad design'. They should concentrate on what could be performed incorrectly or what these errors could cause to the suitability of the item to function. It does not matter how trivial these may seem at the time, they all have their own influence on the outcome.

Potential Effects) of Failure

It can seem impossible to determine what the likely effects of a failure mode can be. For each failure mode there could be numerous ones, or there may be none. Likewise, the effects may cause concerns for other parts of the design or process (datum positions) or the customer.

Take, for example, a car engine. There are one or two brackets attached for lifting it. These are added for several different reasons. Engines are heavy and require assisted help in lifting them. During their assembly they enable the engine, in its unfinished state, to be easily lifted between the various parts of the production lines (assembly to shipping). They also enable easier fitment to the gearbox and in the car, and they help the car mechanic in servicing if it requires a major overhaul. There are no other possible reasons. So, if the potential failure mode is that an operator has failed to assemble it correctly, what could be the potential effects?

We can review this for three separate situations:

1. An operator who is responsible for transporting the engine within the factory, or to shipping racks, cannot use the dedicated equipment. It is possible for other equipment to be used, i.e. ropes. But would these be available when required? The answer is
probably not. Therefore, the operator would be dissatisfied because of the inconvenience, and the production manager because of the loss of production while the error is rectified.

2. It will slow down the speed at which the car mechanic could work. Moreover, emergency modifications could be dangerous because they are not tested, or reliable for that application. Here, as in the factory, the works manager will be annoyed because the next repair will be delayed. Any inspection by the Health and Safety officer could result in legal action. Nevertheless, it may be possible to fit them if they are available.

3. Car owner. None. It is most unlikely that this error would ever be noticed. Why should it? The vast majority of car owners do not service their own cars, let alone remove the engine.

All three of the above will be affected in different ways at different levels. The underlying concern is modifications, and effort costs money and results in dissatisfied people. In this situation the customer will still be happy but many other effects may be more problematic.

Potential effects) of failures may be stated in terms of reducing the operational reliability or the loss of a function e.g. one part of the item will not work correctly or at all. The following are typical descriptions used:

<table>
<thead>
<tr>
<th>Design</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise</td>
<td>Air leaks</td>
</tr>
<tr>
<td>Erratic behaviour</td>
<td>Chatter</td>
</tr>
<tr>
<td>Inoperative</td>
<td>Erratic behaviour</td>
</tr>
<tr>
<td>Unstable</td>
<td>High oil consumption</td>
</tr>
<tr>
<td>Unsafe</td>
<td>High operating cost</td>
</tr>
<tr>
<td>Draft</td>
<td>Insufficient cooling</td>
</tr>
<tr>
<td>Excessive wear</td>
<td>Water leaks</td>
</tr>
<tr>
<td>Ineffective</td>
<td>Positional errors</td>
</tr>
<tr>
<td>Impaired appearance</td>
<td>Reduced tolerances</td>
</tr>
<tr>
<td>Intermittent fault</td>
<td></td>
</tr>
<tr>
<td>Vibration</td>
<td></td>
</tr>
<tr>
<td>Breakage</td>
<td></td>
</tr>
<tr>
<td>Buckling</td>
<td></td>
</tr>
<tr>
<td>Leakage</td>
<td></td>
</tr>
<tr>
<td>Fracture</td>
<td></td>
</tr>
</tbody>
</table>

Several of these effects may also be failure modes, but the cause and effect will be different. If they appear in one column they cannot be used for the other. It is strongly suggested that terms of ‘bad working’ or ‘not right’ are not used to describe any effects, as they will inhibit further discussion.
Again, descriptions of effects can be the same for process and design. This is not that uncommon; however, the potential failure mode will be different. Overall, it can be difficult to develop ways to describe these situations; practice will enhance this and reduce the time spent analysing them. Remember, if one is missed, it cannot be viewed in comparison to the others, hence no action to remove it is possible. Although being a live document, this may be noticed at a later stage.

For similar components the process of the draft is likely to reflect previous work. This can assist in saving time identifying these concerns, but this is also because the experience gained builds up confidence to tackle problems. Remember, if an area is not easy to define, the team approach will often produce assistance.

**Potential Cause(s) of Failure**

Establishing what can go wrong and the effects that this produces are only the first stages of the FMEA. It is paramount to know why these happen, before actions can be taken to overcome them. Another example that may clarify this is a tapped hole. See figure 3.3.

![Figure 3.3 A tapped hole](image)

This type of feature is typical on numerous designs; it forms part of the standard approach for mechanical fixing. There are two principal ways of producing this: manually or automatically.

The manual way is to follow the procedure below:

- Mark position and centre punch;
- Centre drill;
- Spot drill;
- Drill to depth with drill equal to core diameter;
- Tap thread with taper;
- Tap thread with plug.

The automatic procedure, assuming a dedicated fixture or machine, is:

- Spot drill;
- Drill to depth with drill equal to core diameter;
- Tap thread to depth with plug.

There are fewer stages in the automatic procedure because marking is overcome with a drill guide and the machine spindle will enable a plug tap to be square to the surface.

Given these two procedures, how could the potential failure mode of incorrect position of tapped hole be caused? A manual process can cause the tapped hole to be out of line because of several reasons. The first is simply a marking error; if this is incorrect the remaining procedures will also follow this. Secondly, the centre punched mark may not correspond to the marking. The following list attempts to highlight all the reasons why the final hole can be in the wrong position:

- Marking out error - centre punch mark incorrect;
- Centre drill does not match centre punch;
- Spot drill does not match centre drill;
- Drill flanks of different lengths;
- Drill spindle is not square to base;
- Work piece is not square to spindle.

There may be others, but that will depend upon the particular application and equipment being used. In all, there are seven possible causes of one potential failure mode. This example is overestimating the possible causes and there are not usually that many, although there may be more.

For the automatic procedure the causes can be:

- Work is not square to spindle;
- Spindle is not square to machine base;
- Wear in bush guide (drill alignment feature);
- Drill flanks of different lengths.

In all, there are four, with three matching those for the manual procedure. Automatic machines do not always have fewer causes of concern, but it is often the case. Again, the reduction stems from the dedicated equipment that is designed to overcome manual concerns. This is one major reason why manufacturing companies prefer automatic machines if possible. (This assumes that the machine has been designed correctly and proves an acceptable capability ranking). See chapter 4.

The following list states typical descriptions of causes for Design and Process FMEAs.
<table>
<thead>
<tr>
<th>Design</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incorrect grain structure</td>
<td>Chipped cutting tool</td>
</tr>
<tr>
<td>No preventive maintenance</td>
<td>Tool burnt out</td>
</tr>
<tr>
<td>Insufficient thickness</td>
<td>Material failure</td>
</tr>
<tr>
<td>Incorrect load-strength design</td>
<td>Wrong tooling used</td>
</tr>
<tr>
<td>Not balanced</td>
<td>Excessive torque</td>
</tr>
<tr>
<td>Loads too high</td>
<td>Coding error</td>
</tr>
<tr>
<td>Misaligned</td>
<td>Coding error</td>
</tr>
<tr>
<td>Excessive stress</td>
<td>Coding error</td>
</tr>
<tr>
<td>Missing</td>
<td>Damage in transport</td>
</tr>
<tr>
<td>Part not to drawing</td>
<td>Overload</td>
</tr>
<tr>
<td>Production fixtures damage</td>
<td>Built up edge on tool</td>
</tr>
<tr>
<td>Non-normal distribution</td>
<td>Localised beat</td>
</tr>
<tr>
<td>Incorrect joint design</td>
<td>Non-tool set-up</td>
</tr>
<tr>
<td>Hydrogen embrittlement</td>
<td>Machines not capable</td>
</tr>
<tr>
<td>Work hardening</td>
<td>Non-normal distribution</td>
</tr>
<tr>
<td>Poor surface finish</td>
<td>Non-normal distribution</td>
</tr>
<tr>
<td>Too hard</td>
<td>Too brittle</td>
</tr>
<tr>
<td>Too brittle</td>
<td>Tool burnt out</td>
</tr>
<tr>
<td>Too hot</td>
<td>Tool burnt out</td>
</tr>
<tr>
<td>Too cold</td>
<td>Tool burnt out</td>
</tr>
<tr>
<td>No lubrication</td>
<td>Tool burnt out</td>
</tr>
<tr>
<td>Torque too high</td>
<td>Tool burnt out</td>
</tr>
<tr>
<td>Incorrect thread</td>
<td>Tool burnt out</td>
</tr>
<tr>
<td>No corrosion resistance</td>
<td>Tool burnt out</td>
</tr>
</tbody>
</table>

21
There are, of course, far more potential causes of failure. However, if you think about all the ways something can be incorrectly used, a long list will evolve. The simplest way to determine causes is to consider the possible variables that may occur; these are likely to be the causes.

**Current Controls**

This is the last main heading on the draft FMEA. It is intended to analyse the potential causes of failure. Controls will assist in establishing whether any of the previous causes can be detected and, if so, how easily.

Controls have various levels of success, usually relating to their cost. Many people consider the ideal control to be 100% inspection; this is not true. In fact, quality decreases in this scenario. First, no human can work and not make a mistake. This applies to inspectors also: they often detect many errors, but not all. You cannot inspect quality into a component. It is there, or it is not. Inspection may identify a problem; it might miss it. Secondly, when working in an environment of 100% inspection the operators assume that if they do make a mistake it will never reach the customer. It typically does. An assumption that someone else will rectify errors is bad operating practice.

Control, for the purpose of FMEAs, assumes that it will prevent the causes of failure from occurring. It will be either an open or a closed loop.

A closed loop control is one which assumes the action has occurred, i.e. a dead stop on a travel or the operation of the pressure overload switch. There is no feedback to check this has happened. Typically, they are mechanically based and are carry-over procedures from yesteryear. They are also cheaper than open loop.

Open loop control will process feedback if it detects that the required action has not happened and will adjust to suit. These are typically electronic in operation and more expensive.

To return to the example of the tapped hole, here it is assumed that the drill will travel to the correct depth. This may be achieved by having a mechanical stop to prevent further travel; this is open control. If the stop is moved accidentally, there is no mechanism to determine this. Subsequent holes will be too deep. Likewise, if the travel is prevented through something obstructing the movement, the hole will be too shallow. Not until a physical measurement of the part is carried out will the error be detected. Although a checking procedure is a control, it will not prevent the manufacture of those rejects until actions are taken to adjust or repair the travel.
Where machines are used, it is easier to use control mechanisms. A design may not be so simple. The initial design can be tested for reliability, strength and durability, but will this carry through to production items?

A modern day passenger-carrying aeroplane is perhaps one of the most critical designs. There are several airworthiness certificates required before it can be flown. Where excessive loading is placed on the airframe a sensor will detect and notify the pilot on the control lights. If an undercarriage does not lower, a positional sensory device will also inform the pilot.

Between these two extremes there will be controls that are suitable for all applications. It may be that the material is checked for particular features when delivered, to ensure the specification is met. Or a simulated use is performed to see if it is meeting the necessary design specification.

Summary

For every potential failure mode there will be the associated potential effects and causes. These will be controlled or not, as the case may be. One potential failure mode may have numerous effects and causes, but will not always have control over them.

This is how far the engineer who drafts out the FMEA should go. It is worthwhile leaving it for a short period before checking the entries, otherwise they may be missed. The draft FMEA can then be presented to the team for further analysis. This will involve establishing any missing items and the corresponding numbers for the three columns. Only then can the Risk Priority Numbers (RPN) values be obtained.
CHAPTER 4
SEVERITY, OCCURRENCE AND CURRENT CONTROL

Severity

When the first draft of the design or process FMEA is ready it can be presented to the FMEA team. It can be circulated in advance of the meeting, or only when it is decided to meet. For non-technical team members who will need guiding through the descriptions and the implications, there is no real reason for doing this. Technically based personnel may use an advance copy to follow through the procedures or check for errors. In both instances it may save time, but it defeats the team approach. Any expert who decides that a particular action is of no concern may not be aware of any other factors. The action of ignoring the team defeats one of the main objectives and advantages of FMEAs.

Figure 4.1 introduces the first collective problem that a team will have to agree on. Each of the first three columns requires a corresponding number (from 1 to 10) that will mathematically describe the potential failure mode, effect and cause. Every individual line will require such a number; these will be used at a later stage.

Design and process FMEAs have the same description for severity. Introducing this topic, we must classify the severity in terms of:

Minor - Unreasonable to expect such a problem will cause a failure.
A customer will probably never notice.

If we refer back to the tapped hole in a cylinder head, the severity can be related to the design and process. We have already established the fact that the tapped hole must not be too close to the water jacket for several reasons. A design that specifies the bottom of the hole 1 mm closer to the water jacket than the ideal position is in error. A problem may result and the design is not the optimum. Nevertheless, would a customer ever notice? Probably not; it would be hard enough for an inspector to do so. A machine that produced the same hole 1 mm too deep will also be in error. Again, the customer is unlikely to notice.

This description corresponds to a ranking value of 1; it is this value that will appear in the severity column.

Low - Failure causes only slight customer annoyance, i.e. minor rework action.

The engine bracket is missing, although whether this is because of a design or a process error is irrelevant. A customer that might notice this is unlikely to be annoyed. It would not stop any function or use by the customer.
<table>
<thead>
<tr>
<th>Level</th>
<th>SEVERITY</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINOR</td>
<td>Unreasonable to expect such a problem will cause a failure. Customer will probably never notice</td>
<td>1</td>
</tr>
<tr>
<td>LOW</td>
<td>Failure causing only slight customer annoyance i.e., minor rework action</td>
<td>2, 3</td>
</tr>
<tr>
<td>MODERATE</td>
<td>Some customer dissatisfaction, may cause unscheduled rework</td>
<td>4, 5, 6</td>
</tr>
<tr>
<td>HIGH</td>
<td>High degree of customer dissatisfaction, rework required before further use</td>
<td>7</td>
</tr>
<tr>
<td>VERY HIGH</td>
<td>Affects safe operations or government regulations</td>
<td>8, 9, 10</td>
</tr>
</tbody>
</table>
Take the example of watches. Expensive ones, which recognise the leap year and do not jump from 28th February to 1st March (allowing for the 29th February) are only checked occasionally. If the watch was very expensive, and had not functioned as claimed, the owner may be annoyed, but the majority of us would not rush to the shop on the next available day to complain. This too, can be classified as a low severity and ranked as 2 or 3. A decision that the team can make is whether it is closer to one or other. Services, especially domestic ones, can end up with a customer who is not specifically annoyed, but requires one more visit to their house to rectify the final point. Plumbers often return to fix a leaky tap; it was not leaking when they left but settling down actions have caused it to do so. This may be more typical than it appears; it is also likely to be expensive for manufacturing and service alike.

**Moderate** - Some customer dissatisfaction, may cause unscheduled rework.

Unscheduled rework refers to a customer who arranges an extra visit to fix the concern. This is undesirable but avoidable. Here, a customer will have to spend his own time to arrange what is necessary. If this involves taking an item back to a shop, this is all extra time and effort.

A radio cassette player that does not receive a particular radio station clearly can be described as having a problem that is moderate in severity. It would not prevent the other radio stations being listened to, or use of the tape player. Eventually, it will be returned for repair, but not necessarily the next day.

The ranking is 4.5 or 6 with a larger range; the option to classify accordingly exists. Moderate may mean different things to different people. These numbers, in this case, are not a linear scale, they are only an attempt to rank the severity.

**High** - High degree of customer dissatisfaction; rework required before further use.

Once again, let us consider the tapped hole above the water jacket. A drilled hole that is too deep can be a problem. In use, the water can leak through the thread to escape. If the water is required to operate the item, once a certain amount has been lost the item can no longer function, i.e. it must be repaired before further use.

Regardless of whether the design or process is wrong or slightly wrong, this will only delay the leak. Time or use problems are typical in electronic components. Some degrade prior to use; they are described as having a shelf life similar to food. When an item fails under the guarantee, the expense is considerable. The main reason an item falls into this category is that further work is required before it can be used again. This accounts for many practical situations and is clear in description.

**Very high** - Affects safe operation or contravenes government regulations.

The vast majority of severity rankings are not expected to be ranked higher than 8. Classifications of 9 and 10 (very high) are used for extreme situations; sometimes classified as safety/critical. Any item with a severity ranking of this category can result in loss of life or severe injury when something goes wrong. Nowadays, where many government and European legislations exist to cover numerous areas, this category of the FMEA is for these too. It allows for compliance with legal aspects.
For example, petro-chemical companies that are checked by Her Majesty's Inspectorate of Pollutants, HMIP or its European counterparts, have the power to stop a product being sold or a factory operating. This situation would not directly affect a customer, but is still classified as very high to show the important aspect it plays in a company.
<table>
<thead>
<tr>
<th>DETECTION</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERY HIGH – Will almost certainly detect the existence of a defect</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>HIGH – Have a good chance of detecting the existence of a defect</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td>MODERATE – May detect the existence of a defect</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>LOW – Have a poor chance of detecting the existence of a defect</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>8</td>
</tr>
<tr>
<td>VERY LOW – Probably will not detect the existence of a defect</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>
Detection

Detection relates to the procedures that may be detected if anything goes wrong with that particular function. Here, a design FMEA is harder to control. Weak sections on a casting may result if the thickness is not controlled. Identifying the potential failure modes/causes/effects is necessary, but how can the design detect it? The simplest answer is that it cannot. The production process will allow or prevent this situation from arising. Again, this goes to highlight the interface that is necessary for the whole product. Design must know production’s limitations, and production the importance of a design feature, thereby allowing for a systems approach.

Process detection will incorporate many detection features into the production line. These may be through inspections or dedicated control features on a machine. The cost may become prohibitively expensive, but what other ways are there?

Figure 4.2 summarises the classifications of detection and the ranking which corresponds to it. This is not a linear scale, but a simple approach to rank each set relative to another.

Very high - Will almost certainly detect the existence of a defect.

A domestic fridge will be assembled on a semi-automatic production line. One process will be to fit the door assembly to the frame. We could review all the potential failure modes, and the list would be similar to that for the bracket assembly. One potential failure will be missing/omitted. What is the probability of that item completing its assembly process, packaged, shipped and installed, where nobody notices the door is missing? It must be as close to zero as you can get.

This may seem extreme in principle, and it is meant to be. For a detection ranking of 1 it must be almost impossible for that process or design to be delivered to a customer in a faulty condition. Take care not to over use this classification; if the detection value is good/excellent it is best to rank it 2.

High - Have a good chance of detecting the existence of a defect.

Most process FMEAs use this category; a high chance of detecting a failure means exactly that. A 100% inspection stage could not realistically have more than a high level of detection; even inspection gauges have their own tolerances which may pass a reject or reject a pass. The latter case does add some assistance to the procedure, but it still costs money to a company that scraps good parts.

Designs are subjected to various loading conditions. Where the design is sensitive to small changes it is important to detect its limiting features. With 100% inspection we know it can only be high. Therefore, if it is that critical it would be best to design the sensitivity out.

Moderate - May detect the existence of a defect.

The distinction between high and moderate is a major one. Where the former has some recognised system for detection, the latter one is only a last attempt to prevent an error. ‘May detect’ is at best a 50-50 chance: it is no more than a lucky day if the errors) is/are found.
Where design and process do not work together, this is the usual detection for a design, because the process team are not aware of what is important. Knowing that these sections are critical, actions can be employed to overcome this. Otherwise, no extra action is likely.

**Low** - Have a poor chance of detecting the existence of a reject.

Where moderate meant that 50% of rejects would reach the customer, low means at least 80% will not be detected. Usually, this type of detection is only an add-on, or some other facet that can be combined to detect errors. In such cases, it is best not to try modifications as they may cause a serious concern to be overlooked. Remember, the aim is to determine the worst parts of the design or process.

**Very low** - Probably will not detect the existence of a defect.

It can be argued that this approach is not a detection system. Anything that will miss more than 90% of the errors is not conclusive, but ineffective.

Detection systems range from near perfect to something approaching useless. Each can be expensive, directly or indirectly. Nevertheless, in terms of a satisfied customer, very high detection is an effective method of controlling a design or process.

**Occurrence**

The final number to establish is the occurrence, regardless of how critical it is, i.e. how often does it happen? This may be the hardest scenario to imagine, but there are very good guidelines to establish the correct ranking number.

Unfortunately, this method is not so directly linked to design, and here the experience and common sense of the team play a crucial role. Before explaining how these numbers are ranked, it is necessary to highlight the statistical concepts involved.

**Statistics**

To the general public, this word means confusion and lies. Examples exist where statistics have been distorted to suit individual cases. These situations may have proved many points, but the strength of statistics is where their repeatability is very high. Knowing, or being able to calculate with confidence what is likely to occur, is a powerful tool. Statistics, or the use of data, enable many problems to be identified at an early stage. It is not necessary to be an expert in mathematics to use this approach; indeed, many on an FMEA team are unlikely to have a technical background.

For statistics to be used in a simple form it is paramount that the distribution of data is normal, i.e. it is bell-shaped in appearance, see figure 4.3. This distribution (spread) is representative of many things that occur naturally (IQ levels, height of the population etc). There are other distributions but these cases are ignored and the responsible engineer should aim to have the steady state situation normally distributed.
The real advantage of this distribution is that the areas (percentages) under the curve can be readily defined by the value (standard deviation). See figure 4.4. Because it is symmetrical in shape, the percentage distribution will be equal, therefore, at the centre, half will be below and half above.

Without covering all the aspects of the distribution, there are some that are paramount:

Average - The value that is most likely to occur. This can be defined mathematically as:

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n}$$
Standard - The relationship of the data to the limits and the deviation distribution of percentages.

\[ \sigma = SD = \sqrt{\frac{\sum (X - \bar{X})^2}{n - 1}} \]

The standard deviation, SD, must be used in relationship to the average. Once these two items are known, there are numerous values that can be obtained.

Many statisticians argue about the end limits of the distribution. In many cases, it is not clear exactly where the ends fall. Engineering is not a pure science, but an applied one. A breakdown of the percentage distribution is shown in figure 4.4. Engineering assumes that all realistic values will fall between the limits of:

Average - 3 SD to Average + 3 SD

Therefore, the total spread is six standard deviations. In fact, this is not that true since only 99.73% of data will lie between +/- 3 S.D. This is where pure statistics and engineering statistics part. Even if the spread were increased to +/- 4 SD the total percentage would be less than 100%. For ease of use the value of three is maintained; it is close enough.

Although calculating this value was time consuming in years gone by, electronic calculators can perform this task in a very short time. Knowing these values, we can relate them to the design or process.

First, the tolerances specified must be related to the capability of the equipment being used. If the equipment cannot reliably meet these, rejects will be produced. If it leaves them with an enormous spare capacity, the equipment is over sensitive, and not an economical match. Between these two extremes there is a situation that will suit all processes.

Capability values are defined by Cpk values. Three distinct values are stated to divide the various levels of acceptance and are shown in figure 4.5.
Figure 4.5 Cpk values

($LSL = \text{Lower Specification Limit and } USL = \text{Upper Specification Limit}$)

$LSL$ \hspace{5em} $USL$

$Cpk > 1.33$

$LSL$ \hspace{5em} $USL$

$Cpk = 1$

$LSL$ \hspace{5em} $USL$

$Cpk < 1$
All three values show the distribution to the limits that are acceptable or specified. The simplest value to discuss is when the $C_{pk} = 1$. The limits of the distribution match those of the specification. It may seem like an ideal situation, but what do the limits correspond to? The $+/- 3 \, \text{SD}$ only allow for $99.73\%$. Therefore $0.27\%$ will fall outside the limits (rejects), $0.135$ below and $0.135$ above. If a thousand items were produced, between two to three rejects would be produced. Only you can determine if this is satisfactory for your company or whether it can be improved on.

Where a $C_{pk}$ of less than 1 is achieved, the amount of rejects being produced will increase proportionally to the number. Typically, where a $C_{pk}$ value of less than 1 occurs, 100% inspection is added to detect the extra rejects. This does not solve the problem, but assists until improvements can be implemented.

Higher values of $C_{pk}$s are best, with 1.33 being an acceptable value in most companies. Long term, L67 is seen as the goal. Here, the likelihood of a reject diminishes. However, there must be an economic cut-off point. Most quality gurus strive for neverending improvements, but at what cost? If a $C_{pk}$ of 2 relates to 1 reject per million, will a $C_{pk}$ of 3 produce a better quality output? In financial terms, it would be better to concentrate on weak areas, not further improve the good ones. This, as with everything, depends on the company and the product. Most cases follow the norm.

Where does this leave the FMEA team? They have a guideline that allows for accurate rankings of occurrences for all situations. $C_{pk}$s are quoted in manufacturing capabilities and form part of the basic engineers’ description. They are not so readily used by designers and hence, differences arise.

**Design Occurrence**

The classification of occurrence has to be measurable to the designer. In reliability engineering, a design is considered over a finite period of time: this is its useful life. All designs must be related to this; used long enough, all items can fail by wear, fatigue, corrosion etc. It is when they occur early that problems arise. Table 4.1 relates occurrence to values. The basis of the statistics are used to enable realistic ranking of categories.
Using the descriptions and possible failure rates, an overall ranking can be obtained for a design FMEA. As a reference point, consider the Cpk=1. On the above scale this would roughly lie between S and 6 (slightly closer to S). It may be tempting in this case to use fractions of numbers, i.e. 5.2, but this is strongly argued against by the authors. It will eventually lead to confusion and problems.

Finally, ranking an occurrence as 1 covers all situations above 1 in 500,000. If you reach this level, even military specifications will be satisfied in all but a few cases. The importance is now to focus these to the Process FMEA.

**Process Occurrence**

Capability studies are paramount in modern manufacturing facilities. Numerous standards specify them, and it is not surprising that they are used to clearly define the process occurrence values. Figure 4.6 shows the general classification adopted for this:

<table>
<thead>
<tr>
<th>Probability of Failure</th>
<th>Rank</th>
<th>Design Life Possible Failure Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remote: failures are considered very unlikely</td>
<td>1</td>
<td>&lt; 500,000</td>
</tr>
<tr>
<td>Low: few failures</td>
<td>2</td>
<td>1 in 25,000</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1 in 5,000</td>
</tr>
<tr>
<td>Moderate: occasionally failures occur</td>
<td>4</td>
<td>1 in 1000</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1 in 500</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1 in 100</td>
</tr>
<tr>
<td>High: many repeated failures</td>
<td>7</td>
<td>1 in 50</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1 in 25</td>
</tr>
<tr>
<td>Very high: failures are almost inevitable</td>
<td>9</td>
<td>1 in 10</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1 in 2</td>
</tr>
</tbody>
</table>
## OCCURRENCE

<table>
<thead>
<tr>
<th>Probability of Failure</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>REMOTE – Unlikely, no failure ever associated with identical process (Cpk &gt;= 1.67)</td>
<td>1</td>
</tr>
<tr>
<td>LOW – Process in control. Only isolated failures associated with similar process (Cpk &gt;= 1.3)</td>
<td>2</td>
</tr>
<tr>
<td>MODERATE – Process only just in control. Some failures with similar processes (Cpk &gt;= 1)</td>
<td>3</td>
</tr>
<tr>
<td>HIGH – Similar processes experience frequent failures (Cpk &lt;1)</td>
<td>5, 6</td>
</tr>
<tr>
<td>VERY HIGH – Failure is almost inevitable</td>
<td>9, 10</td>
</tr>
</tbody>
</table>
Before each of the ranking values are discussed, it is worth stating why a Cpk of 1 is not acceptable. In theory, there are many situations where a reject rate of 2/3 per thousand is good. However, does this Cpk value change over time? Yes, it does. If a shaft is being turned at a specified diameter, and the Cpk is 1, what happens when the cutting tool is replaced? If it is not set correctly the corresponding Cpk could be anything. Likewise, as the tool wears and the output dimensions change, these will reduce the Cpk value. Hence, Cpk's are subjected to real industrial situations. Shifts in the process average are typical. Having a Cpk of 1.33 or 1.67 introduces a certain factor of safety, which allows small hiccups to have no direct effect on the reject rate. It also minimises the need for constant inspection, because the probability of a reject is small.

Remote - Unlikely, no failure ever associated with identical process (Cpk > 1.67).

Referencing a process to other similar ones is useful where it may be hard to clarify a particular point. If it has been achieved at that level before, there is no reason why it cannot continue as such. A Cpk of 1.67 is using the limits as +/- 5 SD; rejects are fewer than 1 in 500,000. With large production volumes (above 1,000,000/year), the phrase 'no failure ever' must be taken as a guide. The probability that a reject will be produced becomes a reality where the sample size is sufficiently large.

Low - Process in control. Only isolated failures associated with similar processes (Cpk ≥ 1.33).

Isolated failures can be from 1 in 25,000 to 1 in 5,000; this is of a magnitude less than the 1 in 500,000. There is a clear distinction between these two categories and it could be hard to separate them without the Cpk values.

Moderate - Process only just in control. Some failures with similar processes (Cpk ≥ 1).

A Cpk value is the lesser of:

\[
\text{Upper specification limit} - \text{Average} \quad \frac{3 \text{ SD}}{}
\]

or

\[
\text{Average} - \text{lower specification limit} \quad \frac{3 \text{ SD}}{}
\]

A Cpk of 1 does not necessarily mean both of the limits equal the +/- 3 SD. Only one may do so. A process can be represented as in figure 4.7:
The shift of the mean in one direction will reduce the total number of rejects being produced, while a shift in the other direction will increase them. This can be a problem, especially if it is not clear whether the distribution is central. Assuming it is not can be detrimental: all shifts in averages are a potential problem. Even when fewer rejects are produced, there is no control over the process and this is incorrect:

High - Similar processes experience frequent failures (Cpk < 1)

When the capability falls to below a value of 1, the amount of rejects becomes the predominant factor. No control exists and assuming the next item produced is going to be correct is hopeful at the best of times. Many large companies insist that all items produced when the Cpk< 1 are 100% inspected. This does not solve the problem, but if both companies are fixed in a just-in-time philosophy the customer cannot afford to wait for changes. Moreover, deliveries with high reject rates are problematic. Insisting on 100% inspection will reduce (not eliminate) the high defect percentage, thereby allowing the customers' production to continue. This is at the on-cost to the supplier.

Ranking values of 8, 7 and 8 can describe the situation adequately, any latitude being at the discretion of the FMEA team. A value of 8 means 1 in 25 is expected to be a reject (4%). Values of less than this are best described by the following.

Very high - Failure is almost inevitable.

Indeed, where major problems arise, 100% reject rate can easily be obtained, although not condoned. Any occurrence value that is ranked at 9 or 10 is drastically wrong; regardless of FMEAs, this would be identified as a major problem requiring immediate action. When it has not happened, and is only likely to, how else could you foresee such a concern?
**Risk Priority Numbers (RPN)**

This is the last column on the draft to be filled in, and the easiest one. To calculate it, the values of the seventy, occurrence and detection are multiplied together. If the ranked values were further divided (5.5, 6.7) this would produce numbers that have several decimal places. Accuracy of this magnitude cannot be traced back to the original concept; it does not mirror the situation. Whole numbers are typically easier for everyone to handle and appreciate.

All ranked values have a potential range of 1 to 10. Therefore, the extremes of the values will be:

\[
\begin{align*}
1 \times 1 \times 1 &= 1 \\
10 \times 10 \times 10 &= 1000
\end{align*}
\]

Note: not every number between these is obtainable, and it is not a representative scale. These RPN numbers do not dictate how effective or ineffective the design or process is. All they can suggest is how each compares to another for supplying a defect free item to a customer: Comparisons between designs and processes are not recommended; it would only confuse the situation.

The next step is to review the critical ones (high RPNs) and establish which require actions. It may be ideal for all to be actioned with the aim of having all RPNs = 1. This is not feasible for two reasons: resources are limited and not every situation could have a RPN of 1.

Assuming the highest ones should be reviewed first of all, at what cut-off point should the division occur? There are several recommended routes:

- Significant/important/safe (SIS);
- Pareto;
- Occurrence.

**SIS**

The classification of significant, important and safe is a crude but effective procedure. In the philosophy identifying the major problems, this is as good as any. A safe characteristic has a RPN of 1-200. Disregarding any individually high numbers, if it is below 200 why take action if there are other more serious ones? Important characteristics are 201-400. These are considered slightly more serious than safe, but not as serious as significant characteristics, 401-1000.

All significant characteristics should be actioned, and if there are none then the important ones should be. Eventually, only safe characteristics will be left; here, individual preferences are allowed. It may take many years to obtain only safe characteristics, if at all. It is likely there will always be ones in the other two categories.

**Pareto**

This is a conventional and accepted tool for problem solving. In the late 19th century, E.Pareto, an Italian academic, discovered a ratio between the wealth of people and
distribution of them. He concluded that 80% of the wealth was owned by 20% of the population. Likewise, 20% of the wealth was created by 80% of the population. Juran concluded that there were:

The vital few and the trivial many.

This distribution follows many situations, not least engineering. In many instances, 80% of the problems arise from 20% of the design. This is the basis for Pareto analysis of the RPN. Why concentrate your effort on one part if the result will reduce a small problem to a smaller one (even if the problem was halved)? If a large problem can be reduced by a half, this will have a major impact.

Concentrating the efforts on the larger problem not only allows for easier improvement, but also removes the worst problems. A process that has a high severity and occurrence may not be ideal; however, if the detection is very high, would the problem ever reach a customer?

All the RPNs should be ranked, and the top 20% reviewed for possible action.

**Occurrence**

This is simple in principle, and perhaps the least effective of the three methods. Reducing the occurrence can be effective, but it does not always remove the real problem. The only real solution may be a re-design.

Whatever approach is used, and it does not have to be one of the three listed, several items will be addressed for action. This is the last stage for the first draft, data has been generated and can be used accordingly.
CHAPTER 5
USING THE FMEA FORM

Completing the draft FMEA, both sections and columns, finishes the procedure for that sheet. All this data should be transferred onto the main sheet—see final form. This is not drastically different as the copies in the appendix have the same format as the draft, plus associated headings and continuing sections. Typing the FMEA is not paramount, but it may overcome bad writing and assist in the data presentation. It also adds to the professional appearance.

The key action is to focus on the parts of the design or process that are potentially the largest problems. When these have been identified a maximum effort on these can produce the most important results. When the FMEA has identified many features that produce high RPNs, it is unwise to attempt tackling too many. It is best to finish several that are a concern rather than never finish all of them.

As part of a quality system, FMEAs need to be integrated into the actions that are occurring elsewhere. No FMEA team should assume that all other quality actions are irrelevant; they are just as important. If the company's philosophy is to use automatic inspection on problematic production areas, this must be realised in the actions recommended by the team. Likewise, customer returns may indicate areas where design should focus their attentions, regardless of the FMEA process. Do not assume that outsiders cannot identify a potential problem just because they have not formed part of the team. They may be wrong, but without fully investigating their statement, who could know?

When an FMEA is large (numerous pages) it is not in an ideal format to be presented to management. Even if they had the time to read it, the information may not appear clear. Where other people have to work with it, the practical implications of distributing numerous copies of many pages is unrealistic.

A Control Plan is an ideal way to present the most important data and the actions others are expected to follow. Condensing the principal items onto a couple of pages assists in communication. There are no firm recommendations for the format, but it usually includes the following:

- **Title page.** The actual design or process involved. People responsible and an issue column to control new releases and assist in its control.

- **Individual concerns.** Potential areas of major concern, and the actions to be planned or taken.

- **Signature page.** Every team member 'must' sign to show both the importance and commitment of the whole team.

This last point is for FMEA teams that are geographically removed from the factory (multinationals). It shows their department's commitment.
Without a control plan, non-team members will find it hard to keep abreast of the team's aims. Departments and individuals may have to action the problems. When they struggle to follow the recommendations, time may be wasted in individual communications to team members, or even worse, delays can occur which could postpone the production date.

**New Column Headings**

*Recommended actions* is a summary of what is planned, or where improvements are sought. These can be diverse in description, and may even be subject to a brainstorming session. Most problems can be solved when there is no limit on funds; but this is not an effective answer where quality is concerned. Finding the ideal solution may be impossible and panacea answers are seldom found first time. Even if the proposed action may seem weak, it is better to attempt than to ignore.

*Responsibility and completion date:* FMEAs are completed by teams, but individuals have to action the work. By identifying who is responsible will place ownership on that individual. Completion dates are set to minimise the action being lost in the future. Everyone will be aware of what is planned and the end date.

*Actions taken:* it is unlikely that this column can be filled in at the first review of the major problems. If money is to be spent, this requires the approval of senior management. Alternatively, the aim could be to discover which of two ways is the most suited; then orders can be raised.

The last four columns (*severity, occurrence detection and RPN*) are used to evaluate the new approach. Even if a firm decision on exactly what to do is not known, estimates can be placed into these. Subsequent data can confirm or modify this accordingly. When the item is closed - finished - this will then replace the previous information and supersede the initial RPN value. However, this will then distort the balance of the major problems - if successful.

FMEAs are live documents; they will constantly be reviewed for the whole period that the design/process is in use. It is expected that revisions will imbalance the major problems, and this causes no direct problems. What it does show is that continuous improvements are occurring, no matter how small. Used collectively, over a long period, all these small parts will reduce the major problems, thereby offering a better product to the customer. This fulfils one of the requirements that our quality definition stated at the beginning.

Never-ending improvements should be a goal of any organisation; most quality gurus agree on this point. What FMEA offers is a system to tackle this and show through documentary forms that it is occurring. The improvements may be small, but this is a step in the right direction.

What other benefits? FMEAs work and have been re-used because they allow for the requirements of an organisation or product, and the needs of individuals. Never-ending improvements are the requirements of the former, but the latter needs assistance for all this effort.

If we refer to figure 3.3, the tapped hole, we can evaluate one such situation. A potential failure mode that was ignored is a broken drill. On its own this is not a major problem, and can be easily repaired. Nevertheless, a broken drill will not produce a hole to the correct depth, and even worse, if the broken bits are left in the hole, the tap will break. What will
this mean to a customer? First, the hole cannot be used, which will limit its use. Secondly, if it is not detected quickly, many will be produced (a high probability of the customer receiving it). Finally, the product may be weaker (less reliable) than it should.

This assumes the failure to the drill is not rated. A manually operated system will almost certainly detect this (detection value of 1 or 2). This is a good system. An automatic system may detect this if the hole is probed, but this adds complexity and cost to the equipment, which is undesirable. A cheaper way would be to add tool load monitoring to the drill spindle, thereby detecting immediately. However, these cost a large amount of money and use on every spindle would be prohibitively expensive. If the feature was problematic (geometrical, clamping, design or accuracy) it may be worthwhile for an individual application. In this case, the FMEA can be supporting evidence to the management, especially if it forms part of the control plan. Who could argue against it?

**Frequency of meetings:** post draft stages will require meetings to support the on-going actions. These can vary according to the level of work that is necessary. Once the design/process is in production, the frequency can be reduced to a less strenuous rate, but anything less than twice yearly is questionable. Real improvement requires constant effort, otherwise the momentum will be lost and it will become a paper exercise to support the company's quality philosophy. The need to update and re-issue the control plan will become a driving force. The long-term objective now is to reduce all the high numbers into values below 400 (at minimum). Experience gained, coupled with successes, may be the only encouragement to support the effort if it is not used as a part of a larger quality system. Many useful techniques and plans fail because of the lack of management commitment. No FMEA team can realistically alter this scenario, but if the driving force to start the team was such a commitment, the result may be far in excess of those possibly expected.

**Future Trends**

FMEAs are time consuming, and will probably remain so; meetings take a long time. Perhaps one of the biggest concerns is the time involved for constantly updating the document. There are many useful software packages that can assist, and remove the need for a typist. These can be cheap and easy to use on most office PCs. Q-PAK, by Oscar Quality Systems in Essex, is a typical example; it combines FMEA and quality plans with automatic updating. There are many more, but this is an extra investment that a company will have to decide upon.

In the past, where the driving force of quality was BS 5750, this required a minimum standard to be maintained. Total Quality Management (TQM) which is likely to be the driving force of the future stipulates the need for never-ending improvements. FMEAs are one such way. It offers a realistic approach for both technical and non-technical people to work as a team. On its own, it can have a limiting effect; combined with a quality system it forms a power tool, if companies are to be expected to show neverending improvements, this is perhaps the simplest and easiest way to do so.

**Summary**

FMEAs can be a powerful tool for any organisation. The various levels of success enable sensible decisions to be made about complex problems. Whether analysing piston ring breakage in assembly or the most logical way of handling a component, FMEAs can give a
systematic approach. They will not guarantee the removal of all problems, but they can ensure that if a feasible solution exists, it can be found.

**Stages**