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# A Decision Support Methodology for Improving Equipment Reliability

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To the Graduate Council:

I am submitting herewith a thesis written by Caiqiao Xu entitled "A Decision Support Methodology for Improving Equipment Reliability." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

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***A Decision Support Methodology for Improving Equipment Reliability***

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# DEDICATION

I would like to dedicate this research to my English teacher, Guorong Shan, who worked as a research fellow in Central South University of Forestry and Technology, China.

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There are other individuals, but to list them all would require many pages. If you are reading this, then you know who you are.

## Abstract

**Purpose -** Aggressive Maintenance Strategy can improve the overall operation and reliability through redesigning or modifying equipment. A decision support tool is proposed that could aid in discovering the many options and in selecting the best approach for redesigning or for modifying the equipment. The new tool has three sections that correspond to the equipment life cycle:

1. Keeping the equipment in perfect running condition.
2. Identifying defects as soon as the equipment starts to degrade.
3. Minimizing losses after the equipment has ceased functioning.

**Design/Methodology –** The first section seeks to keep the equipment running in perfect condition. There are three approaches:

1. Eliminate the root cause.
2. Prevent outside causes from affecting the equipment.
3. Increase the equipment's resistance against outside influences.

The second section seeks to identify the defect as soon as possible. There are three approaches:

1. Modify the equipment so that defects may be detected more easily.
2. Improve the detecting instruments such as enhancing the sensitivity or adding machine intelligence.
3. Improve the work environment so that equipment operators may more easily notice any changes in the machinery.

The third section seeks to minimize any losses. The three approaches are:

1. Modify the equipment and relevant tools to enable the equipment's lost function to be recovered sooner.
2. Add a resilient system.
3. Add buffer inventory.

**Findings –** After a very extensive literature review, only two tools appear to exist for helping practitioners to make proper decisions concerning their equipment. Edward de Bono's "Six Thinking Hats" and Genrich S. Altshuller's "Theory of Inventive Problem-Solving" methodology are used extensively, but these are not very practical and lack a systematic scheme.

**Research Limitations/Implications –** Any implementation assumes that root cause identification has been made by another tool such as by the 5 Whys, Cause and Effect Diagram, Fault tree analysis, or another tool.

**Originality/Value-** This tool could be implemented in any equipment reliability management program. It guides the practitioner for redesigning and for modifying the equipment in order to achieve high equipment reliability and to reduce the equipment's usage costs.

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## ABRREVIATIONS AND SYMBOLS

| | |
|---|---|
| 8D | Eight Disciplines |
| AMS | aggressive maintenance strategy |
| BPFI | Ball-pass Frequency of the Inner-race |
| BPFO | Ball-pass Outer-race Frequency |
| BSF | Ball-spin frequency |
| CDM | Condition-Directed Maintenance |
| CMS | Condition Monitoring System |
| FRB | Failure Review Board |
| FMEA | Failure Mode and Effect Analysis |
| FRACAS | Failure Reporting, Analysis, and Corrective Action System |
| FTA | Fault Tree Analysis |
| FTF | Fundamental Train Frequency |
| MTBF | Mean Time Between Failures |
| MTTF | Mean Time to Failures |
| MTTR | Mean Time to Repair or Mean Time to Recovery |
| PdM | Predictive Maintenance |
| PM | Preventive Maintenance |
| PRA | Probabilistic Risk Assessment |
| RCA | Root Cause Analysis |
| RCM | Reliability Centered Maintenance |
| ROI | Return on Investments |
| RPN | Risk Priority Number |

| | |
|---|---|
| TDM | Time-Directed Maintenance |
| TIPS | Theory of Inventive Problem Solving (English rendering) |
| TPM | Total Productive Maintenance |
| TQM | Total Quality Management |
| TRIZ | Theory of Inventive Problem Solving (Russian rendering) |

# Chapter 1: Introduction and General Information

## 1.1 Background

Product manufacturers are constantly seeking ways to increase output, to improve product quality, and to reduce costs. The motivation is for seeking a competitive edge.

One very successful way is the assembly line, which uses sequential steps to mass produce a product. This was pioneered by Henry Ford in 1907 in his Ford Motor Company's Michigan plant. Not much has changed in this approach except robots are replacing human hands.

Despite the efficiencies, such assembly lines have one weakness. If one machine or component completely fails, generally all prior machines must be stopped immediately. The "downstream" machines could continue operating until the last piece is processed, then these would become idle. This situation creates six problems (Ohno, 1988):

- Decreased machine utilization
- Increased overhead
- Decreased labor productivity
- Increased queue time
- Additional set up time
- Might increase the scrap rate

These six problems must be "funded" by adding an additional markup to the final product cost, which the customer does not wish to pay. Thus any approach that

decreases failures, that increases uptime, and that makes equipment resilient against failures would give any manufacturer a huge competitive edge.

The key research question is, “How does one decrease failures?” In this research, a tool was developed that would guide the practitioner on how to redesign and to modify the new and the existing equipment in order to increase the reliability of the equipment.

### 1.2 Problem Statement

Manufacturers are using approaches such as aggressive maintenance strategy (AMS) to attempt to eliminate the root causes of equipment failures and to improve its reliability. However, in order to implement any AMS, practitioners must use different tools to identify process errors before these occur (such as Failure Mode and Effect Analysis - FMEA), to detect the root causes of failures (such as Fault Tree Analysis, 5Whys, or Cause-and-Effect Diagrams), and to generate optimizing solutions (such as Six Thinking Hats or “Theory of Inventive Problem Solving” (TRIZ) methodology (Andersen & Fagehaug, 2006). Yet, there is not a systematic approach that addresses how to redesign or to modify the equipment as it undergoes its three life cycle phases. For example, Six Thinking Hats and TRIZ are not systematic tools since these cannot explicitly point out how many solutions practitioners could choose to solve the equipment’s problems.

Could these tools be modified to provide the missing information? Or could a new tool be developed?

### 1.3 General Approach

This research was undertaken for finding the best solution. It became clear that the solution would need to deal with the three equipment life cycle stages. (See Figure 1.) When the equipment is brand new, it has very few problems. As different components undergo stress and aging, parts will wear down and the early signs of total failure will appear. In the last stage, abrasion has reached the point that metal integrity has weakened and it is matter of time when the equipment completely stops running. Viewing the equipment in this fashion resulted in the need to have three approaches. The first stage approach would be to sustain the perfect status. The second state approach would attempt to detect the degradation as soon as possible. The third stage approach would be to minimize the losses caused by complete shutdown.

We considered different approaches. We found for the first stage, the best approaches would involve addressing the root cause of failure, which is aging. Efforts to eliminate the root cause, to decrease the impact of root cause on the equipment, and to increase the equipment's' resistance would improve the equipment's reliability

We found for the second stage that the best approaches would involve improving the equipment's ability to detect a failing component sooner. This might require enhancing the detecting tools and instruments' sensitivity for detecting problems. Another option is to add machine intelligence for noticing changes in the machine's operations. Another option is to modify the machine or add machine intelligence to allow for easy detection of small changes in the machine's operations.

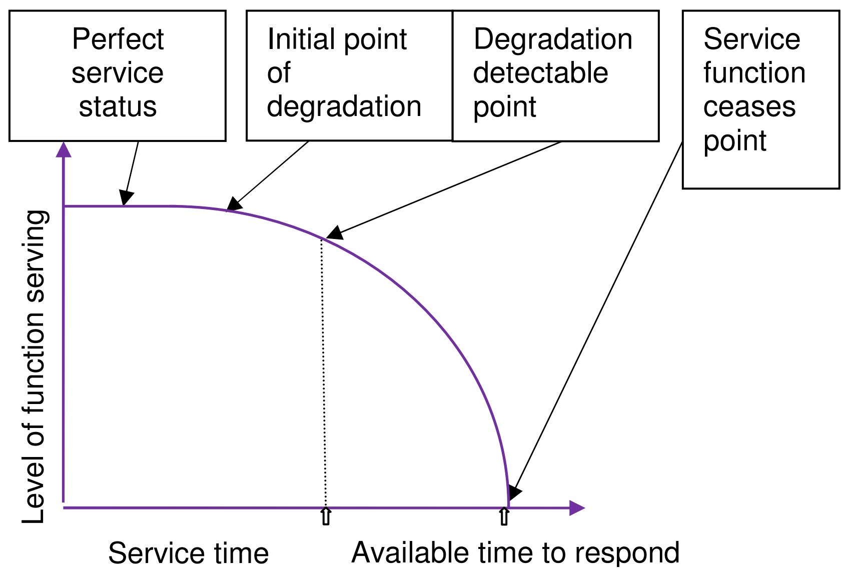


Figure 1. Three Equipment Life Stages[1]

We found for the third stage that the best approaches involve using a nearby spare. This could be buffer inventory or a redundant machine that could immediately be pressed into service. Or the equipment could be modified so that failed components could be quickly swapped out for a good one and thus reduce the down time. For these approaches, special tools might be needed that would enable a person to quickly accomplish the necessary tasks.

[1] Figure source: (Fischer, Besnard, & Bertling, 2012)

## 1.4 Thesis Road Map

This thesis contains five chapters plus extra materials in the appendices. Chapter 1 is the introduction. Chapter 2 is a comprehensive review of currently employed tools plus an in-depth coverage of maintenance issues. Chapter 3 is a detailed report on our research methodology plus how the new tool was developed. Chapter 4 is a detailed case study of the deep draw machine. Chapter 5 summarizes the major conclusions of this thesis and indicates where future work needs to be done.

# Chapter 2: Literature Review

## 2.1 Introduction

This chapter provides a brief description of contemporary root cause analysis tools and of popular problem solving management tools. The strengths and weaknesses are discussed. In addition, a literature review was conducted for what practitioners and researchers perceive as future trends in the field of equipment reliability. The summary section explains why a new tool such as the proposed tool is needed.

## 2.2 Tools for Root Cause Analysis in Equipment Reliability

### 2.2.1 Tools classification.

The literature review revealed that tools that are labeled as eliminating root cause tools or as identifying root cause tools are in fact only capable of identifying problems. Andersen and Fagerhaug (2006) wrote in their book, *Root Cause Analysis: Simplified Tools and Techniques*, that only Edward de Bono's "Six Thinking Hats" and Genrich S. Altshuller's "Theory of Inventive Problem-Solving" (TRIZ or TIPS) methodology are tools for root cause elimination whereas the other tools such as Nominal Group Technique, 5 WHYS, Ishikawa diagrams (also known as fishbone diagrams and as Cause-and-Effect diagrams), Fault Tree Analysis (FTA), Failure Modes and Effects Analysis (FEMA) are classified as root cause identification.

#### *2.2.1.1 Six Thinking Hats.*

Edward de Bono (De Bono, 1985) wrote in his book, *Six Thinking Hats*, how the brain could be trained "to maximize its sensitivity in different directions at different times." This technique uses six colorful metaphorical hats for improving group discussions. Each hat represents a way of thinking or of acting. (See Table 1 for the definitions.) Each participant "wears" two or more hats in order to view the other sides of an issue. This method encourages the human brain to view things in several distinct ways. A group leader could scheme an organized discussion to motivate the members to think about particular issues with new aspects. The resulting interconnected ideas are combined so as to encourage even more effective thinking among the participants.

Table 1. Hat Colors and Functions[2]

| Hat Color | Function |
|---|---|
| White hat<br>Neutral | The person is focused on the available data and information. The person determines what additional data and information is needed. |
| Red hat<br>Emotional | The person is using emotions, affection, and hunches. The person is concerned about all participants' reactions and feelings to the situation. |
| Black hat<br>Somber | The person is thinking about the topic in terms of difficulties and of challenges. The person considers whether something is feasible. |
| Yellow hat<br>Sunny | The person is concerned with the positive aspects such as benefits. The person would look for the positive values and ignore the negative ones. |
| Green hat<br>Growth | The person is interested in exploring the undiscovered aspects. The person would look for new ideas and suggest these to the group. |
| Blue hat<br>Cool | The person is concentrating on the thought processes such as managing the process of thinking, summarizing the obtained decisions, listing the next work group step. The person would be able to add structure to the group's efforts. |

[2] Table source: De Bono, 1985

#### ***2.2.1.2 TRIZ.***

TRIZ (Terninko, Zusman, & Zlotin, 1998) uses a knowledge base, a model-based technology, tool sets, and a practical methodology. TRIZ can be applied to system analysis and to problem analysis. Its strength is the ability to handle challenging problems and to analyze the system's evolution. It is used widely in the industrial field for improving products, systems, service, safety, and cost structure. TRIZ is covered in greater detail in Appendix 1.

## 2.3 Tools for Reliability Management

### 2.3.1 Failure Reporting, Analysis, and Corrective Action System.

Failure Reporting, Analysis, and Corrective Action System (FRACAS) (Nicholls, 1999) is a closed-loop feedback method whereby the user and the equipment supplier work together to increase the reliability of the equipment by continually correcting the design. Their responsibilities include collecting, recording, and analyzing failures of both hardware and software data sets. The user submits the relevant data about all problems to the supplier. The supplier convenes a Failure Review Board (FRB) for analyzing the failures and to consider all relevant factors such as: time, money, and engineering personnel. The FRB's outcome would be a list of corrective actions which would be implemented. The user would report the results of any problems resulting from the new changes.

### 2.3.2 Eight Disciplines Problem Solving.

Eight Disciplines (8D) Problem Solving (Bhote, 2002) is a method that uses a step-by-step approach for solving problems. This includes identifying, correcting, and eliminating recurring problems. The 8D approach has been adopted widely in the manufacturing world, but it is a management process. It needs other tools in order to complete the tasks in each step. See Table 2 for more details.

### 2.3.3 The Principles of Gemba Kaizen.

Gemba Kaizen is a Japanese management philosophy (Tarlow, 2002). It states that better productivity can be achieved through continuous process improvement in manufacturing, in engineering, and in business management. It is used widely in manufacturing and other industries. See Table 3 for the five principles of Gemba Kaizen. The strength of these principles is that a manager can track the progress of any deviations.

Table 2. Eight Disciplines in Problem Solving[3]

| Discipline Number | Definition |
|---|---|
| D1. | Use Team Approach. |
| D2. | Describe the Problem. |
| D3. | Implement and Verify Short-Term Corrective Actions. |
| D4. | Define and Verify Root Causes. |
| D5. | Verify Corrective Actions. |
| D6. | Implement Permanent Corrective Actions. |
| D7. | Prevent Recurrence. |
| D8. | Congratulate Your Team. |

[3] Table resource: Bhote, 2002

Table 3. Gemba Kaizen Principles[4]

| Principle Number | Principle Definition |
|---|---|
| 1 | When a problem/abnormality/opportunity occurs, go to gemba (the workplace) first. |
| 2 | Check with gembutsu like machines, equipment, tools, jigs, fixtures or rejects etc. |
| 3 | Take immediate or even temporary counter-measures on the spot. |
| 4 | Find out the root cause and remove the root cause of the abnormality. |
| 5 | Implement the solution and standardize to prevent further trouble/recurrence. |

## 2.4 Development Trends of Maintenance

### 2.4.1 Equipment failure and maintenance.

For the purpose of this thesis, failure is defined to be a condition when the equipment does not meet an intended objective due to worn components or due to other reasons. Geraerds (1985) and his contemporaries defined maintenance as an activity whereby the equipment can be returned to full service or at least to an operational state. Along the way, the definition of maintenance has evolved to be an activity that seeks to optimize all aspects of business effectiveness, of safety, of environmental integrity, of energy efficiency, of product quality, and of customer service (Moubray, Reliability-centered maintenance (2nd ed.), 1997).

### 2.4.2. Significance of maintenance strategies.

When maintenance is properly performed, the result is that the system is working perfectly, is highly reliable, is readily available, and is providing good safety

[4] Table resource: Tarlow, 2002

assurance—these benefits are achieved at the lowest possible cost (Pham & Wang, 1996). The economical bottom line is improved since the extended equipment life means longer period before the need to replace it and the improved equipment availability mean longer times between failures (also known as means time between failures or MTBF). Conversely, equipment that is poorly maintained may lead to more equipment failures, to lower equipment utilization, to greater product quality rejection rates, to questionable quality, and to delayed production schedules. Finally, poor maintenance may cause higher operational costs due to the need to frequently replace equipment components (Swanson, 2001).

##### *2.4.2.1 Development of maintenance strategies.*

The traditional maintenance strategy was reactive (Swanson, 2001). When a machine completely failed, then on-site repairs were performed. When market competition became more intensive, manufacturers began to adopt a proactive maintenance strategy. But this would require the maintenance person to master very sophisticated skills and to predict when preventive maintenance activities are needed. More recently, the AMS is beginning to appear in some industries. AMS emphasizes that the overall equipment operation must be improved to ensure increased equipment availability and to reduce product cost through improved equipment design (Teresko, 1992). A detailed description of each of the maintenance strategies is given below.

*2.4.2.1.1 Reactive Maintenance strategy.*

This strategy focuses on how to restore the equipment back to the operating condition after it totally shuts down. Prior to this point, no maintenance is undertaken (Swanson, 2001). One advantage is that no production time is lost to preventive maintenance. Another advantage is that the equipment is used to the end of its service life instead of replacing it while it is still functioning. There are several disadvantages with this strategy. The operational cost is higher due to decreased machine utilization, to lost labor productivity, to increase overhead, to increased queue time, to higher scrap rate, and to increased set up times (Sullivan, Pugh, & Melendez, 2010).

*2.4.2.1.2 Preventive Maintenance Strategy.*

Preventive maintenance is maintenance that is performed based on a schedule. Common activities include inspecting, analyzing, and detecting. The goal or the intent is to prevent any equipment degradation. The main objective of this strategy is to extend the equipment's operational life (Sullivan, Pugh, & Melendez, 2010).

The advantage of proactive maintenance strategy is that the equipment life is extended and the maintenance costs are reduced. But its disadvantage is that the production work is impeded due to scheduled maintenance operation (Bateman, 1995).

#### *2.4.2.1.3 Predictive Maintenance.*

The primary objective of predictive maintenance strategy is to eliminate or to prevent causal stressors from developing to cause an undesirable failure. The onset of system degradation (or a lower functional state) must be detected as early as possible. When the performance parameters of the equipment are collected and compared with established engineering limits (the equipment parameters when brand new or a defined example) continuously, the type of action which may be taken to restore the equipment to perfect running condition can be determined (Sullivan, Pugh, & Melendez, 2010).

Both predictive maintenance strategy and preventive maintenance strategy, will remove parts that have not completely failed. Preventive maintenance follows a set schedule whereas predictive maintenance reacts to the actual condition of the machine (Sullivan, Pugh, & Melendez, 2010).

The advantages of a predictive maintenance strategy are increased machine utilization, improved labor productivity, improved environmental safety, enhanced worker morale, decreased overhead, reduced queue time, reduced scrap rate, and reduced set up time. The disadvantages are the need to purchase diagnostic equipment and the need to invest in staff training (Sullivan, Pugh, & Melendez, 2010).

*2.4.2.1.4 AMS.*

AMS is an effort to improve the overall equipment operation through improving the design of new and existing equipment. In this strategy, the AMS team might include individuals from maintenance, from production, and from engineering (Swanson, 2001). They work together to modify or to redesign the equipment in order to have equipment that can run with high reliability at low cost plus provide high production levels (Goto, 1989).

*2.4.2.1.5 Reliability Centered Maintenance.*

Reliability Centered Maintenance (RCM) (Moubray, 2001) is used to determine when maintenance is needed through the use of a decision logic tree. This takes into consideration the degradation mechanism responsible for the failure and a hierarchy of the consequences generated by each failure. See Table 4 for the details.

RCM provides a disciplined methodology to help maintenance departments determine the optimum mix of maintenance activities that would ensure very reliable equipment at the lowest possible operating costs.

Table 4. Hierarchy of Consequences[5]

| Hierarchy Level | Consequences of the Failure |
|---|---|
| 1. Safety consequences: | Will the failure hurt or kill someone? |
| 2. Mission consequences: | Will the failure impact the mission? |
| 3. Risk consequences: | Will the failure risk in other economic loss or damage to machines or system? |
| 4. Condition-Directed Maintenance consequences | Is condition-directed maintenance (CDM) effective for the failure? |
| 5. Time-Directed Maintenance | Is time-directed maintenance (TDM) effective for the failure? |

## 2.5 Development of AMS

Many companies are adopting AMS instead of using a reactive maintenance strategy in order to achieve improvements on several levels (Swanson, 2001).

### 2.5.1 Total Productive Maintenance.

Total Productive Maintenance (TPM) is an aggressive strategy that helps to improve performance with even lower production cost by organizing a work place to prevent all losses and to achieve a perfect management performance. This strategy uses innovations, equipment modifications, and changes in equipment usage in order to realize the maximum utilization of the existing equipment plus obtaining energy efficiencies through the employment of environmentally friendly controls (Prasanna, Akula, & Desai, 2011). The result is higher level performance with low maintenance frequency.

[5] Table resource: Moubray, 2001

### 2.5.2 Integration of maintenance strategies.

A maintenance section may not use AMS as the one single approach. The maintenance section may use of one of the intensely proactive maintenance approaches for some of the machines. But for other machines, the maintenance section may use a reactive maintenance approach. The challenge is to determine which combination will yield the best results (Prasanna, Akula, & Desai, 2011).

Prasanna, Akula, and Desai (2011) provided a method that would help a maintenance section to determine which combination would be best to use. His method selected among six strategies:

- Preventive Maintenance (PM)
- Predictive Maintenance (PdM)
- Reliability Centered Maintenance (RCM)
- Root Cause Analysis (RCA)
- Total Productive Maintenance (TPM)
- Total Quality Management (TQM)

Each maintenance section has unique situations and so the suggested combinations would be different (Prasanna, Akula, & Desai, 2011).

## 2.6 Summary of Literature Review

From the extensive literature review, it is clear that a tool is “missing.” There is no tool that will guide practitioners to systematically solve problems through the equipment’s life cycle (from perfect running status to total failure). Current tools are incomplete.

The root cause tools focus on identification. Eliminating root cause tools do not provide any information about possible options for improving the equipment's reliability. For example, TRIZ and Six Thinking Hats are tools for eliminating root cause, but these only provide practitioners "inspiration" and no further guidance.

Eight Disciplines Problem Solving and the Five Principles of Gemba Kaizen essentially focus on solving problems from the level of macroscopic equipment management.

The primary objective of AMS is to improve utilization of the equipment through lower production cost, through improved safety operations, and through enhanced environment friendly modifications of the equipment and its use. AMS falls short, because it does not indicate how to modify the equipment nor how many options are available.

These numerous weaknesses provided the motivation to develop a better tool. The rest of this thesis will provide information on this effort.

# Chapter 3: Methodology

## 3.1 Introduction

Equipment maintenance is a significant job. As noted in the previous chapter, approaches to maintenance have changed from reactive maintenance to proactive maintenance (Swanson, 2001). The long term approach requires changing the actual equipment in order to achieve increased equipment availability and reduced product costs (Teresko, 1992). A noteworthy example is RCM (Moubray, RCM II: Reliability-centered maintenance, 2001). The weakness of RCM and of similar approaches is the lack of information about the possible options. These approaches do not provide a clear path to improving the equipment.

This chapter explains and describes the proposed tool. It illustrates the methodology and shows that the proposed tool could be an excellent addition to the AMS “tool box.” There are three alternative solutions suggested for each equipment life cycle stage.

## 3.2 The Need for Identifying the Failures

The proposed tool assumes that the failure cause has been identified. Some of the better approaches are described over the next few pages.

### 3.2.1 Methods for identifying the failure causes.

There are two methods used to identify the failure causes. One method analyses the cause by using a suitable tool such as the FTA or the fishbone diagram after the occurrence of a real failure. The other method assesses the potential risk by using a suitable tool such as the FMEA before the actual occurrence of the failure. Maintenance could be performed after the cause has been identified. Following the RCM decision tree (see Figure 2), it is not necessary to fix every potential problem. If these will not result in safety problems, in mission problems, or in property damages, then these could be ignored until these develop into something that causes the equipment to stop functioning. On the other hand, if these would cause a safety problem, a mission problem, or any property damage, then CDM or TDM must be used. When these two maintenance approaches are not effective, then the maintenance department needs to consider redesigning the equipment or the system.

### 3.2.2 Fishbone diagram analysis and FMEA risk analysis.

Fishbone diagrams are used to analyze the cause of a specific event (Yazdani & Tavakkoli-Moghaddam, 2012). The potential factors that will cause an overall effect could be identified through fishbone diagram analysis. This could be used in equipment management and quality defect prevention. Causes and reasons could be grouped into major categories to locate their sources. See Table 5.

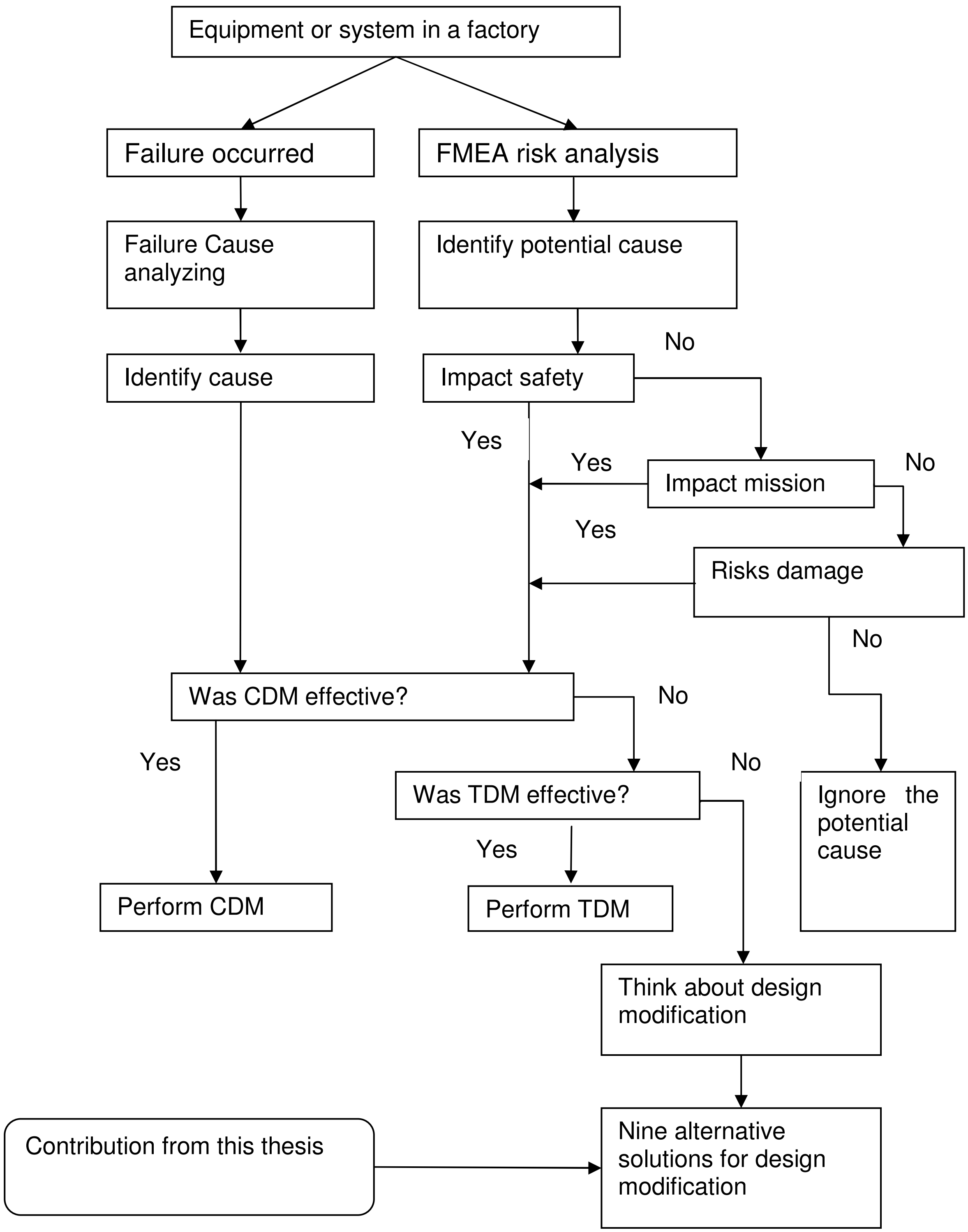


Figure 2. Failure Cause Identification Flow Chart and RCM Decision Tree[6]

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[6] Figure source of RMC Decision Tree from: Moubray, 2001

#### *3.2.2.1 Fishbone diagram analysis example (personal experience).*

In 1999, I worked on the medium density fiberboard production line for Hainan Yalong Timber Company, Ltd. (in Sanya, China). A blower fan was used to convey wood chips from the wood chip bin to the wood chip washing machine. The blower fan system was designed to move 1.2 metric tons of wood chips with 100% moisture content per hour. The blower fan would frequently stop working due to blockage. Using the Fishbone Diagram Analysis, the root cause was identified as being that the wood chips were fed into the blower fan at an uneven pace and sometimes the supply was greater than the feeder opening could handle. On occasion, the supply volume was as great as 1.4 metric ton per hour.

Figures 3 through 5 show an extract from the actual fishbone diagram analysis. The extract starts with the human operator noticing that the chip fan blower is in a stop status. Figure 3 is the next step in the fishbone diagram analysis. The entry in the rectangle is the postulate reason or cause for the failure.

Table 5. Major Fishbone Diagram Categories[7].

| Sources | Comments |
|---|---|
| People | Anyone relevant to the process |
| Environment | External conditions |
| Methods | How the process is performed and the specific requirements for doing it |
| Machines | Any equipment, tools, etc. used to accomplish the job |
| Materials | Raw materials, parts used in process |
| Measurements | Data collected from the process that are used to evaluate its level of performance |

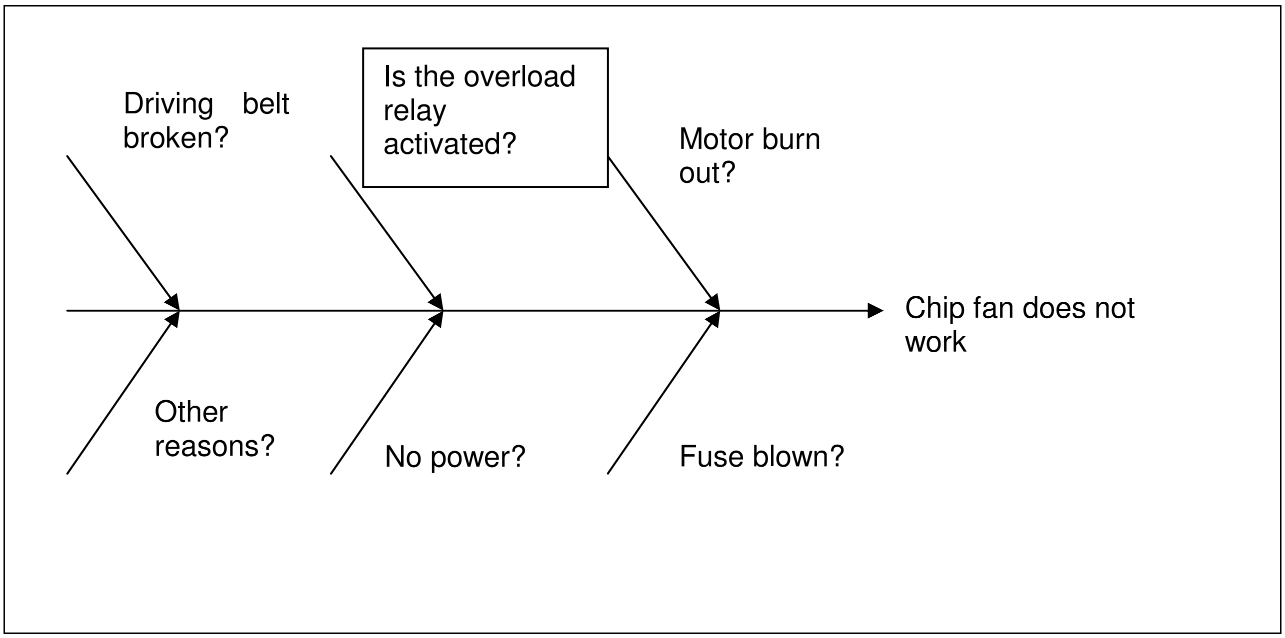



Figure 3. Step 1: Why does the wood chip fan not work?

[7] Table source from: Yazdani & Tavakkoli-Moghaddam, 2012

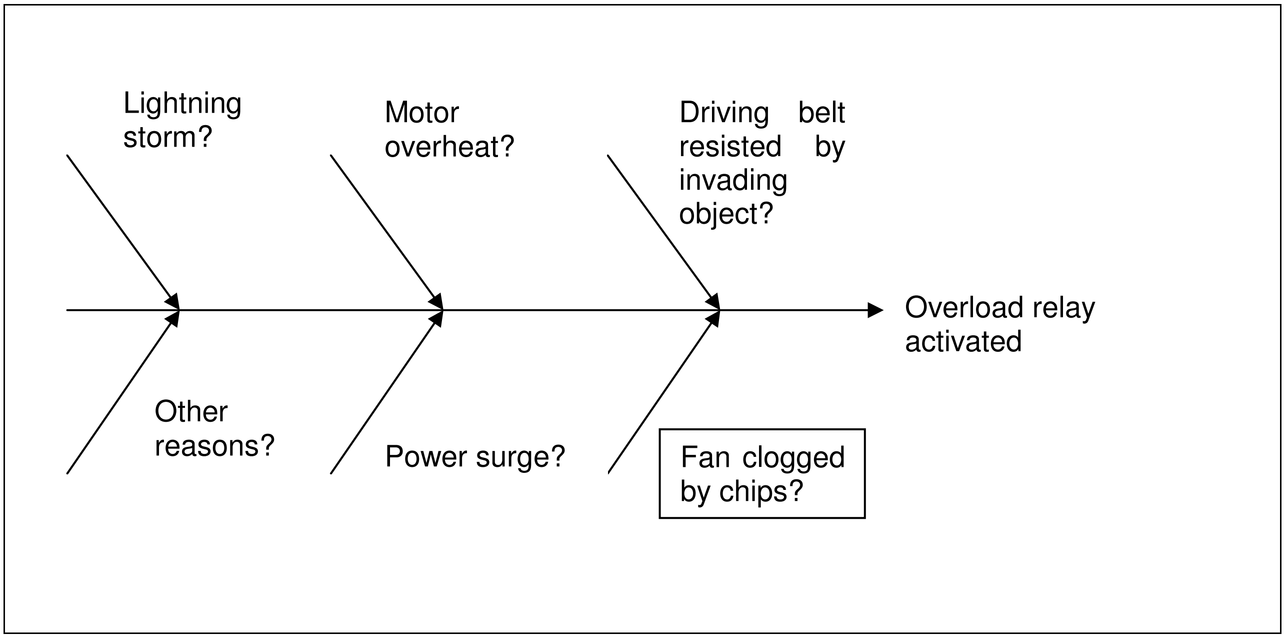



Figure 4. Step 2: Why was the overload relay activated?

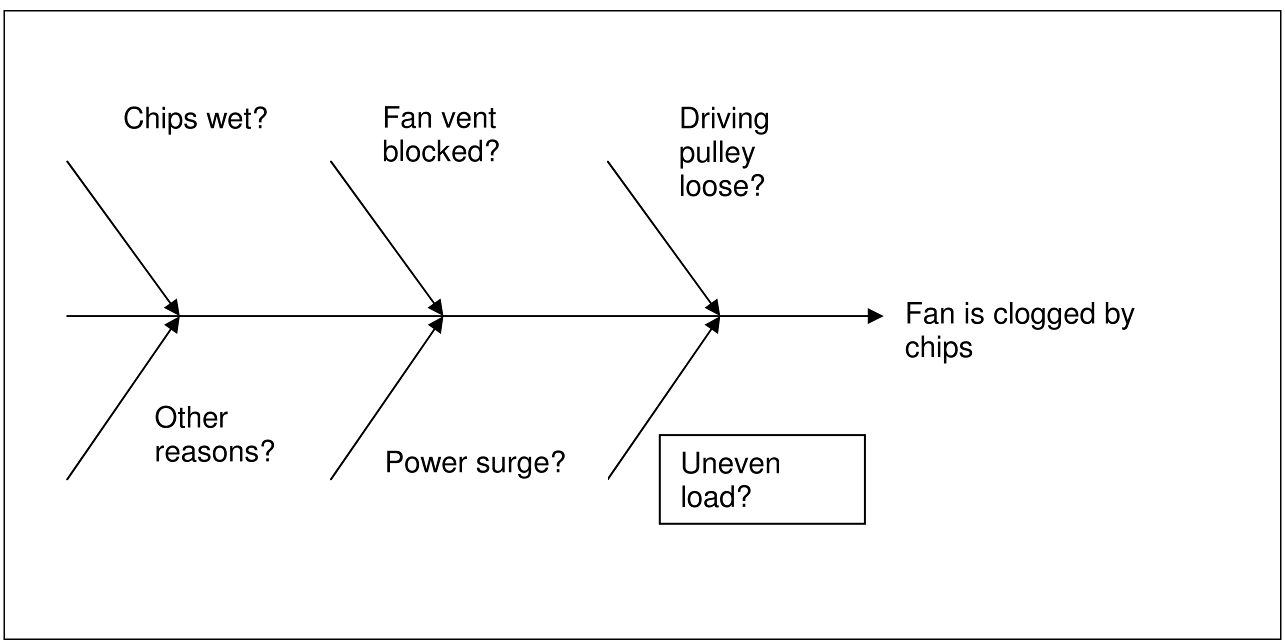



Figure 5. Step 3: Why is the fan clogged by the wood chips?

The fishbone diagram analysis leads to the conclusion that the cause of the work stoppage is an uneven load in the wood chip fan blower entrance.

### 3.2.3 FMEA tool for risk analysis.

FMEA process provides an ideal tool for improving the equipment design during the design stage (Stamatis, 2003). This tool can identify the potential problems and keep inspecting the ongoing revisions until an acceptable configuration is achieved.

This tool could be used for analyzing an existing design. The FMEA tool is able to identify any new latent defect that might not appear until sometime later. With other designing tools, latent defects are difficult to identify.

FMEA analyses a system by beginning with the basic components. It determines which component process could lead to a system failure. The detailed report identifies each component with a list of possible failure scenarios and the impact upon the equipment.

In the risk assessment section, FMEA is used to analyze the risks of following a suggested modification. The information is presented as nine alternative solutions. See Table 6. In addition to the nine alternative solutions, there are FMEA schemes for a system, for a design, and for a process. See Table 7 for these plus a brief description of the each objective.

Table 6. A Stepwise Methodology for Equipment Maintenance

| **The equipment life cycle stages:** | **Perfect running status** | **Degradation status** | **Service function ceasing status** |
|---|---|---|---|
| **The three purposes** | Sustaining reliability of equipment: | Detecting the inception as soon as possible: | Minimizing the loss caused by the equipment's failure: |
| **The three alternative solutions** | A1. Eliminating root cause | A4. Modifying equipment for more sensitive detection | A7. Modifying facility and equipment to allow quick repair |
| | A2. Preventing or decreasing the impact of root causes on equipment | A5. Improving sensitivity and reliability of detecting tools instruments | A8. Adding resilient system |
| | A3. Increasing the equipment's resistance to the root cause | A6. Improving the environment for safe and effective inspection | A9. Adding buffer inventory |

Table 7. FMEA Scope and Objectives[8]

| FMEA Scope (Type) | Objectives |
|---|---|
| System FMEA | Identify the consequences of a failure during design modification. Focus attention on those parts that are "high risk."<br>Define the modification requirement for sub-systems and components and develop a validation plan for those systems. |
| Design FMEA | Identify the consequences of a specific defect in the modification of individual components or sub system. Identify actions to manage and control the risk of such defects. |
| Process FMEA | Identify the consequences of a failure caused by errors or omissions. Identify actions to manage and control the risk of such failures. |

#### *3.2.3.1 FMEA methodology and tools.*

The first step is to determine which FMEA analysis type should be used. The possible consequences would aid this decision process.

The second step consists of six tasks as shown in Figure 6. These are to be done in order.

The FMEA Process Flow Chart (Figure 7) provides an illustration of the full FMEA process.

[8] Table source from: Stamatis, 2003

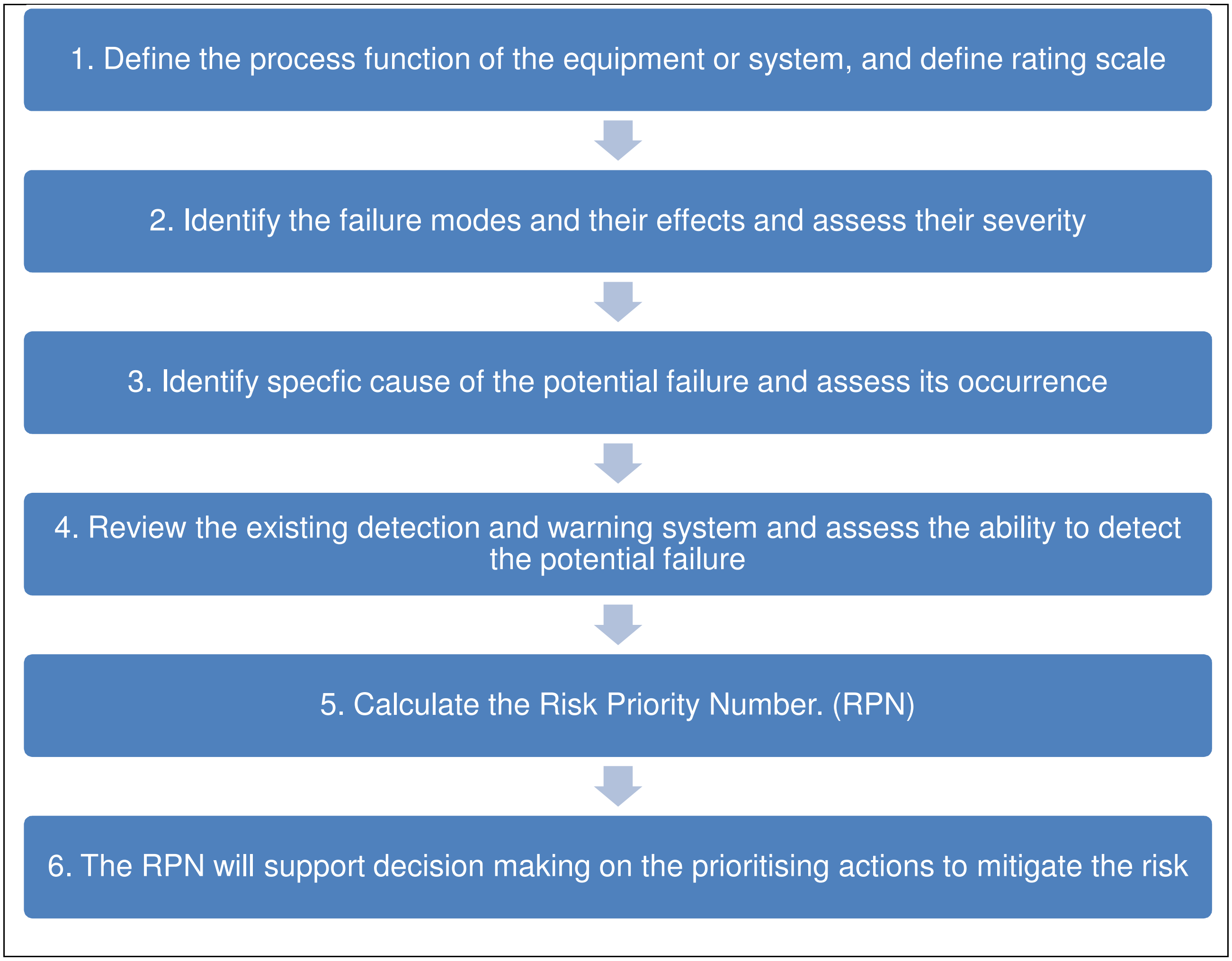



Figure 6  The Six Actions in the FMEA Second Step[9]

When all possible failures have been identified, a Risk Priority Number (RPN) is generated for each possibility. In brief, the RPN is a calculated value determined by the occurrence's probability and its severity plus the effectiveness of detecting the occurrence. The RPN value could be used to indicate the potential risks associated with

[9] Figure source from: Stamatis, 2003

a particular root cause on a piece of equipment. The possible value could range from 1 (representing the lowest risk) to 1,000 (representing the highest risk). Equation 1 shows how the RPN is calculated.

$$\mathrm{RPN} = \mathrm{O} \times \mathrm{S} \times \mathrm{D} \tag{1}$$

Where:

O - Probability of occurrence

S - Severity of the potential effects

D- Effectiveness of detection to control the root cause

The values for these three variables are found in Tables 8 through 10.

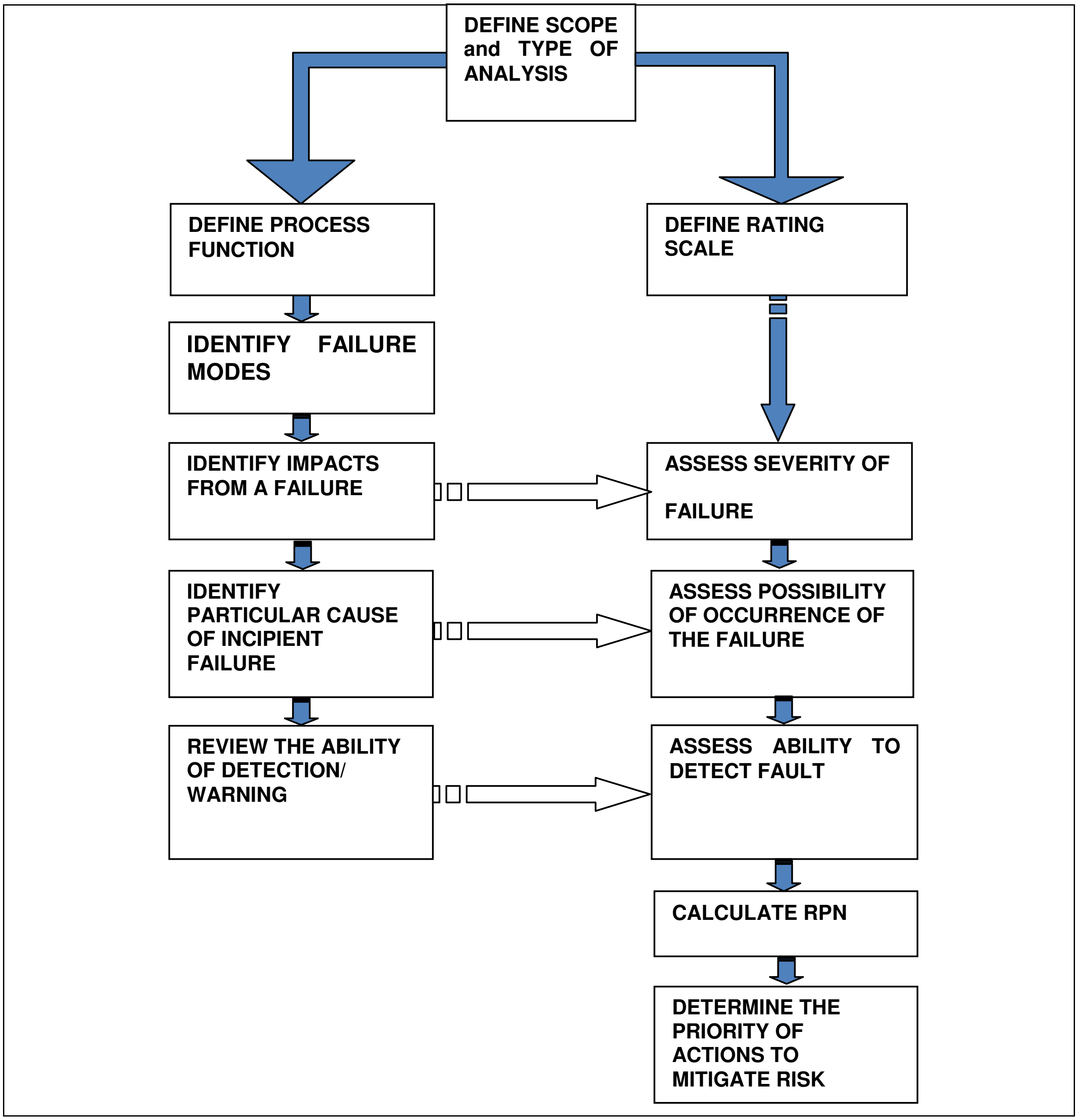



Figure 7. FMEA Process Flow Chart[10].

[10] Figure source: Korayem and Iravani 2008

Table 8. Values for the Probability of Occurrence[11]

| Score | Occurrence |
|---|---|
| 10 | Greater than 100 per thousand units (10%) |
| 9 | Greater than 50 per thousand units (5%) |
| 8 | Greater than 20 per thousand units (2%) |
| 7 | Greater than 10 per thousand units (1%) |
| 6 | Greater than 5 per thousand units (0.5%) |
| 5 | Greater than 2 per thousand units (0.2%) |
| 4 | Greater than 1 per thousand units (0.1%) |
| 3 | Greater than 0.5 per thousand units (0.05%) |
| 2 | Greater than 0.1 per thousand units (0.001%) |
| 1 | Less than 0.1 per thousand units (0.001%) |

Table 9. Values for Severity[12]

| Score | Severity |
|---|---|
| 10 | Potential failure affects safe operation or involves non-compliance with government regulations without warning. |
| 9 | Potential failure affects safe operation or non-compliance with government regulations, but user receives "adequate warning." |
| 8 | Unit inoperable (loss of primary function). |
| 7 | Unit operable with reduced performance, users very dissatisfied. |
| 6 | Unit operable, but secondary or optional functions not available, users dissatisfied. |
| 5 | Unit operable, but performance of secondary functions is reduced. |
| 4 | More than 75% of users would notice defect. item does not conform to spec, but still functions. |
| 3 | Majority of users would notice defect. Item does not conform to spec. but still functions. |
| 2 | Less than 25% of users would notice defect. Item does not conform to spec. but still functions. |
| 1 | No discernible effect. Users do not complain. |

[11] Table source from: Stamatis, 2003
[12] Table source from: Stamatis, 2003

Table 10. Values for Detection.[13]

| Score | Detection |
|---|---|
| 10 | No effective means of detecting cause of failure, users have no warning of failure. |
| 9 | Detection is possible, but advance warning of failure is very unlikely. |
| 8 | Remote chance of detecting failure and of giving adequate warning. |
| 7 | Very low chance that the failure would be detected or warning would be given. |
| 6 | Low chance that the failure would be detected or warning would be given. |
| 5 | Moderately high chance of detecting potential cause of failure and giving adequate warning. |
| 4 | Moderately high chance of detecting the cause of potential failures. |
| 3 | High chance of detection, with adequate warning. |
| 2 | Very high chance of detection, with adequate warning. |
| 1 | Detection almost certain, with adequate warning for users or a fail safe mode is used for continuing to operate. |

#### *3.2.3.2 FMEA risk analysis example.*

A detailed example is provided in Chapter 4. This is a case study on the deep draw machine.

## 3.3 Classification of Root Causes

Where did the first cause or the root cause originate? As mentioned in 3.2.2, the fishbone diagram is able to identify the cause. There are other tools that are able to do this too. The cause may be a physical or a chemical processes (Rooney & Vanden Heuvel, 2004) and the source could be from anywhere. Table 11 lists five possible sources.

[13] Table source from: Stamatis, 2003

Based on the Figure 8 illustration, root causes can be classified into two broad categories. The first category is external causes, which come from outside of the failed component. The second category is internal causes, which are derived from poor quality, from poor designs, or from manhandling of the component. Table 12 expands upon Figure 8 by presenting additional information.

### 3.4 The presentation of nine alternative solutions

Once a failure or a potential failure has been identified, then the next step is to implement something. The question concerns that "something." Some organizations may wish to use AMS in order to ensure greater equipment availability. Maybe the best answer is to find a way to improve the equipment design.

As Figure 1 showed, failure appears at three points in time. The equipment operates perfectly until the first hint of degradation (the Initial Degradation Point). The equipment continues to operate until the degradation has progressed to the point that the detection devices are able to notice the degradation (the Detectable Point). The equipment continues to operate, but the performance may now be reduced. If no action is taken, the equipment will continue to degrade until finally it shuts down completely (the Total Failure Point or the Service Function Ceasing Point).

Table 11. Possible Sources for Root Causes.

| Source | Comments |
|---|---|
| Quality aspect | The machine failure is due to quality defect. |
| Design aspect | Shortcomings in the original design or initial poor design practices lead to machine failure. |
| Misapplication aspect | The machine failure could be due to operating practices, maintenance practice, or being in an operation which is not within design parameters. |
| Circumstances aspect | The failure is due to the factors or circumstances that occurred during the design, the manufacture, or the operation. |
| Other aspects | The physical, chemical or other processes that contribute to the occurrence of a failure. |

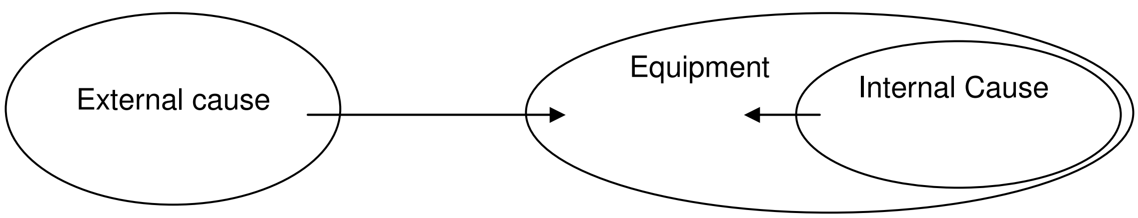



Figure 8. Sources of Failure Root Causes.

Table 12. Sources of Possible Root Causes With Notes.

| Source | Categories | Comments |
|---|---|---|
| Quality aspect | Internal cause | The machine failure is due to quality defect. |
| Design aspect | Internal cause | The error design or initial poor design practices lead to machine failure. |
| Misapplication aspect | External cause | The machine failure could be due to operating practices, maintenance practice, or being in an operation which is not within design parameters. |
| Circumstances aspect | External cause | The failure is due to the factors or circumstances that occurred during the design, the manufacture, or the operation. |
| Other aspects | Internal cause<br>External cause | The physical, chemical or other processes that contribute to the occurrence of a failure. |

In dealing with these three points, the equipment design could be changed. The new design could

- Modify the original design to extend the time the equipment is operating without any failures.
- Modify the original design to enable the equipment incipient failure to be detected much earlier.
- Modify the original design to minimize the losses caused by any failure.

### 3.4.1 Modify the original design to extend the perfect running stage.

When a cause has been identified, equipment designers could modify the original design in order to extend the time that the equipment is operating flawlessly. There are three approaches for doing this:

1. Eliminate the cause.
2. Prevent or mitigate the impact of the cause upon the equipment.
3. Increase the equipment resistance against the cause.

#### *3.4.1.1 Cause elimination.*

As shown in Figure 8, if both external and internal causes could be eliminated, then equipment failure would not happen.

Modifying the design to eliminate the cause is a common improvement method. TRIZ and Six Thinking Hats are good methodologies that support the desire to modify the design in order to eliminate a cause. Table 13 provides detailed information on this topic.

Table 13. Approaches for Eliminating Failure Causing Sources.

| Unwanted Cause | Eliminating | Mitigatin g | Improving | The Proper Course of Action |
|---|---|---|---|---|
| Problems with physical or chemical processes | XX | XX | Note 1. | Change the physical or chemical processes by modifying the design. The approach is to address the conditions that permitted the causes to exist. |
| | | | | EXAMPLE: Clogging in water ducts is a physical process; particles in water are the condition for forming a clog. Add a filter to remove the particles in water to prevent clogging. |
| Poor quality | XX | XX | XX | Detecting poor quality as soon as possible. This could mean obtaining better instruments or extending the function of current instruments.<br><br>Replacing components with high quality components.<br><br>Decreasing the workload so the equipment is not operating near its limits.<br><br>Increasing the equipment's service quality by design modification. |
| Problem with design aspect | XX | XX | XX | Search for new designs that could be employed for correcting or for extending the original design. |
| Problem of misapplication aspect | XX | XX | XX | Search for new designs that would make the equipment easier to use, easier to maintain, easier to repair, and easier to swap out defective parts. Such a design would avoid the following problems:<br><br>Incorrect equipment operations (such as not "resting" the equipment).<br>Improper repairs (such as the wrong parts or damaging other parts).<br>Improper maintenance (such as delayed inspections).<br>Improper installation (such as incorrect configurations).<br>Improper load (such as operating outside of the design parameters). |

Table 13. continued. Approaches for Eliminating Failure Causing Sources.

| Unwanted Cause | Eliminating | Mitigating | Improving | The Proper Course of Action |
|---|---|---|---|---|
| Problem of circumstances aspect | XX | XX | XX | Search for solutions that:<br><br>Correct the defect on a component.<br>Correct the environment by modifying the design.<br>Use monitors that can assist equipment operators to realize a problem is occurring and thus be able to react quickly.<br>Improve the environment for the equipment. |
| Problem of other aspects | XX | XX | XX | Search for solutions that correct the unintended consequences caused by efforts to fix defects. |
| Note 1: Improve the equipment's resiliency to outside processes and forces. | | | | |

#### *3.4.1.2 Prevent or mitigate the impact upon the equipment.*

If a cause cannot be eliminated, then the approach is to attempt to weaken it or to insulate the system from it. As shown in Figure 9, the effect of the targeted cause is diverted and thus the equipment's lifetime is extended. See the appropriate columns in Table 13.

#### *3.4.1.3 Increase the equipment resiliency against the root causes.*

This approach addresses root causes that originate from the external environment. There are various means for doing this that range from making changes to the equipment such as the material, the size, the quality or the design to making changes in how the equipment is used. (Any internal causes have been considered in the "Eliminate the Cause" section.) See the appropriate columns in Table 13.

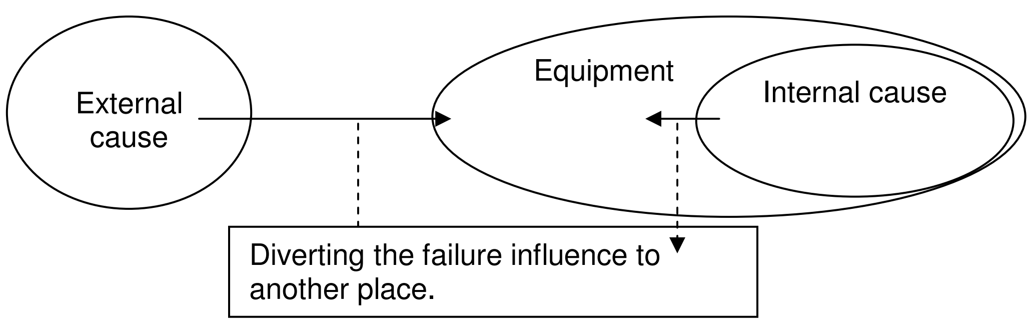



Figure 9. Diverting the Failure Root Cause via Another Route.

#### *3.4.1.4 Example (personal experience, continued).*

Using the example of the wood chip blower fan from section 3.2.2.1, the problem would be labeled as a design aspect problem. To solve this problem, we would proceed as follows:

1. Used the root cause elimination method. We added an adjustable baffle that could adjust the volume of chips being supplied to the blower fan. This worked, but the wood chip moisture content varied considerably. It was very difficult to quickly adjust the baffle to an optimal position that would avoid blocking the blower fan intake. To address this problem, we considered changing our approach to the "Prevent or decrease the impact of root cause on equipment."

2. Used the prevent-or-mitigate-the-impact-of-cause-upon-the-equipment method. We installed an electrical sensor on the absorbing trough wall. This sensor operates similar to an electric garage door opener with a safety feature. When the wood chips are not consumed quickly enough, the wood chips begin to mound up. When the top of the mound is even with the sensor light path, then the sensor sends a signal to the control system to delay adding more wood chips to the blower fan input. This worked very well for avoiding wood chip jams. But the sensor was calibrated for wood chips with less than 100% moisture content. The result is that when the wood chips had more moisture content, then the system stopped the supply machine needlessly. To address this problem, we

considered changing our approach to increase the equipment resiliency against the root causes.

3. Used the increase-the-equipment-resiliency-against-the-root-causes method. We made two modifications in order to increase the capability of the blower fan. The first modification addressed the blower fan input area by reducing the “swan neck” from three necks to two necks and by changing the angle from 90 degrees to 45 degrees. The second modification addressed the intake volume by replacing the 45-kilowatt motor with a 55-kilowatt unit and thus increased the fan speed by a factor of 1.2 times. Together the two modifications increased the capability from 1.2 metric tons per hour to 1.6 metric tons per hour. The result was that wood chip jams never occurred again.

*3.4.1.4.1 Mathematical proof for the wood chip fan blower example.*

Using the Carlson’s mathematical approach, an equation can be created to prove that the previously described changes were truly effective for solving the wood chip fan blower problem (Christie, 1991). Equation 2 shows how to calculate the volume capacity of a centrifugal fan.

$$q_1 / q_2 = (n_1 / n_2)(d_1 / d_2)^3 \qquad (2)$$

Where:

q = volume flow capacity (expressed in cubic meters/second or gallons per minute)

n = wheel velocity - revolutions per minute - (rpm)

d = wheel diameter (expressed in meters)

If the wheel diameter is constant, then the volume capacity equation could be expressed in a simpler form as shown in Equation 3.

$$q_1 / q_2 = (n_1 / n_2) \tag{3}$$

So mathematically, the capacity increased 1.2 times or from the previous 1.2 metric tons per hour to the new 1.44 metric tons per hour. This compares very well with our actual measurement of 1.4 metric tons per hour. The Carlson equation does not have a term for addressing resistance prior to the blower fan. The changes in the swan neck improved the throughput to 1.6 metric tons per hour.

### 3.4.2 Modify original design or environment to detect failures sooner.

In section 3.4.1, ideas were presented for modifying the original equipment design so that future machines would have longer lifetimes. In this section, ideas are presented for modifying the original equipment design or the immediate environment so that the smallest degradation could be detected much sooner. Currently, when degradation is detected, considerable service ability has already been lost. If no action is taken, then the failure will quickly manifest itself and total shutdown will occur soon. One approach for accessing the amount of degradation is by measuring the deviation from a reference value (such as the amount of vibration or of noise or of temperature). For this approach to work, the deviation from a reference value must occur while the measurement is being recorded. If the appearance is intermittent, then the degradation will not be

detected until the deviation value is consistently present—at that point in time, significant capability has already been lost or considerable damage has already taken place.

In the previous paragraph, three example parameters were mentioned. Hameed, Hong, Cho, Ahn, and Song (2009) provided an extensive list of measurable parameters and these are vibration, thermography, noise, lubricants, the materials physical condition, strain, electrical effects, and process parameters. Not all of these will be present when the equipment is beginning to degrade. Nor are all of these easy to measure. There are two ways for monitoring the equipment's condition. One way uses the human senses and the other way uses non-human senses (mechanical and electrical sensors).

#### ***3.4.2.1 Human senses.***

Not all of the five senses are used. For example, the sense of taste would be hazardous if the item is poisonous. The senses that could be used to monitor the condition of a machine are listed in Table 14.

Table 14. Human Senses

| The Sense | Comments |
|---|---|
| Sight (optical observation) | When technical staffers walk around a machine, they can observe deteriorations such as oil leaking, material physical condition, crack, vibration, or dirt. They can observe fasteners that are loose or missing. They can observe if a machine has shifted on its mounting foundation. |
| Hearing (acoustical observation) | A well trained technical staffer can identify the location and even the amount of failure by recognizing the changes in the noises that are being emitted. Sometimes a device or instrument is used to refine the observation. A mechanic's stethoscope is a common device for this purpose. |
| Touch (haptic observation) | A staffer can estimate the vibration amplitude, the lubricant oil quality, and the temperature change by hand-touching. |
| Smell | Burnt oil gives off a distinctive odor. |

#### *3.4.2.2 Mechanical or electrical sensors.*

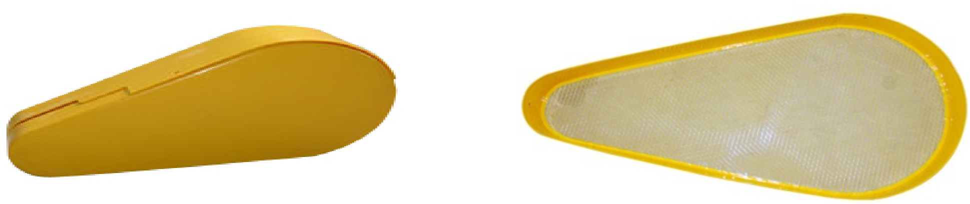
Monitoring tools and instruments are frequently used to identify the occurrence and the amount of the failure. These devices are used to directly measure deviations in the amount of vibration, in the noise level, in the lubricant level, and in the temperature. Indirect measurements may be obtained by using thermography or by measuring environmental parameters. Although the human senses can observe changes, instruments can quantify the amount, can sometimes detect the changes sooner, and can provide additional information.

#### *3.4.2.3 Make equipment modifications for easier and safer inspections.*

The previous sections assumed that the equipment is accessible and is "transparent." The equipment may be hazardous to humans such as a nuclear power plant. Or the equipment may be located in an inaccessible location such as on the bottom of the

ocean floor or in outer space. Or the equipment has covers and shields that prevent observations of the equipment's health.

Modifying the equipment would permit easier and safer access. A well designed solution would be less labor intensive for a person to conduct an inspection. For example, an opaque belt cover (see Figure 10a) would have to be removed in order to inspect the belt and the nearby parts. If this was replaced with a cover that used a metal screen (see Figure 10b), then the parts would be visible and available for inspection.



*a*[14] *b*[15]

Figure 10 Two Belt Covers.

Modifying the equipment to accept probes would make it possible to take measurements. Such "probe ports" would permit more accurate measurements. For

[14] http://www.xxhaibao.com/zscp.asp

[15] http://www.autocarfittings.com/index1.asp

example, an oil level sight glass enables one to determine how much oil is in the engine. The sight glass or a small petcock valve would provide access so a person could obtain a fluid sample while the machine is running.

#### ***3.4.2.4 Use improved devices for easier and safer inspections.***

The previous section addressed modifying equipment to accommodate probes and to make the crucial parts available for visible inspections. Closely related is the corollary instruction to obtain the best or the most capable tools and instruments.

##### *3.4.2.4.1 Inspection tools.*

The simple tools such as the mechanic’s stethoscope and a screwdriver can be useful for ascertaining the health of a machine and for identifying the source of a destructive vibration. An inspection mirror and a telescopic inspection light or a combination telescopic inspection mirror with light would enable the practitioner to inspect inaccessible parts.

##### *3.4.2.4.2 Condition Monitoring*

The condition of a machine could be monitored in various ways. One way would be to schedule visits to the machine. Another way is to use a system such as the Condition Monitoring System (CMS).

CMS can be an important component of a predictive maintenance program. CMS attempts to detect incipient failure by differentiating between normal operations and the early stages of equipment failure. CMS offers an estimate of the time when the component's service life will end (Herbert, Iniyan, Sreevalsan, & Rajapandian, 2007).

CMS includes two separate fields of technology. One is sensor technology and the other one is a diagnostic and condition monitoring technology (Rao, 1996). CMS is able to monitor the following conditions (Rao, 1996):

- Vibrations
- Oil (temperature and composition)
- Sounds (loudness and source)

A CMS could use thermography to capture thermal images. A CMS could examine and analyze strains.

#### *3.4.2.5 Modify tools and instruments to make these better.*

Mass produced tools and instruments may not be configured to meet the special or unique needs of a work environment. The practitioner may find it necessary to modify the tools and the instruments. If several practitioners make the same in-house modification, then a tool or an instrument manufacturer might produce a more polished product.

#### *3.4.2.6 Modify the working place environment to make things better.*

When the environment is favorable, then the workers and the staff may focus on the work and not on creature comfort or on safety issues. For example, technical staff with specialized training and experience could walk around the machines looking for anything out of the ordinary.

If the environment is not favorable, then changes are needed. This could involve installing sound absorbing materials, providing ladders, building platforms, adding a central heating, ventilation, and air conditioning system, or attaching hoods and equipment shields.

#### *3.4.2.7 A CMS example*

In this example, CMS is used on a wind turbine. Figure 11 shows how two wind turbines are connected to a bank of sensors for reporting on any incipient failure. Table 15 provides a description of each sensor node's purpose.

Sensor Node 1 is an inductive distance sensor. Its function is to measure the absolute rotor position. The CMS receives the signal and a Fast Fourier Transform algorithm is used for special signal processing. The signal is routed to the CMS component that performs phase sensitive narrow band analysis. The output is useful information that the practitioner can use for making a wise decision concerning the equipment.

Sensor Nodes 2 through 4 are static accelerometers. These are connected to the nacelle (a wind turbine's streamlined enclosure) for the purpose of measuring any oscillations or vibrations in the axial and transverse direction as related to the rotor axis. The identification of incipient failure depends on the variation of amplitude and frequency of the oscillations.

Sensor Nodes 5 and 6 are vibration sensors for measuring the vibrations that are induced by the bearings and the gearwheels. The identification of incipient failure depends on the variation of the amplitude and of the frequency.

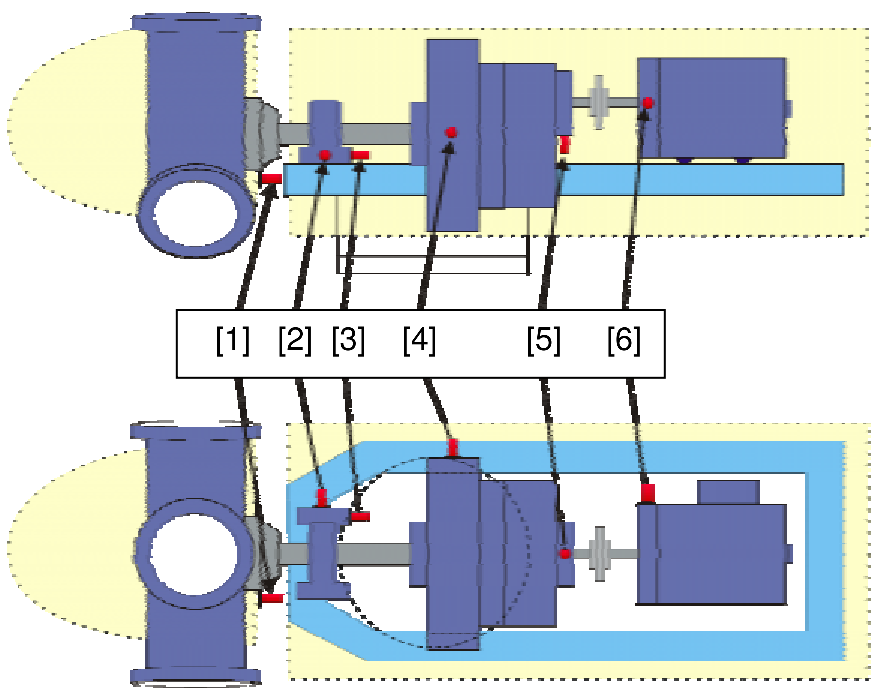



Figure 11. Sensor Placement on a Wind Turbine[16].

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[16] Image source: (Hameed, Hong, Cho, Ahn, & Song, 2009)

Table 15. Functions of Sensors in CMS[17].

| Sensor Node Numbers | Description |
|---|---|
| 1 | Measure absolute position of rotor to perform phase sensitive narrow band analysis (special Fast Fourier Transform algorithm for signal processing) |
| 2, 3, and 4 | Measure the nacelle oscillation induced by rotational speed of the rotor with static accelerometers (with lower cutoff frequency of 0 Hz |
| 5 and 6 | Measure the vibration induced by bearing and gearwheels at a frequency range from 1 to 20,000 Hz |

#### *3.4.2.8 The wood chip example (personal experience).*

In the Hainan Yalong Timber Company, Ltd. wood processing plant, ten blower fans were used to convey wood chips from one place to another. All fans were connected to the electrical motors via V-belts. If a belt should break or come off, the wood chips would back-up and quickly block the intake duct and fill the fan blades and the blade housing. Restoring the machine back to service was not just the task of installing a new V-belt. The ducts and the fan housing had to be opened up and the wood chips removed. For the ducts that are mounted high above the floor, the clean-up task was very difficult since scaffolding had to be placed around the main machines.

For solving this problem, we needed to identify when the V-belts would break as soon as possible. We used the following steps:

[17] Table source: (Hameed, Hong, Cho, Ahn, & Song, 2009)

- We selected the approach whereby the equipment would be modified to permit easier and safer inspections.
  - Replaced the opaque V-belt cover with a metal net face, in which the V-belts are visible and thus make observing the condition easier.
- Also we selected two approaches concerning the inspection devices.
  - We obtained improved devices and we made modifications in order to make these devices work better.
  - We modified the retained devices to enhance the functions.
- Lastly, we selected the approach whereby the workplace environment was improved so that inspections could be easier to perform.
  - We added ladders, a platform, and guardrails.

A noteworthy example of the work involving inspection devices, we installed on the fan axle cover a speed sensor. It monitored the rotation speed of the fan axle. As soon as the sensor detected a drop in the rotation speed, it would signal the control system to stop all the "upstream" equipment from working.  This would prevent the wood chips from jamming the fan and thus would avoid massive clean-ups.

### 3.4.3 Modify original design so that equipment failure can be minimized.

In any manufacturing activity, the motivation is to find ways to modify the equipment with the goal of mitigating the impact of any equipment failure. The following are examples of this effort:

- Reduce repair time.
- Add a hot spare. [18]
- Add buffer inventory. [19]
- Reduce setup time.

The following sub sections will cover each one in more detail.

#### ***3.4.3.1 Reduce repair time.***

Repairs tend to follow the same pattern.

1. The spare parts, the tools, the shop materials[20], the calibration instruments, and the workers must be delivered to the proper location.
2. The peripheral components and machine shields must be removed. The broken part is removed and the new one is installed. In the worst case, the entire machine may need to be replaced.

Behind the scenes are logistics support and administrative support. This takes the form of ordering the parts, of inventorying the parts, and of transporting the parts. High value parts would require security support. Cleaning the area around the machine is another task.

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[18] This is a machine that is in the state of being ready to go. In some circles, this is known as a hot standby or as a redundant machine

[19]The word "buffer" is used in this context to mean something that holds material and releases it when the next station is able to handle the input. This is similar to the way that computer scientists use the word. In that context, a buffer is a region in memory that is used to temporarily hold data while being moved from place to place..

[20] These could be lubricants, penetrating oil, towels, cleaning compounds, and so on.

To reduce the repair time certain actions could be taken:

- Modify the existing equipment.
    - Modifying the equipment to last longer between repairs.
    - Modifying the equipment so it is easier to access the interior.
    - Modifying the equipment so the repairs are black box actions.
- Create new tools or modify existing tools so the actual repair can be done quickly.
    - Quick lifting.
    - Quick dismantling.
    - Quick assembling.
- Modify the facilities and the work environment.
    - Provide a heating, ventilation, and air conditioning system.
    - Provide a means to remove continuously the accumulation of dust and dirt.
    - Increase the work space around the equipment.
    - Provide mats and cushioning materials so the maintenance team would be more comfortable during the repair task.
    - Provide sufficient lighting so repairs can be performed at night.
    - Provide shelter kits so that equipment located outside may be shielded from bad weather.

In addition to the primary benefits, the secondary benefits are decreased costs and labor; and increased safety.

*3.4.3.1.1 Examples of simple changes for speeding up repairs*.

The washer has a U-shape hole or slot that is larger than the bolt, but smaller than nut (see Figure 12). It is placed between the work surface and the nut. To remove the nut-and-bolt assembly, the maintenance person would loosen the nut a sufficient amount so the washer could be removed. Then the nut-and bolt assembly drops out of the way and the component could be removed from the machine.

A clamping device that uses a quick locking mechanism such as used in locking pliers would enable the maintenance person to quickly remove a component. If such an approach was used on a machine, then the rotating cam mechanism could be quickly removed and the axle could be quickly swapped out. Figure 13 shows a cam that is held in place by a straight pin. A better pin might be the cotter pin since part of the pin will not vibrate off of the connection point. In terms of time saving, it is the difference between two or three minutes to tighten or to loosen a regular nut-and-bolt assembly and about ten seconds to install or to remove the cotter pin.

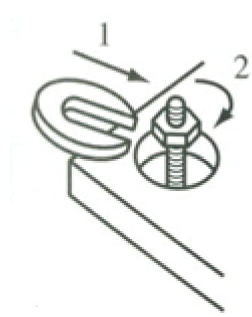



Figure 12. Using the U-Shaped Washer

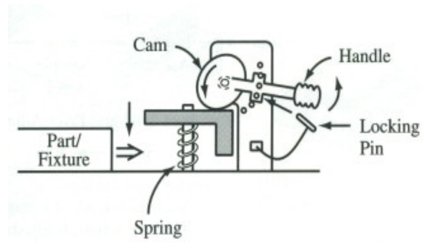



Figure 13. Using a Pin to Attach the Cam Component.

Mounting wheels on the side of the pallet platform or casters underneath it would make it possible to move the platform around without the need for a fork lift. Thus, large parts could be quickly moved to the broken machine.

Adding extensions would enable the fork lift to transport oversized parts. This would do away with the need to obtain another device. For other purposes, the fork extensions could be modified to perform different functions.

#### *3.4.3.2 Add a hot spare.*

There are three resilience methods for adding resiliency to the system:

- Parallel method
- Series method
- Redundant method

For those machines that breakdown frequently and cannot be repaired within the critical time period, adding another machine would solve this issue. The benefit is that the production line does not experience any slowdowns. The drawback is that this method is very expensive. The maintenance department will need to determine which process needs this approach. An alternative version of this approach is to add critical parts in some fashion to the production machine.

Other engineering disciplines use expressions such as over-engineering, reliability engineering, and fault tolerance to describe the efforts to keep a system from failing due to the shutdown of a component. The redundant component could be in active status, be in standby status, or be in passive status. The maintenance department will need to determine which approach is best.

*3.4.3.2.1 Example of redundancy.*

In Hainan Yalong Timber Company, Ltd. there is a steam boiler. Although it is a closed loop system, steam does escape and that requires a steady and reliable source of water. Any reduction in the amount of water would result in a boiler explosion.

We added redundancy to the system by enhancing the water pumping system. Our design used three high pressure water pumps powered by independent electric motors and one high pressure water pump powered by the high pressure steam. The design uses the partially activated or standby redundancy approach. When the boiler is running, it only needs one pump for supplying the necessary water and the other pumps are in a

standby mode. As soon as the primary pump stops working, one of the secondary pumps immediately picks up the task of supplying water to the boiler. There are two more pumps available. This should give the maintenance department enough time to repair the problem. Although China has the second highest electrical generation capacity in the world, it is not enough and power rationing is being done (Wu & Fu, 2005). So to address this infrastructure issue, one of the water pumps uses steam and two diesel power generators are nearby. One generator can supply enough power to run all the key systems.

There are limits for how long these backup systems can be used. The diesel fuel tanks will be deleted. Steam pump does not need electric power, but it is not a perpetual motion machine. A point will be reached when the pressure of the steam is not enough to drive the water pumps. The hope is that the local diesel supplier is able top off the tanks and that things can be restored to normalcy with a few days time.

On a positive note, the reliability of the primary electric pump is that it fails on the average once every 100 days. The typical repair takes no more than four hours to complete. This works out to a system availability of 99%. The steam powered water pump has an availability of 98%. The Chinese electrical grid has an availability of 99.9%. The diesel generators have an availability of 80%. The lower figure is due to the fact that periodically diesel generators must be shut down for maintenance and for engine cooling.

The availability values were calculated using Equations 6, 7, and 8.

Series system

$$\boldsymbol{R_s = r_1 \times r_2 \times r_3 \times \ldots\ldots \times r_n} \tag{4}$$

Parallel system

$$\boldsymbol{R_p = 1 - (1 - r_1) \times (1 - r_2) \times (1 - r_3) \times \ldots\ldots \times (1 - r_n)} \tag{5}$$

Redundant system

$$\boldsymbol{R_b = r_1 + r_b \times (1 - r_1)} \tag{6}$$

The Yalong Timber Company, Ltd. boiler system is illustrated in Figure 14. Each component has a letter and a previously determined reliability value. The sub system and the complete system reliability values are calculated as follows:

System reliability for the electrical power (tasks A, B and C) via Equation 8:

$$R_b = r_1 + r_b \times (1 - r_1) = 99\% + 99\%(1 - 99\%) = 99.9\%$$

$$R_{ab} = r_a + r_b \times (1 - r_a) = 99.9\% + 80\%(1 - 99.9\%) = 99.98\%$$

$$R_{abc} = r_{ab} + r_c \times (1 - r_{ab}) = 99.98\% + 80(1 - 99.98\%) = 99.996\%$$

System reliability for the pump (tasks D, E and F) via Equation 8:

$$R_{de} = r_d + r_e \times (1 - r_a) = 99\% + 99\%(1 - 99\%) = 99.999\%$$

$$R_{def} = r_{de} + r_f \times (1 - r_{de}) = 99.99\% + 99\%(1 - 99.99\%) = 99.9999\%$$

System reliability for the combination electrical power and pump (tasks A, B, C, D, E and F) via Equation 6:

$$R_{abcdef} = R_{abc} \times R_{def} = 99.996\% \ \times 99.9999\% = 99.9629\%$$

System reliability for the complete system (tasks A, B, C, D, E, F and G) via Equation 8:

$$R_{abcdefg} = R_{abcdef} + r_g \times \left(1 - r_{abcdef}\right) =$$

$$99.9629\% \ + 98\%(\,1 - \ 99.9629\%) = 99.9992\%$$

Thus we can claim that the reliability is very high when a redundant system is deployed.

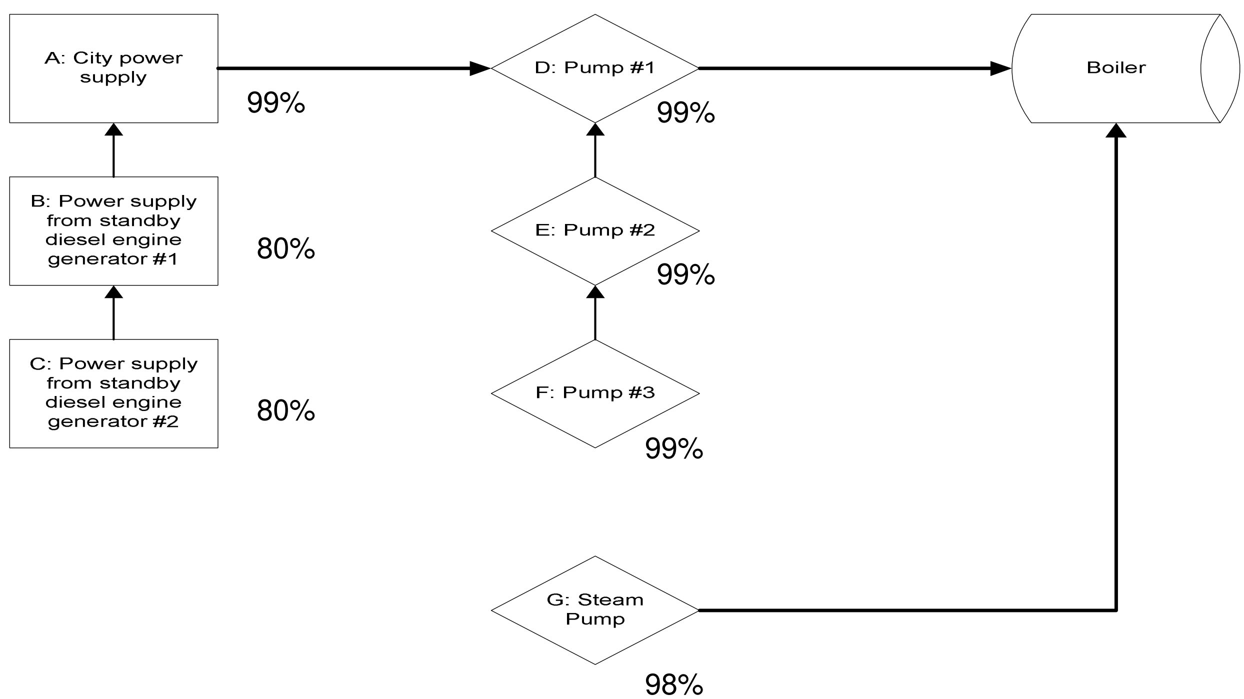


Figure 14. Boiler Water Supply System.

#### *3.4.3.3 Adding buffer inventory*

A buffer inventory in the system can serve as a gatekeeper between a fast producing machine and a slow consuming machine. When the upstream machine fails, the buffer inventory can continue to feed the downstream machine. When the downstream machine fails, the buffer inventory can act as a temporary storage area. Both scenarios would give the maintenance team some time to repair the broken machine.

##### *3.4.3.3.1 Example of wood chip buffering.*

In the Hainan Yalong Timber Company, Ltd. medium density fiberboard production line, wood chipper blades or knives (see Figure 15) wear out quickly and must be replaced after 24 hours of machine usage. To replace all of the chipper knives entails removing the housing, swapping out the knives, and re-installing the housing. For a proficient maintenance team, these tasks would take an hour.

The efficient design is to have the wood chipper (see Figure 16) process faster than the wood chip washer could handle. The wood chips are stored in a wood chip bin (see Figure 17) or in a storage area (see Figure 18). The wood chips are supplied to wood chip washing system at a pace that it can handle. The storage areas contain about eight hours of material. This buffer inventory approach permits the maintenance team sufficient time to change out the wood chipper knives.[21]

[21] In program management, this is known as the critical path. The replacement of the wood chipper knives must be completed prior to the wood chip storage areas being depleted.

Figure 15. Wood Chipper Knife[22].

Figure 16. Wood Chipper Machine[23].

[22] Image source: http://www.cutinfo.cn/mb2/maoyi.php?facid=shanyinjx&page=8
[23] Image source: http://www.mufenji.com.cn/gushixuepianji.htm

Figure 17. An Example of a Typical Wood Chip Bin[24].

Figure 18. An Example of a Storage Field[25].

The critical time could be expressed mathematically by Equations 4 and 5 (Wu & Fu, 2005).

Let:

[24] Image source: http://www.hnrzbsb.com/pros/pro81.
[25] Imagine source: http://news.chinapaper.net/html/84/n-26684.html

If the assembly line can operating without any impact from the presence of the broken equipment, then

$$Q \geq R \tag{7}$$

If the assembly line would suffer from the presence of the broken equipment, then

$$Q < R \tag{8}$$

Thus, if the time to repair is greater than the amount of material in the storage queue, then adjustments are needed. Either increase the size of storage queue or decrease the amount time to perform the repairs. The maintenance department will need to decide upon the best course of action. Of course, this assumes that the replacement wood chip knives are present in the bench stock area and that people are available to perform the work.

#### *3.4.3.4 Reduce setup time.*

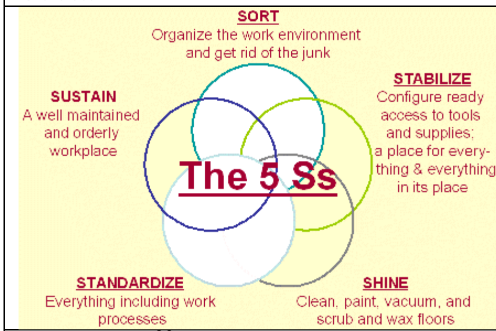
Any approach that would reduce the preparation for performing a repair would enable the maintenance team to be more productive and to be more effective. A number of the suggestions mentioned in the topic on reducing the repair time would apply here. The results would be increased quality, increased capability, increased capacity, increased flexibility, decreased costs, and decreased waste. In addition, the company can react faster to very short lead times.

#### *3.4.3.4.1 The Kaizen process or the Five-S method.*

The Japanese Kaizen process or the Five-S methodology describes how to organize the work place. The Japanese words have been translated in different ways and the order varies from website to website (see Table 16). All of the versions would result in an orderly work area and thus would reduce the time for locating tools and parts.

Table 16. Examples of the Variations in the Elements of the 5 S.

| Steve Hudgik[26]'s Version of the 5 S | UTC[27]'s Version of the 5 S |
|---|---|
| Sort | Sort |
| Set in order | Straighten |
| Shine | Shine |
| Standardize | Standardize |
| Sustain | Sustain |





| Strategos[28]' Version of the Five S | Wikipedia[29]'s Version of the 5 S |
|---|---|
| Sort | Sorting |
| Shine | Set in order |
| Set | Systematic cleaning |
| Standardize | Standardizing |
| Sustain | Sustaining |

### *3.4.3.4.2 Single Minute Exchange of Dies*

Through one smart design change after another, we can make the set-up time shorter and shorter and the procedures simpler and simpler. One approach for doing this is the Single Minute Exchange of Dies (SMED).

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[26] He is a blogger and an employee of Graphic Products, Inc. See http://www.graphicproducts.com/tutorials/five-s/

[27] United Technologies, no author listed, http://www.utc.com/StaticFiles/UTC/StaticFiles/5S.pdf

[28] Strategos International, no author listed, http://www.strategosinc.com/5s_elements.htm

[29] Wikipedia, no author listed, http://en.wikipedia.org/wiki/5S_(methodology)

SMED is a systematic approach that seeks to reduce the time for completing a task to ten minutes or less. Agustin and Santiago (1996) wrote about the benefit of using SMED in a high volume manufacturing enviornment. In their paper, they reported on their experience in implementing this in Manila.

The approach of SMED includes four phases or stages which are illustrated below Figure 19.

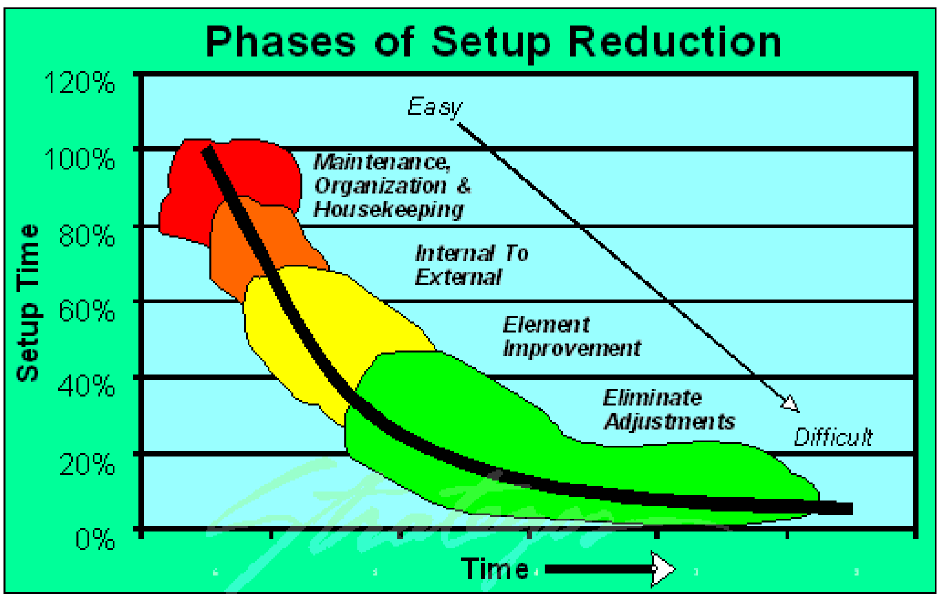



Figure 19. Phases of Setup Reduction[30].

[30] Imagine source: http://www.strategosinc.com/setup_reduction2.htm

##### *3.4.3.4.2.1 Phase 1. Maintenance, organization and housekeeping.*

Some setup problems are related to poorly maintained equipment with the result there are worn parts, worn tool, dirt, and damaged threads. Disorganization and poor housekeeping are also contributors to setup problems. These are easy to fix and should be a first step.

##### *3.4.3.4.2.2 Phase 2. Internal elements to external.*

Internal elements occur when the machine is down. Examine each internal element and see if it cannot be done externally. For example, the pre-heating of an injection molding die could be done before it goes into the machine.

##### *3.4.3.4.2.3 Phase 3. Improve elements.*

Here we examine every element to see how we can eliminate it, can simplify it, and can reduce it. The results should be a significant reduction in the time to complete the tasks.

##### *3.4.3.4.2.4 Phase 4. Eliminate adjustments*

Adjustments are often the most time consuming, the most frustrating and the most error prone part of a setup. There are many ways to eliminate them entirely and this is the ultimate goal.

#### *3.4.3.4.3 Examples from personal experience.*

For Hainan Yalong Timber Company, Ltd. we constructed a special container that would be used to store the spare parts in pristine condition. The container was placed near the relevant machine. In this way, a mechanic could replace the broken part immediately without the need to visit the bench stock room and spend time locating the correct part. This idea is more significant for small parts that break down frequently.

Another effort to reduce the setup time for performing repairs was the replacement of a wall with a large door near a heavy motor. Now a fork lift can enter the area and drive straight to the wood chipper. If it is necessary, the entire machine could be removed.

Another effort was installation of air compressor lines to the work sites. Now it is very easy to clean a machine.

## 3.5 Multi-Hierarchy Design Changes Depend Upon the Structure

### 3.5.1 Introduction.

Most machines are composed of several sub systems such as a dynamic system, a control system, an execute system, and an operational system. These systems might be composed of various sub systems. For example, the 2009 Quincy Compressor QT Series 2-Stages Compressor has a dynamic and control system, a lubrication system, a cooling system, a compression system, a dryer, and a filter system. In turn, the dynamic and control system has a motor, a power supply sub system, and a control sub system. And in turn, the motor has bearings, a rotor, a stator, a fan, a cover, and a power connection case.

Any proposed design modification must consider the various systems and subsystems. In this regard, it is necessary to apply the nine alternative solutions in Table 6 to each subsystem level of the machine.

For example, the previously mentioned 2009 Quincy Compressor QT Series 2-Stages Compressor failures could occur at the lowest level (such as the bearings and rotor) or at the sub system level (such as the motor and power supply).

If the 2009 Quincy Compressor QT Series 2-Stages Compressor was experiencing problems with water leaking into it, then we could use the following steps for finding a solution:

1. Add a protective cover to prevent water from spilling onto the motor.
2. Add a vibration sensor to identify the incipient failure as early as possible.
3. Add a redundant motor as stand by unit that could be put into service as soon as needed whether for maintenance or for another reason. (Below the system level.)
4. Add a redundant air compressor as stand by unit that could be put into service as soon as needed whether for maintenance or for another reason. (The whole system level.)

From the foregoing steps, it is easy to see that the problems could be solved by modifying the design for each subsystem level and for each component. Table 17 makes it clear what are these subsystem levels and how the subsystem levels relate to

each other. The placement of the entries roughly shows the arrangement of the parts and components into a subsystem and into a major system.

Table 6 presents this information plus other additional information which was covered in the previous paragraphs. For ease of understanding, the solution for design modifications for each hierarchy level are summarized in Table 18. The reliability equations (Equations 6 through 8) may be used.

Table 17. FMEA Hierarchical Analysis of the QT Series Compressor.

| **Hierarchy** | **FMEA Hierarchical Analysis** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| The whole Equipment level | Air compressor | | | | | | | | | | | | | |
| System level | Dynamic and control system | | Lubrication system | Compression system | Cooling system | Dryers and filter system | | | | | | | | |
| Component | Motor | | | | Power supply and Control system | | | | | | | | | |
| | | | | | | | | | | | | | | |
| Parts | **Bearings** | **rotor** | **Stator** | **Fan** | **Cover** | **Power Connection case** | **Switch** | **Contactor** | **Overload relay** | | | | | |
| Failure mode | **broken** | **Quality defect** | **burn out** | **broken** | **Loose** | **Seal wear out** | **Fail** | **Fail** | **Fail to work** | | | | | |
| | | | | | | | | | | | | | | |
| Parts | **Press switch** | **Fuses** | **Cable** | **Switch box** | | | | | | | | | | |
| Failure mode | **Fail to work** | **melt** | **broken** | **Ingress of water** | | | | | | | | | | |

Table 18. Solutions Based on Table 6 and in Terms of Each Level.

| Level | From Nine Alternative Solutions (Table 6) |
|---|---|
| The whole Equipment level | A1, A2, A3, A4, A5, A6, A7, A8, A9 |
| System level | A1, A2, A3, A4, A5, A6, A7, A8, A9 |
| Component | A1, A2, A3, A4, A5, A6, A7, A8, A9 |
| Parts | A1, A2, A3, A4, A5, A6, A7, A8, A9 |
| Failure mode | A2 |
| Cause | A1 |
| Root cause | A1 |
| NOTE: The prefix of the letter “A” is to remind the reader that Table 6 needs to be used for each system and sub system in a machine. | |

Table 19 shows how to view the issue of the motor bearings failing. This table shows something for each level of the machine.

### 3.6 Risk and Economic Assessment and Continuing Improvement

When the recommended solutions are presented to the maintenance department, how will the department make its selection? The decision would be based on assessing risks and the economic benefits.

Table 19. Example of a Motor Bearing Failure Analysis

| Level | FMEA Hierarchical Analysis | Nine Alternative Solutions for different levels |
|---|---|---|
| The Whole Equipment Level | Air compressor | 1. Add redundancy by adding another air compressor (A8) |
| System Level | Driving and control system | 2. Monitoring current peak (A5) |
| Component Level | Motor | 3. Add a sensor to monitor motor vibrations (A5)<br>4. Add a redundant motor (A8)<br>5. Dismantle motor and replace bearing quickly (A7) |
| Sub Component Level | Bearing | 6. Selecting high quality bearings (A3)<br>7. Add proper protection for the motor(A2)<br>8. Add a clean system that removes dust and dirt automatically from the motor shaft automatically(A1) |
| Failure mode | Bearing broken | |
| Cause | Invading dirt | |

Risk assessment is a component in risk management. The likelihood of a risk occurring and the degree of possible harm can be determined by three factors:

- The magnitude of the potential loss *(L)*
- The probability *(p)* the loss will occur
- The qualitative value of the risk as it relates to a situation and a recognized threat (also called hazard) (Haimes, 2004).

In the manufacturing world, the department that is responsible for risk management is also normally concerned about the threats to life and to the environment plus machine functions (Greenberg & Cramer, 1991).

FTA, FMEA, and Probabilistic Risk Assessment (PRA) are tools normally used in various types of engineering activities that support complex manufacturing systems.

### 3.6.1 Risk assessment.

#### *3.6.1.1 Introduction to risk assessment.*

Although engineers have improved the tools and approaches for generating a list of proposed design modifications, the maintenance department has the final say about which proposal should be implemented. The maintenance department will need to consider other issues such as safety, health and environment factors before selecting a solution from all recommended alternative solutions (Carbone & Tippett, 2004).

The detailed treatment of the FMEA risk assessment methodology has been covered in the sub sections of 3.2.

### 3.6.2 Economic assessment.

The maintenance department makes an economic assessment as part of the decision process. There are different tools that could be used such as break-even analysis, net present value, and return on investment (ROI). For this thesis, ROI will be used.

#### *3.6.2.1 ROI.*

ROI (Erdogmus, Favaro, & Strigel, 2004) is a helpful tool that can be used to evaluate the performance of an investment or to compare the performance of a number of

different investments. ROI is a very popular method not only because of its versatility but also due to its simplicity.

The ROI calculation has two steps:

1. Step 1: The benefit (return) of an investment equals gain from investment minus cost of investment.
2. Step 2: The ROI equals the benefit (return) of an investment divided by the cost of the investment; the result is expressed as a percentage or a ratio.

Equation 9 is the ROI formula.

$$ROI = \frac{Gain\ from\ Investment - Cost\ of\ Investment}{Cost\ of\ the\ Investment} \quad (9)$$

For long term investments, all of the monies must be expressed in the same time period prior to using Equation 8 (Newnan, Eschenbach, & Lavelle, 2004). For short time periods, this step is not necessary.

If the period payback amounts are equal, the "gain from investment" can be converted to present worth by using Equation 10 (*P/A, i, N*):

$$P = A\left[\frac{(1+i)^N - 1}{i(1+i)^N}\right] \quad (10)$$

*Where:*

P = single cash flow at time 0 for a set of cash flows

i = interest rate per period
N = number of accounting periods from 0
A = uniform periodic amount per period for N periods

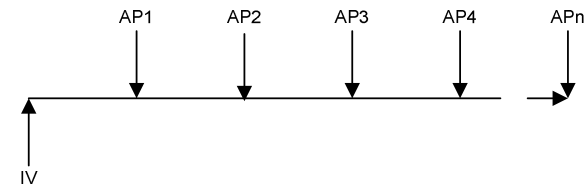
If the period payback amounts are linear gradient, the "gain from investment" can be converted to present worth by using Equation 11 (*P/G, i, N*):

$$P = G\left[\frac{(1+i)^N - iN - 1}{i^2(1+i)^N}\right] \quad (11)$$

To analyze the ROI for a proposed equipment design modification, the maintenance department needs to consider all of the relevant costs including the impact on liquidity or cash flow that would come from implementing the modification. The following is a list of possible relevant costs areas:

- Initial cost
- Purchasing cost
- Modification investment
- Installation and start up costs
- Increased energy consumption cost
- Increased operating cost (including regular maintenance labors)
- Increased maintenance and repair cost
- Increased environmental impact cost
- Salvage value
- Dismantle or return of goods value cost

The cash flow of relevant costs are illustrated and listed in Figure 20.




IV = Initial investment cost = IC + IN

AP = IP – ( IE + IO + IM + IEN )

AP1 = AP by the end of year 1

AP*n* = AP by the end of year *n*

IC = initial cost, purchasing cost, modification investment.

IN = Installation and start up costs equipment.

IP = Increased production benefit.

IE = Increased energy consumption cost

IO = Increased operating cost (including regular maintenance labors)

IM = Increased maintenance and repair cost

IEN = Increased Environment impact cost

D = Salvage value and dismantle or return of goods value cost of modified part

Figure 20. Net Cash Flow for Calculating ROI.

From the calculated result, if an investment does not have a positive ROI, or if the result is less than other opportunities with a higher ROI, then the investment is not the optimal solution (Hammerschlag, 2006).

#### *3.6.2.2 ROI example.*

Hainan Yalong Timber Company, Ltd. was considering two alternative solutions (A and B) for a cooling system design modification. Alternative solution A would require an investment of $60,000 and it could produce a value that is equal to an annual profit of $20,000. Alternative solution B would require an investment of $100,000 and it could produce a value that is equal to an annual profit of $30,000. The lifetime of both

Alternative solution A and Alternative solution B are 10 years. Both have a salvage value are $0. The interest rate is 8%. The maintenance department needs to compare Alternatives solution A and B, and select one for implementation. The detail calculations follow:

For alternative solution A:

Step 1: Find the present worth of annual profit.

$$P = A\left[\frac{(1+i)^N - 1}{i(1+i)^N}\right]$$

$$P = 20{,}000\left[\frac{(1+0.08)^{10} - 1}{0.08(1+0.08)^{10}}\right]$$

P = $134,201.60

Step 2:

$$ROI = \frac{\text{Gain from Investment} - \text{ Cost of Investment}}{\text{Cost of the Investment}}$$

$$\mathrm{A_{ROI}} = \frac{134201.6 - 60000}{60000} = 1.236694$$

For alternative solution B:

Step 1: Find the present worth of annual profit.

$$P = A\left[\frac{(1+i)^N - 1}{i(1+i)^N}\right]$$

$$P = 30{,}000\left[\frac{(1+0.08)^{10} - 1}{0.08(1+0.08)^{10}}\right]$$

P = \$201,302.40

Step 2:

$$ROI = \frac{\text{Gain from Investment} - \text{Cost of Investment}}{\text{Cost of the Investment}}$$

$$\mathrm{B_{ROI}} = \frac{201302.4 - 100000}{100000} = 1.013024$$

Compare $\mathrm{A_{ROI}}$ and $\mathrm{B_{ROI}}$: $\mathrm{A_{ROI}} > \mathrm{B_{ROI}}$

Therefore, choose alternative solution A.

## Chapter 4  Case Study

### 4.1  Introduction

A metal bellows manufacturer was selected as a case study for illustrating the application of the proposed tool.

Metal bellows (see Figure 21) are elastic vessels made from stainless steel and alloys for use in ultra high vacuums or in positive pressure environments. A metal bellow can be compressed when pressure is applied to the outside or it can be extended under vacuum. When the pressure or vacuum is released, it will return to its original shape. Metal bellows are used as actuators, accumulators, mechanical seals, expansion joints, volume compensator, lifters, mechanical feedthroughs, and vibration dampeners[31]. In addition, some bellow manufacturers are able to create miniature bellows for use as flexible shaft couplings and electrical contact springs.[32]

[31] These examples came from the web page that lists metal bellows by product type.

[32] These two examples came from a web page that provided information on miniature bellows produced through electrodeposition.

 [33]

Figure 21. Examples of Metal Bellow.

### 4.1.2 The manufacturing process for metal bellows.

The manufacturing process consists of nine individual stages that are described in Figure 22.

## 4.2 The Focus of the Case Study: The Stage 3 (the Draw Machine)

The deep draw machine is used to process the raw form in the third stage. It fails on the average two to three times a year. A fishbone analysis (see Figures 23 through 25 and Tables 20 through 22) was used and the cause was identified as an over tightened pressure adjustment screw on the hydraulic pump (see Figure 27), which caused it to fail (see Figure 26). Each repair costs about $1,000 and it will take about three weeks to

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[33] Image source: http://www.ameriflex.neet/bellows.php.

complete the repair. Quantifying the lost production cost is difficult to estimate since the company uses a redundant approach with a ready standby deep draw machine.

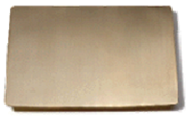
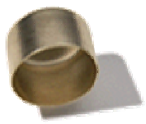
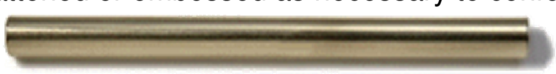
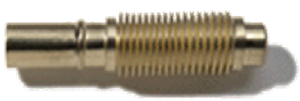
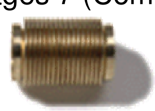
| |
|---|
| Stage 1 (Raw Material): The process begins with a flat strip of raw metal.  |
| Stage 2 (Cup Shape): The raw metal is fed into a press that shapes the material into a cup shape.  |
| Stage 3 (Intermediate Draws): The desired length and thickness for the cup shape could be achieved through several secondary deep draws that gradually reduces the diameter and the wall thickness.  |
| Stage 4 (Final Draw): While the tube is being drawn, the grain size is carefully monitored and the wall thickness is microfinished. The tube may be trimmed to length. The enclosed end may be flattened or embossed as necessary to conform to the specifications.  |
| Stage 5 (Bellows-Forming): A special machine performs the process forming the bellows.  |
| Stage 6 (End Trimming): Based on the specifications, addition steps may be needed such as trimming, cleaning and heat treating.  |
| Stages 7 (Compressing): Based on the specifications, the bellow my need to be compressed.  |

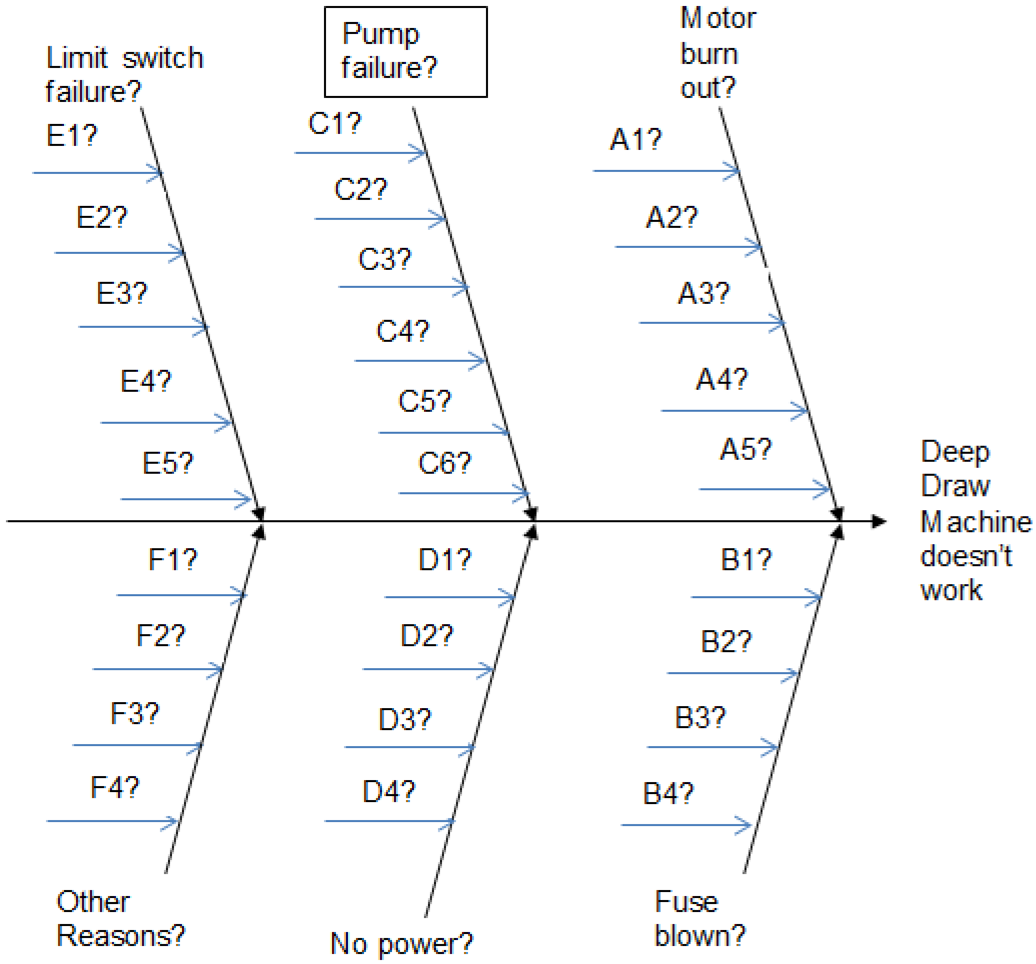
Figure 22. Manufacturing Steps[34].

[34] Imagine source: http://www.cliflex.com/manufacture.html

| |
|---|
| Stages 8 (Assembling the Units): Parts from other assembly lines are used to create the final product.<br> |
| Stages 9 (Finished Assembly): The final result is a metal bellow.<br> |

Figure 22. Continued. Manufacturing Steps

Step1: Why doesn't the deep draw machine work?



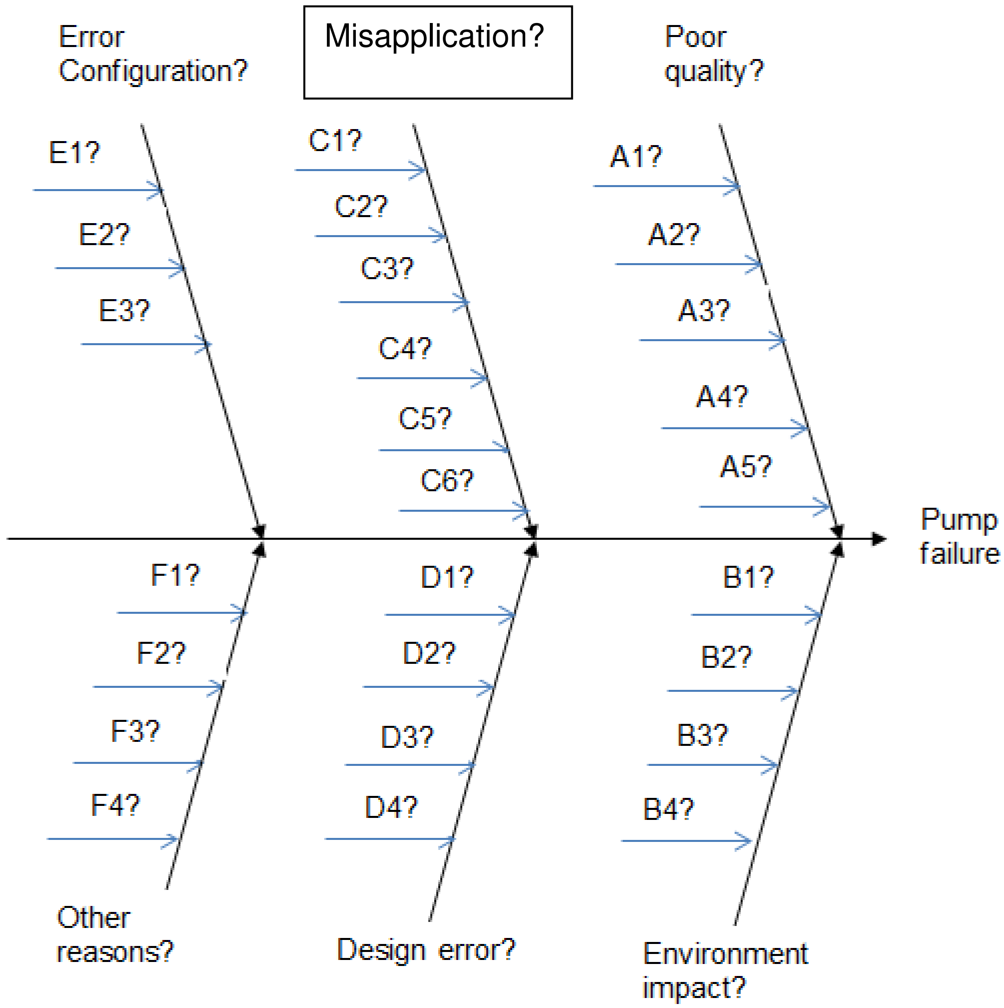

Note: Codes are defined in Table 20.

Figure 23. Fishbone Diagram Step 1.

Table 20. Code Definitions for Figure 23.

| Code | Description | Code | Description |
|---|---|---|---|
| A1 | Overload | D1 | Maintenance |
| A2 | Bearing broken | D2 | Bad weather |
| A3 | Short circuit | D3 | Equipment failure |
| A4 | Voltage fluctuation on power supply | D4 | Other reasons |
| A5 | Other reason | E1 | Poor quality |
| B1 | Overload | E2 | Design error |
| B2 | Short circuit | E3 | Configuration error |
| B3 | Voltage fluctuation on power supply | E4 | Environment impact |
| B4 | Other reasons | E5 | Misapplication |
| C1 | Poor quality | F1 | Oil tank leaking |
| C2 | Misapplication | F2 | Hydraulic cylinder failure |
| C3 | Design error | F3 | Lubricant system failure |
| C4 | Configuration error | F4 | Other reasons |
| C5 | Environment impact | | |
| C6 | Other reasons | | |

Step2:  Why did the pump fail?



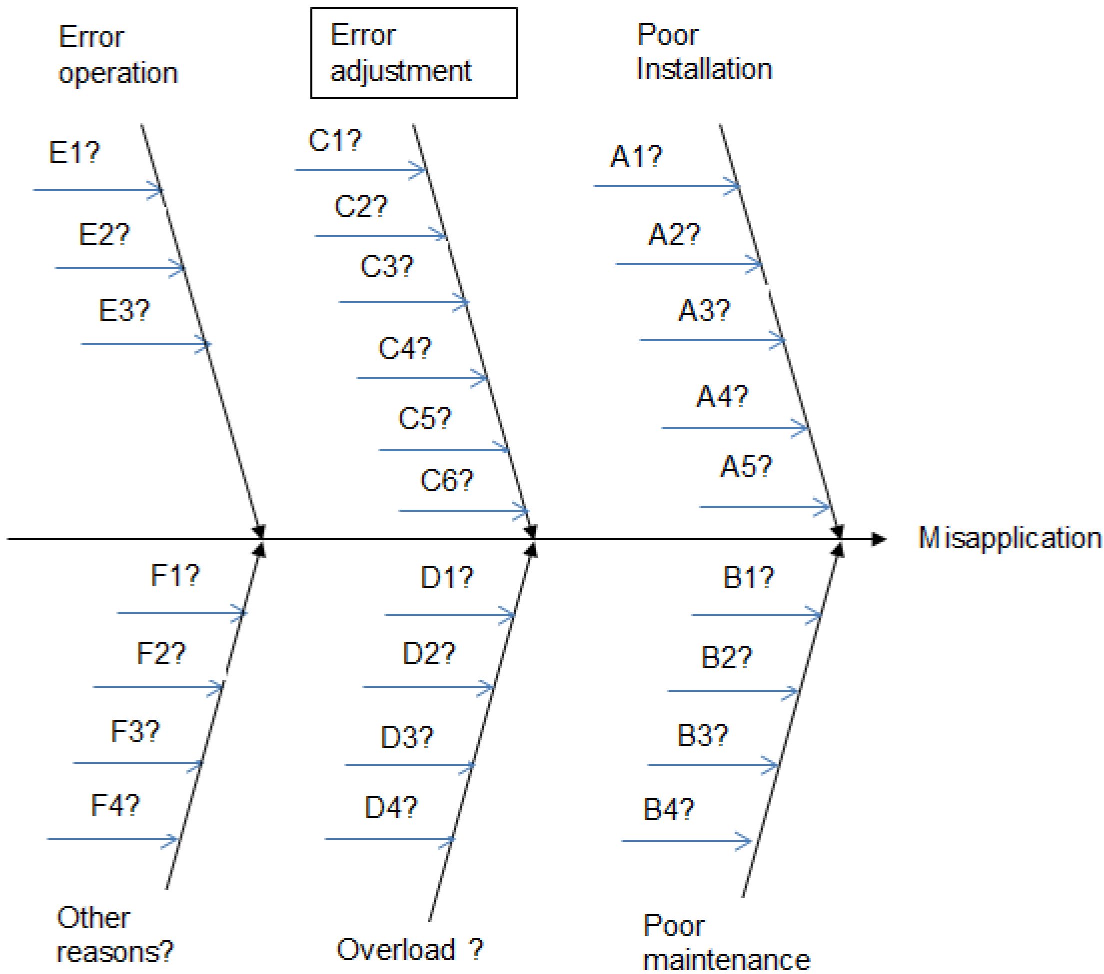

Note:  Codes are defined in Table 21.

Figure 24.  Fishbone Diagram Step 2 (Focus on the Pump Failure).

Table 21. Code Definitions for Figure 24.

| Code | Description | Code | Description |
|---|---|---|---|
| A1 | Poor quality material | D1 | Poor designer's skills |
| A2 | Poor quality part | D2 | Poor information communication |
| A3 | Poor assembly | D3 | Beyond design capacity |
| A4 | Improper handling during transport and storage | D4 | Other reasons |
| A5 | Other reason | E1 | Poor instructions from manufacturer |
| B1 | Too high environment temperature | E2 | Poor configuration person's skills |
| B2 | Water invaded | E3 | Other reasons |
| B3 | Dirt invaded | F1 | Pumping running without oil feeding |
| B4 | Other reasons | F2 | Pump broken by an accident |
| C1 | Poor operator's skills | F3 | Oil tank leaking |
| C2 | Overloaded | F4 | Pump catches fire |
| C3 | Poor maintenance | | |
| C4 | Error adjustment | | |
| C5 | Poor installation | | |
| C6 | Other reasons | | |

Step 3: What is wrong in the “misapplication” stage?




Note: Codes are defined in Table 22.

Figure 25. Fishbone Diagram Step 3 (Focus on the Misapplication Question).

Table 22. Code Definitions for Figure 25.

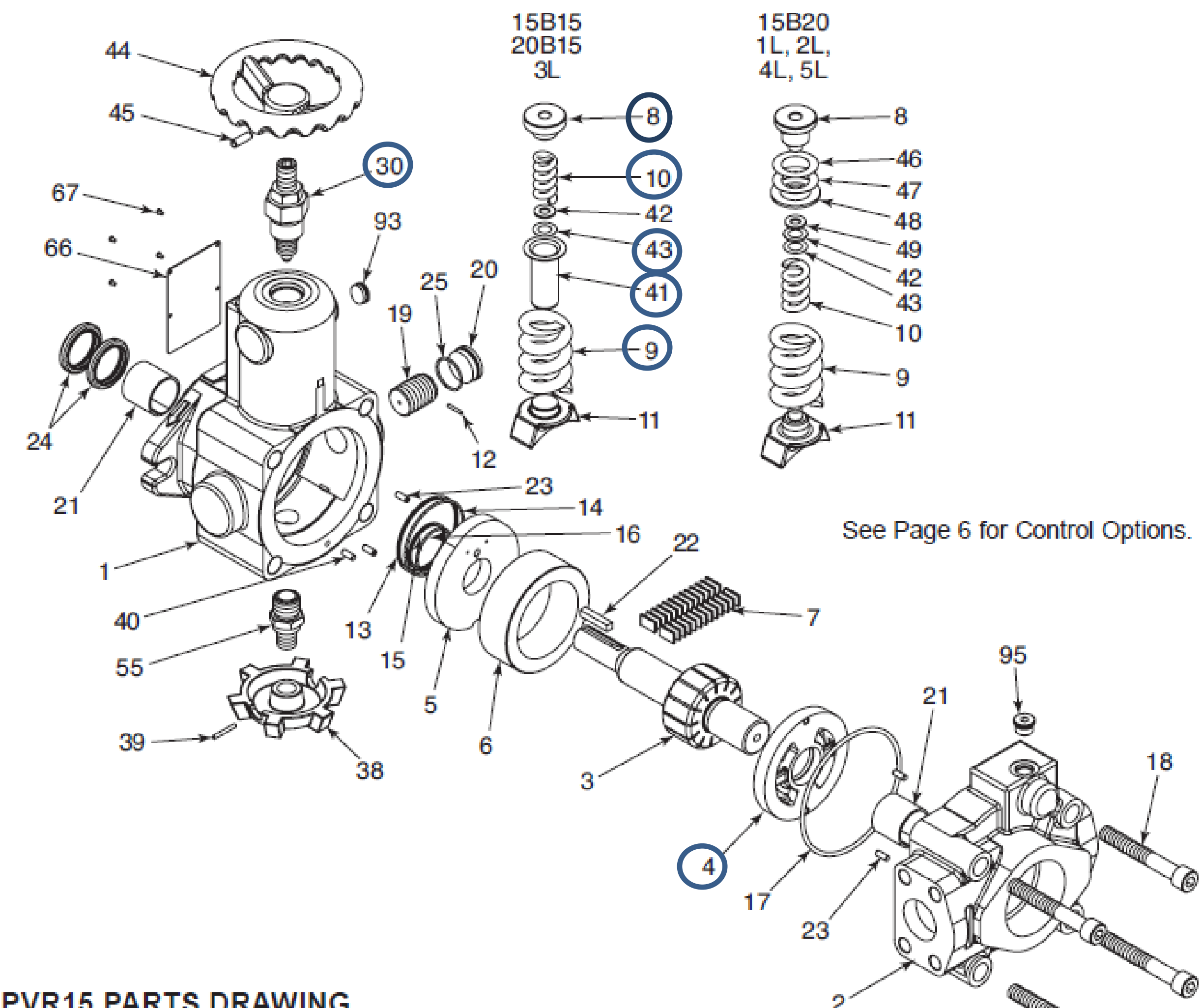
| Code | Description | Code | Description |
|---|---|---|---|
| A1 | Poor instructions from manufacturer | D1 | Poor operator's skill |
| A2 | Parts size error | D2 | Operation beyond design capacity |
| A3 | Poor installation person's skills | D3 | Equipment system failure |
| A4 | Poor installation tools | D4 | Other reasons |
| A5 | Other reason | E1 | Poor instructions from manufacturer |
| B1 | Poor maintenance person's skills | E2 | Poor operator's skills |
| B2 | Poor maintenance tools | E3 | The difficulty of operation is too high |
| B3 | Poor instructions from manufacturer | E4 | Other reasons |
| B4 | Other reasons | F1 | Operator was inattentive to the job |
| C1 | Poor operator's skills | F2 | Operator did not follow the regulations |
| C2 | Poor instructions from manufacturer | F3 | The equipment was abused |
| C3 | Poor adjustment tools | F4 | An accident happened |
| C4 | It is too difficult to adjust properly | | |
| C5 | Wrong pressure indicates in gauge | | |
| C6 | Other reasons | | |

The Continental Hydraulics Model PVR15-Flanged Series pump was sent to a repair facility. The pressure adjustment screw assembly was damaged. This required replacing the spring retainer (item # 41), the follow spring (item # 10), the spring seat (item # 8), the governor spring (item # 9), the port plate (item # 4) and the shim (item # 43).

The root cause analysis found that the cause from an over tightened assembly (item 30). Also, if the assembly is installed incorrectly, it will not work properly.

The conclusion is that the reason for the failure was caused by the pressure adjustment screw (item # 30) being over tightened and as a result it broke.

**PVR15 PARTS DRAWING**




**PVR15 PARTS DRAWING**
**Codes 12, 21, 22, 31** Tandem Mounting

Source:
http://www.continentalhydraulics.com/UserFiles/File/Manuals/Pumps/265294%20REV%207-08%20PVR15%20Flanged%20Service%20Manual.pdf

Figure 26. Maintenance and Repair Notes.

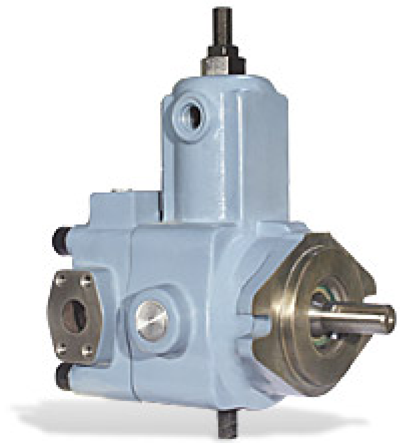


Figure 27. The Continental Hydraulics Model PVR15-Flanged Series Pump[35].

### 4.2.1 The deep draw machine configuration.

The deep draw machine consists of the machine frame, the hydraulic system, the dynamic system, and the lubrication system. A hydraulic cylinder pulls the cup-shaped raw material into a model hole.

To sustain the stability of the piston rod's stroke, the piston rod is held in place by a piece that can slide along two fixed sliding rods, which are parallel to the entire travel of piston rod. When this piece is moving along the sliding rods, it needs lubricant oil on the sliding rods in order to reduce friction and to avoid wearing down the involved parts.

---

[35] Imagine source: http://www.continentalhydraulics.co.uk/pvr_vane.htm

The lubricant system consists of an oil tank, a pump driving by a small motor, an injector, and feeder hoses.

The hydraulic system consists of a hydraulic pump, a hydraulic cylinder, a solenoid valve, a relief valve, a pressure gauge, four hoses, and three limit switches. The hydraulic cylinder is driven by the hydraulic pump and its stroke is limited by the three limit switches. The three limit switches control the solenoid valve. The pump is driven by a motor.

### 4.2.2 Using the FMEA tool.

The FMEA tool was used to determine the reliability of the Deep Draw Machine. The detailed results are provided in Table 23. The table was populated by using Equation 1 and the values from Tables 8 through 10. The result of the FMEA analysis indicated that the pressure adjusting assembly (item 14 in Table 23) has the highest RPN value (RPN value = 72).

A special FMEA analysis (see Figure 28) used the information from Table 23 to explicitly indicate the hierarchical relationship of the pressure adjusting assembly (item 14 in Table 23) to the rest of the pump. This extra analysis would enable one to determine how to improve the pump's reliability via the design modification method.

### 4.2.3 Application of the Stepwise Methodology

To solve the problem of the over tightened pressure adjusting screw, the stepwise methodology for equipment maintenance could be used for generating possible design modification solutions. This tool must be applied for each level of the Deep Draw Machine. Tables 25 through 28 show each application. Table 29 summarizes these efforts and narrows them down to the viable solutions.

Table 23.  FMEA Hierarchical Analysis of Deep Draw Machine.

| Whole machine level | Deep Draw Machine | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| System level | Motor and power control system | | | | | | | Lubricant system | | | | Hydraulic system | | | | | | | | Machine frame |
| Component level | Motor | | | Power control system | | | | Motor & Pump | | Oil tank and Hose | | Pump | | | Cylinder | Solenoid valve | Pressure gauge | Hose | Limit switch | Frame |
| Parts level* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 20 | 21 |
| Failure* | a | b | c | d | e | f | g | h | i | j | k | l | m | n | o | p | r | s | t | u |
| Occurrence (O) | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 1 | 1 | 1 |
| Severity (S) | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 7 | 7 | 1 | 7 | 8 | 1 | 8 | 7 | 8 | 7 | 7 | 7 | 1 |
| Detectable (D) | 4 | 4 | 3 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 3 | 1 | 3 | 2 | 2 | 1 | 1 | 2 | 1 |
| O × S × D | 32 | 32 | 24 | 8 | 8 | 16 | 16 | 14 | 14 | 1 | 7 | 24 | 1 | 72 | 14 | 16 | 7 | 7 | 14 | 1 |

*See Table 24 for the definitions of the above codes.

Table 23. Continued. FMEA Hierarchical Analysis of Deep Draw Machine

| **System level** | Motor and power control system | | | | | | | Lubricant system | | | | Hydraulic system | | | | | | | | Machine frame |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Component level | Motor | | | Power control system | | | | Motor & Pump | | Oil tank and Hose | | Pump | | | Cylinder | Solenoid valve | Pressure gauge | Hose | Limit switch | Frame |
| Parts level* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 20 | 21 |
| Failure* | a | b | c | d | e | f | g | h | i | j | k | l | m | n | o | p | r | s | t | u |
| RPN for Part level | 32 | 32 | 24 | 8 | 8 | 16 | 16 | 14 | 14 | 1 | 7 | 24 | 1 | 72 | 14 | 16 | 7 | 7 | 14 | 1 |
| RPN for Component level | 88 | | | 48 | | | | 28 | | 8 | | 97 | | | 14 | 16 | 7 | 7 | 14 | 1 |
| RPN for System level | 136 | | | | | | | 36 | | | | 155 | | | | | | | | 1 |
| Order of RPN | #2 | | | | | | | #3 | | | | #1 | | | | | | | | #4 |

*See Table 24 for the definitions of the above codes.

Table 24.  Code Definitions for Table 23.

| Part level | Description | Failure | Description |
|---|---|---|---|
| 1 | 2 Motor bearings | a | Motor bearing failure |
| 2 | Motor stator | b | Motor stator burn down |
| 3 | Motor rotor | c | Motor rotor damaged |
| 4 | Air switch | d | Air switch failure |
| 5 | Contactor | e | Contactor failure |
| 6 | Overload relay | f | Overload relay failure |
| 7 | Fuse | g | Fuse burn down |
| 8 | Mini Motor for driving lubricant pump | h | Mini motor failure |
| 9 | Lubricant pump | i | Lubricant pump failure |
| 10 | Lubricant oil tank | j | Lubricant oil tank leaking |
| 11 | Hydraulic hose | k | Hydraulic hose leaking |
| 12 | Hydraulic pump rotor | l | Hydraulic pump rotor failure |
| 13 | Hydraulic pump house | m | Hydraulic pump house damaged |
| 14 | Hydraulic pump adjustment assembly | n | Hydraulic pump adjustment assembly damaged |
| 15 | Piston and piston rod of Hydraulic cylinder | o | Piston and piston rod of Hydraulic cylinder damaged |
| 16 | Solenoid valve | p | solenoid valve failure |
| 17 | Relief valve | q | Relief valve failure |
| 18 | Pressure gauge | r | Pressure gauge damaged |
| 19 | Hydraulic hose | s | Hydraulic hose |
| 20 | Limit switch for locating the position of piston rod end | t | Limit switch failure |
| 21 | Frame | u | Fame damaged |

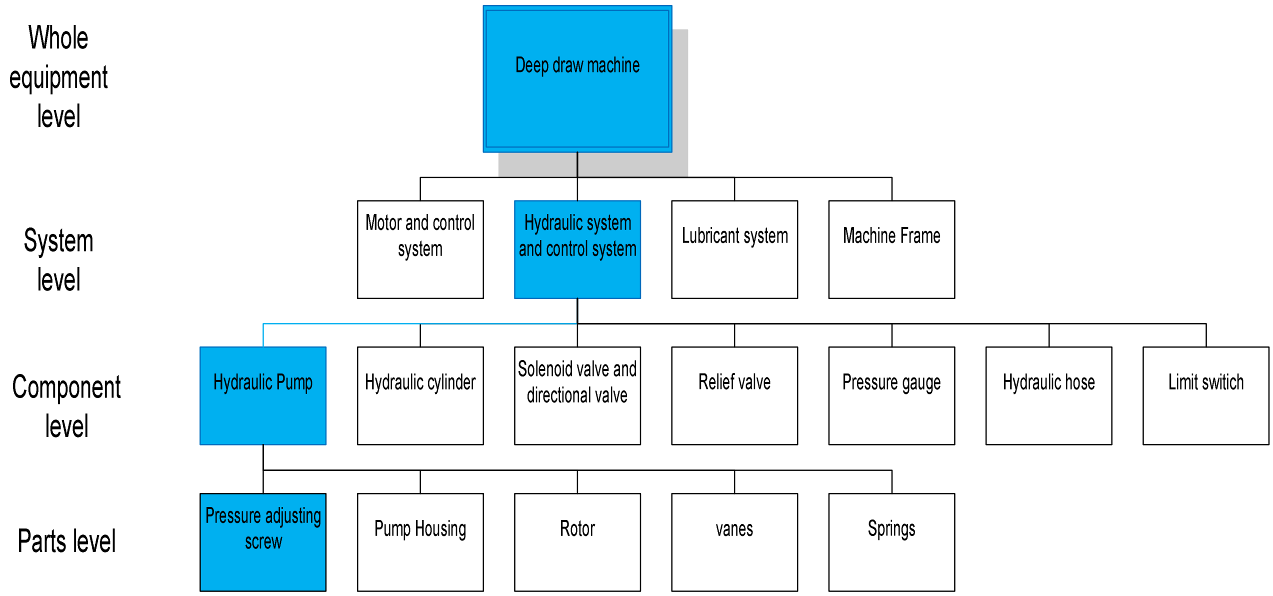



Figure 28. FMEA Analysis Procedure on the Deep Draw Machine.

Table 25. Level 1: Solution for the Part Level.

| Level 1: Solution for the Part (the Pressure Adjustment Screw) | |
|---|---|
| Number | Description of solutions |
| 1 | **Eliminating root cause.**<br>To eliminate the root cause of the over tightened pressure adjusting screw, one could consider adding a distinct mark to show where the adjustment screw should not advance beyond. When the mark on the screw aligns with the mark on the housing, then the screw has been sufficiently tightened.<br>This would require knowing that special point and this would require painting all of the screws and pump housings. |
| 2 | **Preventing or decreasing the impact of the root causes on the equipment.**<br>To prevent or to mitigate the impact of the over tightened adjustment screw, one could consider adding a stopper on the adjustment screw that would prevent a person from over tightening the adjustment screw.<br>This would require adding this stopper at the screw production plant or being added at the user level. In addition to determining where to add the stopper, one must determine where exactly to install the stopper. |
| 3 | **Increasing the equipment's' resistance to the root cause.**<br>There are no viable approaches for this using the nine alternative solutions |
| 4 | **Modifying equipment for more sensitive detection.**<br>There are no viable approaches for this using the nine alternative solutions. |
| 5 | **Improving sensitivity and reliability of detecting tools instruments.**<br>There are no viable approaches for this using the nine alternative solutions. |
| 6 | **Improving the environment for safe and effective inspection.**<br>There are no viable approaches for this using the nine alternative solutions. |
| 7 | **Modifying facility and equipment to allow quick repair.**<br>There are no viable approaches for this using the nine alternative solutions |
| 8 | **Adding a resilient system.**<br>There are no viable approaches for this using the nine alternative solutions. |
| 9 | **Adding butter inventory.**<br>There are no viable approaches for this using the nine alternative solutions. |

Table 26. Level 2: Solution for the Component Level

| Level 2: Solution for the Component Level (the pump) | |
|---|---|
| Number | Description of solutions |
| 1 | **Eliminating root cause.**<br>To eliminate the root cause for component level, one could consider using a different hydraulic pump model that comes with a better pressure adjustment screw configuration or with a different approach for adjusting the relief valve. Feasibility studies would be needed to explore whether such a hydraulic pump exists, to ascertain whether the proposed hydraulic pump would be a suitable replacement, and to assess what might be the operating costs of any proposed replacement hydraulic pump. |
| 2 | **Preventing or decreasing the impact of the root causes on the equipment.**<br>To prevent or to mitigate the impact of the root causes on the component level, one could consider adding a vibration sensor on the pump housing, which would monitor the vibration level. When the vibration amplitude level is above a certain threshold, then a signal would trigger an alarm (Woods, 2000) . When operator hears the alarm, the person would take the appropriate actions such as to loosen the pressure adjustment screw immediately. Hence the pressure adjustment screw could be prevented from being too tightly adjusted. The problem is that the damage may already been done when the alarm condition is reached. Another problem is that the operator may not know how far to loosen the pressure adjustment screw. If the effort is not enough, damage will still be done although not as fast. On the other hand, turning the adjustment screw too much could result in other problems. |
| 3 | **Increasing the equipment's' resistance to the root cause.**<br>There are no viable approaches for this using the nine alternative solutions. |
| 4 | **Modifying equipment for more sensitive detection.**<br>There are no viable approaches for this using the nine alternative solutions. |
| 5 | **Improving sensitivity and reliability of detecting tools instruments.**<br>There are no viable approaches for this using the nine alternative solutions. |
| 6 | **Improving the environment for safe and effective inspection.**<br>There are no viable approaches for this using the nine alternative solutions. |
| 7 | **Modifying facility and equipment to allow quick repair.**<br>There are no viable approaches for this using the nine alternative solutions |

Table 27 Continued. Level 2: Solution for the Component Level

| **Level 2: Solution for the Component Level (the pump)** | |
|---|---|
| Number | Description of solutions |
| 8 | **Adding a resilient system.**<br>Since the company runs the production line only eight hours a day and since the company has several redundant machines, adding a redundant pump is not necessary. |
| 9 | **Adding butter inventory.**<br>There are no viable approaches for this using the nine alternative solutions. |

Table 27. Level 3: Solution for the System Level

| Level 3: Solution for the System Level (the Hydraulic System) | |
|---|---|
| Number | Description of solutions |
| 1 | **Eliminating root cause.** To eliminate the root cause for the system level, one could consider adding a relief valve to the system so that the pressure is adjusted via this means instead of the pressure adjusting screw. A cover could be added that would prevent the operator from having access to the pressure adjustment screw. The result is that only a professional technician would be permitted to access this part of the pump. To do this would receive the existence of an appropriate relief valve, the ability for the pump to accept this modification, and someone to install the relief valve. Also if the decision is made to add a cover, then the same three issues would need to be addressed for this item. |
| 2 | **Preventing or decreasing the impact of the root causes on the equipment.** To prevent or to mitigate the impact of the root causes on the system, one could consider adding a vibration sensor on the pump housing, which would monitor the vibration level. When the vibration amplitude level is above a certain threshold, then a signal would trigger a relay that would switch off the power supply. With the motor turned off, developing damage from an over tighten pressure adjustment screw has been stopped. The problem is that the damage may already been done when the shutdown condition is reached. Another problem is that the operator may perceive this as a transient event and decide to restart the motor. Another problem is that the maintenance person may not be present and he or she is present may not be able ascertain what caused the system shut down. |
| 3 | **Increasing the equipment’s’ resistance to the root cause.** There are no viable approaches for this using the nine alternative solutions. |
| 4 | **Modifying equipment for more sensitive detection.** There are no viable approaches for this using the nine alternative solutions. |
| 5 | **Improving sensitivity and reliability of detecting tools instruments.** There are no viable approaches for this using the nine alternative solutions. |
| 6 | **Improving the environment for safe and effective inspection.** There are no viable approaches for this using the nine alternative solutions. |
| 7 | **Modifying facility and equipment to allow quick repair.** There are no viable approaches for this using the nine alternative solutions |

Table 28 Continued. Level 3: Solution for the System Level

| Level 3: Solution for the System Level (the Hydraulic System) | |
|---|---|
| Number | Description of solutions |
| 8 | **Adding a resilient system.**<br>Since the company runs the production line only eight hours a day and since the company has several redundant machines, adding a redundant hydraulic system is not necessary. But it might be wise to consider adding a parallel relief valve that could protect the pump and thus the hydraulic system from an overload situation. That is, a failing relief valve may not draw attention to itself while the system is slowly degrading into a serious situation. |
| 9 | **Adding butter inventory.**<br>There are no viable approaches for this using the nine alternative solutions. |

Table 28. Level 4: Solution for the Entire Machine

| Level 4: Solution for the Entire Machine (Deep draw machine) | |
|---|---|
| Number | Description of solutions |
| 1 | **Eliminating root cause.**<br>There are no viable approaches for this using the nine alternative solutions. |
| 2 | **Preventing or decreasing the impact of root causes on equipment.**<br>There are no viable approaches for this using the nine alternative solutions. |
| 3 | **Increasing the equipment's' resistance to the root cause.**<br>There are no viable approaches for this using the nine alternative solutions. |
| 4 | **Modifying equipment for more sensitive detection.**<br>There are no viable approaches for this using the nine alternative solutions. |
| 5 | **Improving sensitivity and reliability of detecting tools instruments.**<br>There are no viable approaches for this using the nine alternative solutions. |
| 6 | **Improving the environment for safe and effective inspection.**<br>There are no viable approaches for this using the nine alternative solutions. |
| 7 | **Modifying facility and equipment to allow quick repair:**<br>There are no viable approaches for this using the nine alternative solutions. |
| 8 | **Adding a resilient system.**<br>Since the company runs the production line only eight hours a day and since the company has several redundant machines, adding another redundant machine is not necessary. |
| 9 | **Adding butter inventory.**<br>There are no viable approaches for this using the nine alternative solutions. |

Table 29. Summary of all Viable Solutions

| **Level** | **FMEA Hierarchical Analysis** | **Nine Alternative Solutions for the Different Level** |
|---|---|---|
| The Whole Equipment level | Deep draw machine | None |
| System Level | Hydraulic system | Solution 1: Adding a relief valve in the system, and using it to adjust the pressure instead of using the pressure adjusting screw on the hydraulic pump (A1).<br><br>Solution 2: Adding a vibration sensor to control the motor operations (A2).<br><br>Solution 3: Base on solution 1, adding a redundant relief valve and gauge (A2). |
| Component Level | Pump | Solution 4: Base on solution 1, using a different hydraulic pump model (A1).<br><br>Solution 5: Adding a vibration sensor for triggering an alarm (A2). |
| Part Level | Pressure adjusting screw | Solution 6: Adding a stopper to the actual pressure adjustment screw (A2).<br><br>Solution 7: Adding a distinct mark on the pressure adjustment screw and on the housing (A1). |

### 4.2.4 Using the FMEA risk analysis tool.

The FMEA tool was also used to calculate the change in the reliability of relevant parts, components and systems of the deep draw machine, before and after implementation of each of seven solutions. Tables 30 through 34 show the changes in RPNs (with reference to Table 23) when each of solutions 1 through 7 has been implemented.

Similar to the method used in Table 23, Tables 30 through 34 are populated by using Equation 1 and the values from Tables 8 through 10.

Table 35 summarizes all changes in reliability from Tables 30 through 34. The table also reflects comparison of reliability among seven solutions.

Table 30. The change of RPN when adopting solution 1♣

| Whole machine level | Deep Draw Machine | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| System level | Motor and power control system | | | | | | | Lubricant system | | | | Hydraulic system | | | | | | | | | Machine frame |
| Component level | Motor | | | Power control system | | | | Motor & Pump | | Oil tank and Hose | | Pump | | | Cylinder | Solenoid valve | Relief valve | Pressure gauge | Hose | Limit switch | Frame |
| Parts level* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| Failure* | a | b | c | d | e | f | g | h | i | j | k | l | m | n | o | p | q | r | s | t | u |
| Occurrence (O) | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | **3 → 1** | 1 | 1 | 0 →1 | 1 | 1 | 1 | 1 |
| Severity (S) | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 7 | 7 | 1 | 7 | 8 | 1 | 8 | 7 | 8 | 0 →2 | 7 | 7 | 7 | 1 |
| Detectable (D) | 4 | 4 | 3 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 3 | 1 | 3 | 2 | 2 | 0 →2 | 1 | 1 | 2 | 1 |
| O × S × D | 32 | 32 | 24 | 8 | 8 | 16 | 16 | 14 | 14 | 1 | 7 | 24 | 1 | **72 → 24** | 14 | 16 | 0 →4 | 7 | 7 | 14 | 1 |
| RPN for Component level | 88 | | | 48 | | | | 28 | | 8 | | 97→49 | | | 14 | 16 | 0 →4 | 7 | 7 | 14 | 1 |
| RPN for System level | 136 | | | | | | | 36 | | | | 155→111 | | | | | | | | | 1 |
| Order of RPN | #2 → #1 | | | | | | | #3 | | | | #1 → #2 | | | | | | | | | #4 |

♣ See purple color number in column of part level #14. "→" indicates RPN change from before modification to after modification.
*See Table 24 for the definitions of the above codes.

Table 31. The change of RPN when adopting solution 2 or solution 5♣

| Whole machine level | Deep Draw Machine | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| System level | Motor and power control system | | | | | | | Lubricant system | | | | Hydraulic system | | | | | | | | Machine frame |
| Component level | Motor | | | Power control system | | | | Motor & Pump | | Oil tank and Hose | | Pump | | | Cylinder | Solenoid valve | Pressure gauge | Hose | Limit switch | Frame |
| Parts level* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 20 | 21 |
| Failure* | a | b | c | d | e | f | g | h | i | j | k | l | m | n | o | p | r | s | t | u |
| Occurrence (O) | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | **3** | 1 | 1 | 1 | 1 | 1 | 1 |
| Severity (S) | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 7 | 7 | 1 | 7 | 8 | 1 | 8 | 7 | 8 | 7 | 7 | 7 | 1 |
| Detectable (D) | 4 | 4 | 3 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 3 | 1 | 3 → 2 | 2 | 2 | 1 | 1 | 2 | 1 |
| O × S × D | 32 | 32 | 24 | 8 | 8 | 16 | 16 | 14 | 14 | 1 | 7 | 24 | 1 | **72 → 48** | 14 | 16 | 7 | 7 | 14 | 1 |
| RPN for Component level | 88 | | | 48 | | | | 28 | | 8 | | 97→73 | | | 14 | 16 | 7 | 7 | 14 | 1 |
| RPN for System level | 136 | | | | | | | 36 | | | | 155→131 | | | | | | | | 1 |
| Order of RPN | #2 → #1 | | | | | | | #3 | | | | #1 → #2 | | | | | | | | #4 |

♣ See purple color number in column of part level #14. "→" indicates RPN change from before modification to after modification.
∗See Table 24 for the definitions of the above codes.

Table 32. The change of RPN when adopting solution 3♣

| System level | Motor and power control system | | | | | | | Lubricant system | | | | Hydraulic system | | | | | | | | | Machine frame |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Component level | Motor | | | Power control system | | | | Motor & Pump | | Oil tank and Hose | | Pump | | | Cylinder | Solenoid valve | Relief valve © | Pressure gauge | Hose | Limit switch | Frame |
| Parts level* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| Failure* | a | b | c | d | e | f | g | h | i | j | k | l | m | n | o | p | q | r | s | t | u |
| Occurrence (O) | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | **3 → 1** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Severity (S) | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 7 | 7 | 1 | 7 | 8 | 1 | 8 | 7 | 8 | 1 | 7 | 7 | 7 | 1 |
| Detectable (D) | 4 | 4 | 3 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 3 | 1 | 3 | 2 | 2 | 1 | 1 | 1 | 2 | 1 |
| O × S × D | 32 | 32 | 24 | 8 | 8 | 16 | 16 | 14 | 14 | 1 | 7 | 24 | 1 | **72 → 24** | 14 | 16 | 1 | 7 | 7 | 14 | 1 |
| RPN for Component level | 88 | | | 48 | | | | 28 | | 8 | | 97→49 | | | 14 | 16 | 1 | 7 | 7 | 14 | 1 |
| RPN for System level | 136 | | | | | | | 36 | | | | 155→108 | | | | | | | | | 1 |
| Order of RPN | #2 → #1 | | | | | | | #3 | | | | #1 → #2 | | | | | | | | | #4 |

♣ See purple color number in column of part level #14. "→" Indicates RPN change from before modification to after modification.
*See Table 24 for the definitions of the above codes. © Redundant relief valve

Table 33. The change of RPN when adopting solution 4♣

| Whole machine level | Deep Draw Machine | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| System level | Motor and power control system | | | | | | | Lubricant system | | | | Hydraulic system | | | | | | | | | Machine frame |
| Component level | Motor | | | Power control system | | | | Motor & Pump | | Oil tank and Hose | | Pump | | | Cylinder | Solenoid valve | Relief valve | Pressure gauge | Hose | Limit switch | Frame |
| Parts level* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| Failure* | a | b | c | d | e | f | g | h | i | j | k | l | m | n | o | p | q | r | s | t | u |
| Occurrence (O) | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | **3 → 1** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Severity (S) | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 7 | 7 | 1 | 7 | 8 | 1 | 8 | 7 | 8 | 2 | 7 | 7 | 7 | 1 |
| Detectable (D) | 4 | 4 | 3 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 3 | 1 | 3 | 2 | 2 | 2 | 1 | 1 | 2 | 1 |
| O × S × D | 32 | 32 | 24 | 8 | 8 | 16 | 16 | 14 | 14 | 1 | 7 | 24 | 1 | **72 → 24** | 14 | 16 | 4 | 7 | 7 | 14 | 1 |
| RPN for Component level | 88 | | | 48 | | | | 28 | | 8 | | 97→ 49 | | | 14 | 16 | 4 | 7 | 7 | 14 | 1 |
| RPN for System level | 136 | | | | | | | 36 | | | | 155→111 | | | | | | | | | 1 |
| Order of RPN | #2 → #1 | | | | | | | #3 | | | | #1 → #2 | | | | | | | | | #4 |

♣ See purple color number in column of part level #14. "→" indicates RPN change from before modification to after modification.
*See Table 24 for the definitions of the above codes.

Table 34. The change of RPN when adopting solution 6 or 7♣

| Whole machine level | Deep Draw Machine | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| System level | Motor and power control system | | | | | | | Lubricant system | | | | Hydraulic system | | | | | | | | Machine frame |
| Component level | Motor | | | Power control system | | | | Motor & Pump | | Oil tank and Hose | | Pump | | | Cylinder | Solenoid valve | Pressure gauge | Hose | Limit switch | Frame |
| Parts level* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 20 | 21 |
| Failure* | a | b | c | d | e | f | g | h | i | j | k | l | m | n | o | p | r | s | t | u |
| Occurrence (O) | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | **3 → 1** | 1 | 1 | 1 | 1 | 1 | 1 |
| Severity (S) | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 7 | 7 | 1 | 7 | 8 | 1 | 8 | 7 | 8 | 7 | 7 | 7 | 1 |
| Detectable (D) | 4 | 4 | 3 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 3 | 1 | 3 | 2 | 2 | 1 | 1 | 2 | 1 |
| O × S × D | 32 | 32 | 24 | 8 | 8 | 16 | 16 | 14 | 14 | 1 | 7 | 24 | 1 | **72 → 24** | 14 | 16 | 7 | 7 | 14 | 1 |
| RPN for Component level | 88 | | | 48 | | | | 28 | | 8 | | 97→49 | | | 14 | 16 | 7 | 7 | 14 | 1 |
| RPN for System level | 136 | | | | | | | 36 | | | | 155→107 | | | | | | | | 1 |
| Order of RPN | #2 → #1 | | | | | | | #3 | | | | #1 → #2 | | | | | | | | #4 |

♣ See purple color number in column of part level #14. "→" indicates RPN change from before modification to after modification.
*See Table 24 for the definitions of the above codes.

Table 35. FMEA Risk Analysis of all Solutions

| level | Part level | | Component level | | System level | | Optimal order of all solutions |
|---|---|---|---|---|---|---|---|
| Solution | previous | new | previous | new | previous | new | |
| Solution 1 | 72 | 24 | 97 | 49 | 155 | 111 | #3 |
| Solution 2 | 72 | 48 | 97 | 73 | 155 | 131 | #4 |
| Solution 3 | 72 | 24 | 97 | 49 | 155 | 108 | #2 |
| Solution 4 | 72 | 24 | 97 | 49 | 155 | 111 | #3 |
| Solution 5 | 72 | 48 | 97 | 73 | 155 | 131 | #4 |
| Solution 6 | 72 | 24 | 97 | 49 | 155 | 107 | #1 |
| Solution 7 | 72 | 24 | 97 | 49 | 155 | 107 | #1 |

Ordinarily, when one uses FMEA risk analysis, the solution with the highest RPN value would be the top candidate for improvement since it has the direst consequences to the system. But if consideration is given only to those solutions that relate to the immediate problem, then one might find that the lowest RPN value becomes the top candidate for improvement since that would result in the highest system reliability, with regard to the very real problem on hand. Using that as the selection approach, then Solution 6 and Solution 7 would need to be implemented. If resources were sufficient, then Solution 3 could also be implemented.

### 4.2.5 Using the economic assessment tool.

For this case study, the production profit data was not available. However, the maintenance records and repair costs were made available. Treating cost avoidance as a profit made it possible to use the ROI formula (Equation 9).

#### *4.2.5.1 Finding the present worth of annual profit.*

Since the payments of annual profit are in the future, these need to be discounted to reflect the time value of the money (Newnan, Eschenbach, & Lavelle, 2004).

According to the maintenance files, the pump fails twice a year. The mean time between failures (MTTF) is calculated by dividing the number of events into the time period (12/2), which is 6 months. The mean time to repair or the mean time to recovery figure came from the maintenance records and this has been about five days. The average cost for repairing the pump came from the maintenance records and this has been roughly $1,000. The figure of 8% interest per year is more an arbitrary figure; an interest figure is needed for the present worth formula (Equation 10) and any figure would work, but the figure of 8% is typical of a healthy return from the stock market. Using 8% means the interest figure for half a year is 3.923%. Figure 29 shows how the present worth of annual profit was calculated based on these values.

$$P = A\left[\frac{(1+i)^N - 1}{i(1+i)^N}\right] \quad (10)$$

For the year: $P_1 = 1{,}000\left[\frac{(1+0.08)^1 - 1}{0.08(1+0.08)^1}\right] = 925.925$

For the half year: $P_2 = 1{,}000\left[\frac{(1+0.03923)^1 - 1}{0.03923(1+0.03923)^1}\right] = 962.25$

Adding the two periods together:

P = $P_1 + P_2$ = 925.925 + 962.25 = $1,888.177

To the nearest whole penny: P = $1,888.18

Figure 29. Calculation Steps for the Present Worth of Annual Profit.

The significance of P (P = $1,888.78) is that if the pump could be modified so as to prevent the every six-month failure, then the “annual profit” would be $1,888.78. Since this is not a true profit, it is actually an outlay that is avoided every six months. Hence, if this value is compared with the modification investment for the same time period, then that would reflect the time value of money (Newnan, Eschenbach, & Lavelle, 2004).

#### *4.2.5.2 Economic assessment for each solution.*

The ROI formula (Equation 9) could be applied to the seven solutions. This would show what the payback is for each solution. The information could be used in the decision process. Or the information could be used for determining which solution would be the

best financially. The underlying assumption is that the investment in a solution would be valid for the year and that the benefit would continue each day in that year.

#### *4.2.5.2.1 Solution 1 ROI.*

There is no one relief valve present on the machine. The investment of adding a relief value is roughly $350. From Figure 30, the calculated return rate of investment for Solution 1 is roughly 4.394 times. That means the net profit is 4.394 times the investment for the same time period. If there is no maintenance fee added to relief valve in the second year, then the investment can be counted as $1 for the second year calculation.

$$[\![\text{Solution 1}]\!]\_\text{ROI} = (1888.177-350)/350=4.394$$

Since this is a ratio, we are rounding it to the nearest whole number: 4.4

Figure 30. Calculations for the Solution 1 ROI.

#### *4.2.5.2.2 Solution 2 ROI.*

Adding a vibration sensor for controlling the motor would cost about $500. From Figure 31, the calculated return rate of investment for Solution 2 is 2.773 times. That means the net profit is 2.773 times the investment for the same time period. If the vibration

sensor does not need to be replaced in the second year, then the investment can be counted as $1 for the second year calculation.

*4.2.5.2.3 Solution 3 ROI.*

Adding a relief value and a redundant relief valve would cost about $700. From Figure 32, the calculated return rate of investment for Solution 3 is 1.697 times. That means the net profit is 1.697 times the investment for the same time period. If there is no maintenance fee added to relief valve in the second year, then the investment can be counted as $1 for the second year calculation.

$$〚Solution\ 2\ 〛\_ROI\ =\ (1888.177 - 500)/500 = 2.773$$

Figure 31. Calculations for the Solution 2 ROI.

$$〚Solution\ 3\ 〛\_ROI\ =\ (1888.177 - 700)/700 = 1.697$$

Figure 32. Calculations for the Solution 3 ROI.

#### *4.2.5.2.4 Solution 4 ROI.*

Adding a different hydraulic pump model would cost about $4,000. From Figure 33, the calculated return rate of investment for Solution 4 is -0.528 times. That means for the year of purchase, the net profit is actually a net loss in the sense that none of expenditures is possible to recoup.

#### *4.2.5.2.5 Solution 5 ROI.*

Adding a vibration sensor that could trigger an alarm would cost about $500. From Figure 34, the calculated return rate of investment for Solution 5 is 2.773 times. That means the net profit is 2.773 times the investment for the same time period. If the vibration sensor does not need to be replaced in the second year, then the investment can be counted as $1 for the second year calculation.

$$[\![\text{Solution 4}]\!]\_\text{ROI} = (1888.177 - 4000)/4000 = -0.528$$

Figure 33. Calculations for the Solution 4 ROI.

#### *4.2.5.2.6 Solution 6 ROI.*

Adding a stopper to the pressure adjustment screw would cost about $10. From Figure 35, the calculated return rate of investment for Solution 6 is 187.817 times. That means the net profit is 187.817 times the investment for the same time period. If the stopper screw combination does not need to be replaced in the second year, then the investment can be counted as $1 for the second year calculation.

#### *4.2.5.2.7 Solution 7 ROI.*

Adding a distinct mark to the pressure adjustment screw and to the housing would cost about $10. From Figure 36, the calculated return rate of investment for Solution 7 is 187.817 times. That means the net profit is 187.817 times the investment for the same time period. If the stopper screw combination does not need to be replaced in the second year, then the investment can be counted as $1 for the second year calculation.

$$[\![\text{Solution 5}]\!]\_\text{ROI} = (1888.177 - 500)/500 = 2.773$$

Figure 34. Calculations for the Solution 5 ROI.

$$[\text{Solution 6}]_{ROI} = (1888.177 - 10)/10 = 187.817$$

Figure 35. Calculations for the Solution 6 ROI.

$$[\text{Solution 7}]_{ROI} = (1888.177 - 10)/10 = 187.817$$

Figure 36. Calculations for the Solution 7 ROI.

**4.3. Solutions suggested from the analysis of the possible investments**

Table 36 shows the ROI values and the RPN values for each solution. The optimal solutions are Solutions 6 and 7, since their RPN values are the lowest and the ROI values are highest. Yet these two solutions may not provide a foolproof approach for adjusting the pressure throughout the day and in different types of production runs. In light of these issues, Solution 1 may be the best solution. A close second is Solution 3 since it provides a very good method for improving the reliability of the hydraulic system and thus avoids “operator errors.”

If sufficient resources are available, then a comprehensive approach could be done. The best combination would be Solutions 1, 6, and 7. If the maintenance department

requires higher reliability and the need to avoid all possibilities of problems with the use of the pressure adjustment screw, then Solution 3 should be added, too.

The company had been using a reactive maintenance strategy for maintaining the pump. The calculations for the seven solutions clearly demonstrated that any design modification would be better than any reactive maintenance strategy. Even though Solution 4 ROI value was a negative number for the first and second year, in the third year the ROI would become a positive number.

Table 36. Comparison of ROI and RPN for all solutions

| Solution Number | ROI | System level RPN |
|---|---|---|
| Solution 1 | 4.394 | 111 |
| Solution 2 | 2.773 | 131 |
| Solution 3 | 1.697 | 108 |
| Solution 4 | -0.528 | 111 |
| Solution 5 | 2.773 | 131 |
| Solution 6 | 187.817 | 107 |
| Solution 7 | 187.817 | 107 |

# Chapter 5 Conclusion

In this chapter, the thesis work is summarized, conclusions are provided, and suggestions for future research are provided.

## 5.1 Summary of Research

The main purpose of this thesis is to develop a methodology for assisting the maintenance department for improving equipment reliability through design modification.

All equipment will pass through three lifetime stages. These are the perfect running status, the degradation status, and the ceasing functioning status (Fischer, Besnard, & Bertling, 2012). The offered methodology as described in this thesis would address unique situations associated with each status.

The proposed methodology addressed the challenges of trying to prolong the perfect service status as long as possible. The methodology uses three approaches, which are eliminating the root cause, preventing the cause from affecting other components of the machine, and increasing the resiliency of equipment to resist the degradation causes.

A machine may have several systems, a system may have several components and a component may have several parts. Any effort that attempts to prolong the equipment's lifetime must address these layers. The case study in Chapter 4 demonstrated that the

equipment’s lifetime could be prolonged by applying root cause avoidance strategy to the part level, to the component level, and to the system level.

The proposed methodology addressed the challenges of trying to identify any defect as early as possible. The alternative solutions are modifying the equipment to allow the defect to be detected more easily; modifying the detecting instruments for the purpose of improving their sensitivity and intelligence; and modifying the environment to allow the defect detecting operators to work in a safer place and to have an easier access to the equipment.

The proposed methodology addressed the challenges of trying to minimize the losses that come when the equipment totally shuts down. The approaches are adding butter inventory, adding a resilient system, and adding to the tool kit tools that enable the equipment’s lost function to be recovered sooner.

In some situations, redundancy could be achieved by adding to the part level or to the component level or to the system level. These efforts would avoid the need to replace a piece of equipment or a major sub system.

Although the proposed methodology does not seek out and identify problems, its strength is that it can generate several solutions. The solutions are presented with ROI values. The decision makers can view all of the options and determine which solution or solutions should be implemented.

## 5.2 Advantages and Disadvantages

The major advantages of the proposed methodology are

1. It can assist the equipment manufacturer to improve the equipment reliability during the design process by using FMEA to analyze the design. Then the proposed method could be used to generate possible modification options.
2. It can assist the equipment operator to improve the equipment reliability by using FMEA to assess when the equipment or a sub entity of the equipment might fail. The presented information addresses the potential risk and identifies the probable cause. The proposed tool uses other analysis tools such as FTA and the fishbone diagram to render opinions.
3. It can assist maintenance departments to develop plans for the day when a piece of equipment fails completely.

The major disadvantages of the proposed methodology are:

1. It cannot function as a complete system. This methodology must be combined with FMEA in order to generate all possible design modification solutions.
2. It cannot identify the cause of the failure by itself. This methodology must be based on results provided by root cause analysis tools such as: FAT, fishbone diagram, and other tools.

## 5.3 Recommendations and Future Research Directions

Future research could focus on ways to combine the optimization models with the nine alternative solutions and with the FMEA hierarchical analysis of equipment structure.

Achieving this would create a tool that is capable of determining the optimal solution, which would aid in maximizing the organizational profit.

Another possible research area would be the Design of Experiments (DOE) tool. Methodology from this thesis provides nine alternative solutions for design modification which could be implemented by equipment manufacturers to come up with the design of a new model that has improved reliability.

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# Appendices

# Appendix 1 The Theory of Inventive Problem Solving (TRIZ)

### A1.1 The Theory of Inventive Problem Solving (TRIZ)

This is a detailed presentation of the Theory of Inventive Problem Solving (TRIZ). TRIZ includes a methodology, a tool set, a knowledge base, and a model for generating new ideas. TRIZ is described in terms of principles and of laws. Genrich Altshuller named the laws as the "Laws of Technical System Evolution." The most important laws deal with the ideality of a system. There are numerous secondary sources that explain TRIZ, but these share very little in common. The TRIZ Journal (Barry, Domb, & Slocum, n.d.) labels the laws as the "Laws of Technical Evolution and Technology Forecasting." The Altshuller Institute for TRIZ Studies does not use a formal name for the names, but regards the laws more as "prevailing trends. (Litvin, Petrov, Rubin, & Fey, n.d.)" The Ideation International Inc. website (Ideation International, Inc, 2012) does not use the word "law," but considers TRIZ to be passé when it states that "the Ideation/TRIZ Methodology [has] move[d] beyond Classical TRIZ." and marked the emergence of Ideation/TRIZ as in the late 1980s. Vladimir Petrov (2002) wrote a paper that went beyond the efforts of Altshuller and others to present a multi-level scheme on the laws of system evolution Daniel Paez (2011) wrote that TRIZ has eight laws and one of these is the law of increasing degree of ideality. In Google's rendering of *Innovation on Demand: New Product Development Using TRIZ*, by Victor Fey and Eugene Rivin, on page 113 (2005)the list has nine laws. Wikipedia (the Wilimedia Foundation, Inc., 2013) mentions three categories of laws with the Law of increasing the degree of ideality of the system being under the category of kinematic laws. For the coverage of this topic,

heavy borrowing has been made of Glenn Mazur's website (2013), which pulled in 1995 to 1996 substantial material from the Ideation International Inc. website.

### A1.2 The Law of Increasing Ideality

This law is also known as the Law of Increasing the Degree of Ideality of the System. This law emphasize that technical systems evolve toward increasing degrees of ideality. Ideality is defined as "the quotient of the sum of the system's useful effects, $U_i$, divided by sum of its harm effects, $H_j$ 3.0 TRIZ: the Theory of Inventive Problem Solving), which is shown in Equation A.1 (Mazur, 2013):

$$Ideality = \frac{\sum U_i}{\sum H_j} \qquad \text{(A.12)}$$

Useful effects refer to the valuable results generated from the system's functioning. Harmful effects refer to the undesirables such as cost, footprint, consumed energy, pollution, and danger (same as the last cite). The ideal state has all benefits and no harmful effects. This state is what engineers and designers continually seek to create.

Glenn Maxur (2013) wrote about the conflict between benefits and trade-offs and about the need to work toward perfection:

> Useful effects include all the valuable results of the system's functioning. Harmful effects include undesired inputs such as cost, footprint, energy consumed, pollution, danger, etc. The ideal state is one where there are

only benefits and no harmful effects. It is to this state that product systems will evolve. From a design point of view, engineers must continue to pursue greater benefits and reduce cost of labor, materials, energy, and harmful side effects. Normally, when improving a benefit results in increased harmful effects, a trade-off is made, but the Law of Ideality drives designs to eliminate or solve any trade-offs or design contradictions. The ideal final result will eventually be a product where the beneficial function exists but the machine itself does not. The evolution of the mechanical spring-driven watch into the electronic quartz crystal watch is an example of moving towards ideality.

### A1.3 The TRIZ Step-by-Step Approach to Problem Solving

The TRIZ problem solving approach has three major steps. Figure 37 is an adapted extracted from the Maxur's website.


Figure 37. Steps for Solving Problems with TRIZ

## Appendix 2  Calculation and Proof for Bearings

### A2.1 Calculations and Proof for the Bearings Example

A bearing is a machine element that constrains or restricts certain motions between moving parts and non-moving parts to a desired motion. These could be small round metal balls or rollers. The service life is very important, because the components around the site of a failed bearing will wear excessively and will have sufficient damage to cause the system to overheat and to shut down. There are three methods available for calculating the lifetime of bearings under different loads and in various speed conditions.

Lundberg and Palmgren (Zaretsky, 1987) established the basic theory of the stochastic dispersion of bearing service lifetime, by using the Weibull Probability Distribution of metal fatigue. The Equation A.2 shows the complexity of this formula.

$$ln\frac{1}{S} \approx N^e \frac{\tau_0^c}{z_0^h} a z_0 l \qquad \text{(A.2)}$$

After Hertzian contact parameters have being substituted into Equation A.2, then Equation A.3 is a simpler form.

$$L_{10} = \left(\frac{C}{P}\right)^p \qquad \text{(A.3)}$$

Where:

$L_{10h}$ = 90th percentile of life in hours (the point at which only 10 percent of bearings in identical applications fail)

Note: Average life = 5 x L10h

C = Published catalog load rating

P = Effective load (actual force applied to the bearing)

*p* = 3 as a constant for ball bearings

*p* = 3 1/3 as a constant for other types of rolling element bearings

The most popular and very simple equation for calculating the service life of bearing is the following constant speed ISO bearing life equation (Equation A.4):

$$\text{Operating Hours, } \boldsymbol{L_{10h}} = \frac{1000{,}000}{60n} \times \left(\frac{C}{P}\right)^p = \frac{16{,}667}{n} \times \left(\frac{C}{P}\right)^p \textbf{ Hrs} \qquad \text{(A.4)}$$

Where:

n = speed of rotation, rpm

C = basic dynamic load rating, N

P = effective load (actual force applied to the bearing)

*p* = 3 as a constant for ball bearings

*p* = 3 1/3 as a constant for other types of rolling element bearings

Examining Equation A.3, we find that by maintaining the same speed, but increase the load (force) “P,” the bearing life will be exponential reduced. Figure 38 illustrates this. Thus, when the load is increase, the lifetime of the bearings are greatly reduced.

Doubling load (while maintaining a constant speed)

From Equation A.3: $16{,}667/n \times (C/2P)^p$ Hrs = $L_{10h}$ / 8 or 1/8 life for ball bearings.

Figure 38. Example of Bearings Lifetime Calculations.

### A2.2. Addressing Machinery Issues as a Way to Improve Bearings Lifetime

A root cause such as excessive vibration could be caused by an unbalanced component, by a shaft misalignment, by an incorrect belt tension, by a loose part, or by other sources. The vibration is actually causing excessive forces to be exerted upon the nearby bearings. If this root cause could be eliminated or reduced, then the bearing lifetime would dramatically increase. Also from Equation A.3, if the basic dynamic load rating "C" is increased and the other factors are unchanged, the result would be another solution for increasing the bearing lifetime.

L. Douglas Berry (1995) in his paper "Vibration Versus Bearing Life" makes a conclusion that the bearing lifetime could be increased by addressing machinery problems. When this is done, then both vibration levels and operating forces are reduced. Berry's Table 7 is reproduced as Table 37.

Table 37. Impact of Vibration Reduction on Bearing Life.

| % Reduction in Vibration | Percent Increase in Bearing Life | |
|---|---|---|
| | Ball Bearing Types | Other Rolling Element Bearing |
| 5 | 17 | 19 |
| 10 | 37 | 42 |
| 15 | 63 | 72 |
| 20 | 95 | 110 |
| 25 | 137 | 161 |
| 30 | 192 | 228 |
| 40 | 363 | 449 |
| 50 | 700 | 908 |

In some applications, a bearing life factor of over 90% reliability may be required. To meet this requirement, the bearing lifetime could be increased by the use of special bearing materials or by special construction techniques.

Not mentioned to this point is the role that lubrication places. The lubricate film prevents contact between the surfaces. This only works when the machinery is running in a constant mode. When the machine is turned on or off, the bearings will touch the nearby surfaces. Contact can occur if the direction of motion is changed. So lubrication must be considered in the issue of bearings lifetimes.

These factors must be considered when calculating bearing lifetimes. ISO 281 (Equation A.5) does this.

$$L_{na} = a_1 \times a_2 \times a_3 \times a_4 \times a_5 \times \frac{16{,}667}{n} \times \left(\frac{C}{P}\right)^p \textit{Hrs} \qquad (A.5)$$

Where:

$L_{na}$: Adjusted life rating in hours; adjusted for reliability, material and operating conditions

$a_1$ : Reliability factor

$a_2$ : Material/construction factor

$a_3$ : Lubrication factor

$a_4$ : Misalignment factor

$a_5$ : Load distribution factor

By examining the above ISO 281 equation (Equation A.5), it is clear that there are three methods available for increasing bearing lifetimes. These are:

- Eliminate or reduce the root causes arising from reliability $(a_1)$, lubrication $(a_3)$, misalignment $(a_4)$, load distribution $(a_5)$ sources.
- Improve the material or the construction $(a_2)$. Thus would result in an increase the basic dynamic load rating (C).
- Decrease the effective load (actual forces applied to the bearings, P) and the speed of rotation (n).

According to Equation A.5, one can estimate the bearing lifetime when values are changed. For example, doubling the rotating speed from 1,800 RPM to 3,600 RPM, would cut the bearing lifetime in half. But when the load on the bearings is reduced by

one-half, the result would be to increase the service life by eight times ($2^3$ or 2 x 2 x 2 = 8). Of course, these estimates of the bearings lifetime do not take into consideration other factors such as inadequate lubrication, lubricant contamination or damage from improper storage or installation techniques.

A detailed treatment of this topic is provided in Appendix 3 and an exhaustive treatment is provided by Randall (2011). This two items use the Brüel & Kjær Sound and Vibration Measurement A/S developed equations for calculating the frequency present in rolling element bearings. The treatment covers the five distinct rolling bearings frequencies (Natural, Ball-pass Outer-race Frequency (BPFO), Ball-pass Frequency Inner-race (BPFI), Ball-spin Frequency (BSF), and Fundamental Train Frequency (FTF)).

### A2.3 Conclusions Concerning Bearings Lifetime

Bearings load, dynamically changing loads, and vibratory sources have a significant effect upon the bearing lifetime and ultimately upon the machine life. Furthermore, the amount of vibration exhibited by a machine is directly proportional to the amount of force generated. In other words, if the unbalance force is doubled, the resultant vibration amplitude will be doubled also.

A machine's vibration should be of great concern to any maintenance department. If the unbalance force is cut in half, the unbalance-generated vibration would be cut in half also. Besides the benefit of having a smooth operating machine, there are three additional benefits:

1. Reducing the dynamic forces would increase the machine’s lifetime.
2. Amplitudes of machinery vibration are directly proportional to the amount of dynamic forces (loads) generated. If the force is halved, then the vibration is halved.
3. Lowering both the amount of generated dynamic forces and the amount of vibration would extend the time between failures.

# Appendix 3  Detailed Coverage on Rolling-Element Bearing Frequencies

### A3.1 Detecting Faulty Rolling-Element Bearings

Brüel & Kjær Sound and Vibration Measurement A/S [36] provides "integrated solutions for the measurement and analysis of sound and vibration (Brüel & Kjær Sound and Vibration Measurement A/S, n.d.)." In a white paper, entitled "Detecting Faulty Rolling-Element Bearings," has four equations (see Figure 39) for calculating the impact rates (Brüel & Kjær Sound and Vibration Measurement A/S, n.d.). Brüel & Kjær expanded that "faulty rolling-element bearings can be detected before [equipment] breakdown (Brüel & Kjær Sound and Vibration Measurement A/S, n.d.). Randall (2011) wrote that by calculating the frequency present in rolling element bearings that this could help to detect the early stages of failure.

In A3.2, we provided examples of rolling element bearings calculations. The real running status (perfect or degraded) of the bearings can be indicated by the result of the Brüel & Kjær calculations.

### A3.2 Detecting Faulty Rolling-Element Bearings

Figure 40 shows some examples of rolling-element bearings. Each of the four equations covers a different bearing construction. The different construction produces five distinct impact rates. There are five distinct rolling-element bearing frequencies present and Singh and Al Kazzar (2003) label these as Natural, Ball-pass Outer-race Frequency

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[36] The United States office renders the company name as "Bruel & Kjaer North America Inc. (HQ)."

(BPFO), Ball-pass Frequency Inner-race (BPFI), Ball-spin Frequency (BSF), and Fundamental Train Frequency (FTF).

The equations will be changed slightly in order to enhance the readers' understanding. The order of the discussions will follow Figure 39 equation order. The variables will be based on Figures A.4 through A.5.

#### *A3.2.1 Natural frequencies.*

New bearings are in a perfect state. All the pieces fit together and rubbing is not happening. The observed frequencies are generated by the impacts of the internal parts and the rolling element bearings. These are normally well above maximum frequency range and so are rarely observed in predictive maintenance. Brüel & Kjær did not provide any equations for this state of affairs.

#### *A.3.2.2 Ball-pass outer-race frequency (BPFO).*

BPFO is a frequency that is generated by the faulty or failing bearing outer-race when defective balls or rollers pass over the outer race. This will produce a different frequency (the outer race defect equation or the first equation in A.3). Equation A.6 shows the relationships of the various variables:

$$BPFO = \frac{n}{2} f_r \left[1 - \frac{d}{d_e} cos\,\beta\right] \qquad (13)$$

Where:

*n* is the number of balls or rollers in the bearing.

$f_r$ is the relative speed between outer and inner race.

β is the contact angle as shown in Figure 41 (b).

*d* is the diameter of ball bearings (Figure 40).

$d_e$ is the pitch diameter (Figure 40).

#### *A.3.2.2 Ball-pass frequency inner-race (BPFI)*

BPFI are balls or rollers that are in the inner race. This interaction between the ball-pass inner-race and the other nearby parts generate a different frequency. Inner race rotates at shaft speed, and the complete set of ball bearings passes at slower speed because of a fault on the inner race. Equation A.7 is a variation of the second equation or the inner race defect equation in Figure 39.

$$BPFI = \frac{n}{2} f_r \left[1 + \frac{d}{d_e} cos\, \beta\right] \qquad 14)$$

Where:

*n* is the number of balls or rollers in the bearing.

$f_r$ is the relative speed between outer and inner race.

β is the contact angle as shown in Figure 41 (b).

*d* is the diameter of ball bearings (Figure 40).

$d_e$ is the pitch diameter (Figure 40).

#### *A.3.2.3 Ball-spin frequency (BSF)*

BSF is a frequency generated by the fault of the bearings. Since the speed of rotation is determined by geometry of bearing, when each of defective balls or rollers rotates

around its own axis as it rolls around races, it will produce a special frequency. The third ball defect equation or the equation in Figure 39 or Equation A.9 follows:

$$BSF = \frac{1}{2}\frac{d_e}{d} f_r \left[1 - \left(\frac{d}{d_e}\right)^2 \times cos^2 \beta\right] \quad 15)$$

Where:

$f_r$ is the relative speed between outer and inner race.

β is the contact angle as shown in Figure 41 (b)

*d* is the diameter of ball bearings (Figure 40).

$d_e$ is the pitch diameter (Figure 40).

#### *A.3.2.4 FTF.*

FTF is a frequency generated by the fault of bearing cage as it rotates around the races. Some friction exists between the rolling elements and the races despite the presence of more than sufficient lubrication. The "cage detect" equation or the fourth equation in Figure 39 is changed slightly to become Equation A.10:

$$FTF = \frac{1}{2} f_r \left[1 - \frac{d}{d_e} cos\, \beta\right] \quad (16)$$

Where:

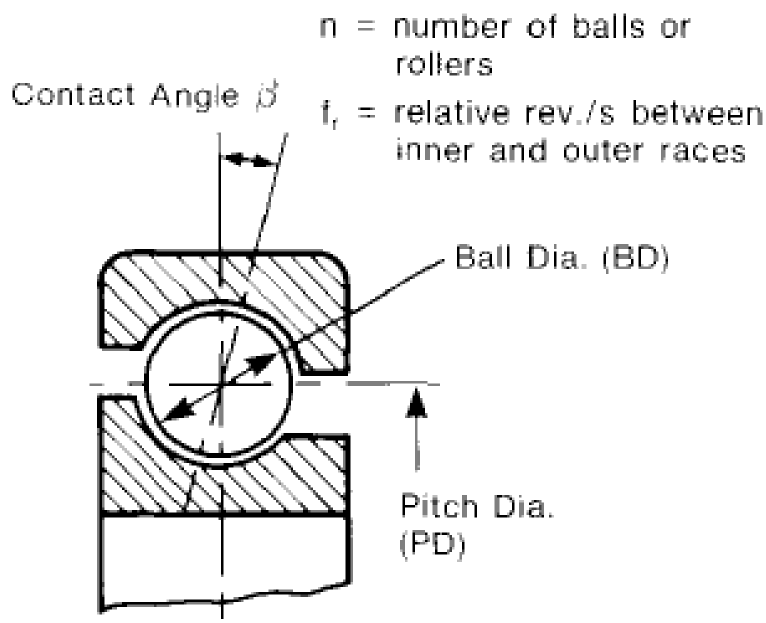
$f_r$ is the relative speed between outer and inner race.

β is the contact angle as shown in Figure 41 (b)

*d* is the diameter of ball bearings (Figure 40).

$d_e$ is the pitch diameter (Figure 40).

**Rolling-element bearing frequencies**




*Impact Rates f(Hz) (assuming pure rolling motion)*

For an outer race defect: $f\,(\mathrm{Hz}) = \frac{n}{2} f_r \left(1 - \frac{BD}{PD} \cos \beta\right)$

For an inner race defect: $f\,(\mathrm{Hz}) = \frac{n}{2} f_r \left(1 + \frac{BD}{PD} \cos \beta\right)$

For a ball defect: $f\,(\mathrm{Hz}) = \frac{PD}{BD} f_r \left[ 1 - \left(\frac{BD}{PD} \cos \beta\right)^2 \right]$

For a cage defect: $f\,(\mathrm{Hz}) = \frac{1}{2} f_r \left(1 - \frac{BD}{PD} \cos \beta\right)$

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Figure 39. Rolling-Element Bearing Frequency Equations[37]

[37] Image source: http://www.bksv.com/doc/bo0210.pdf

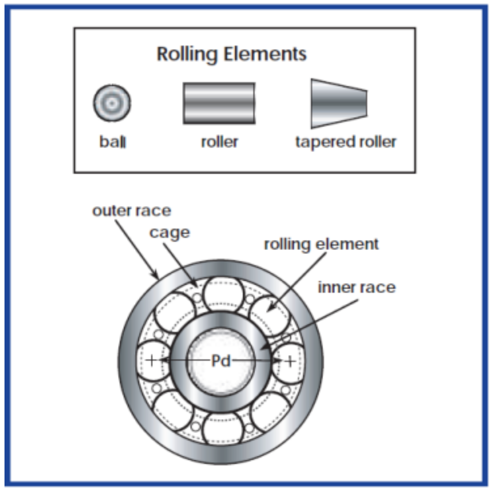


Figure 40. Bearing Examples.

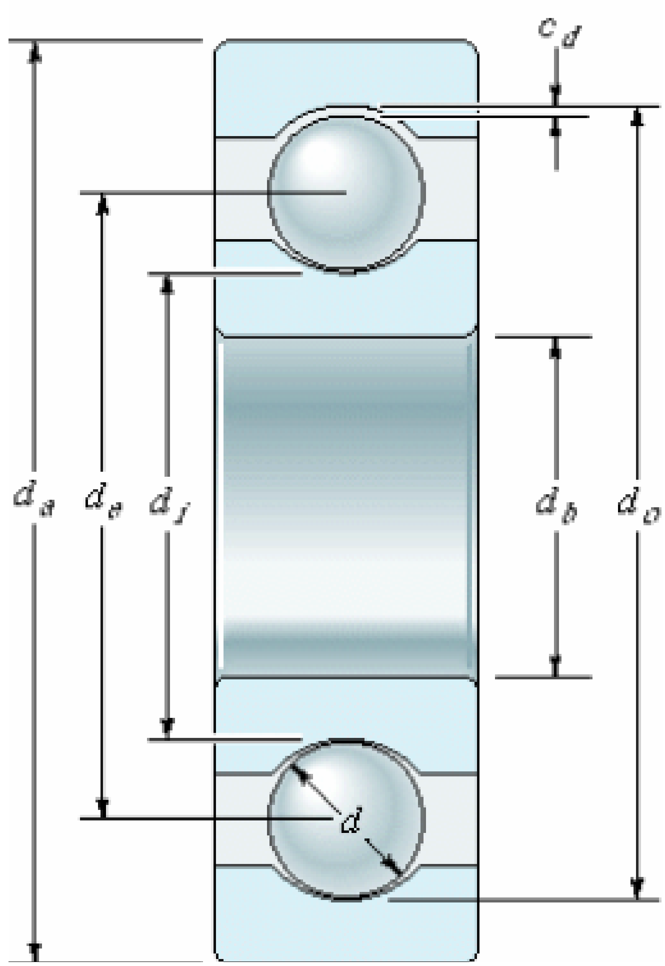


Figure 41. Rolling Element Bearing.

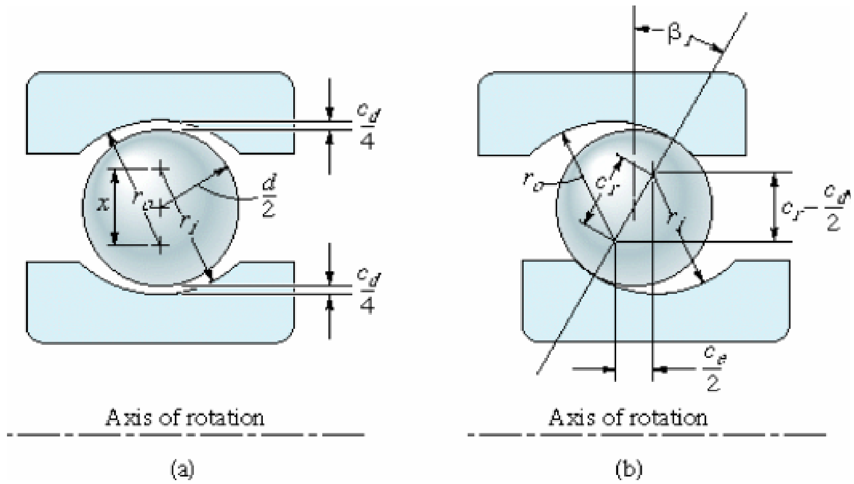


Figure 42. Contact Angles.

### A3.3 Background Information on Converting the Equations

When a vibration spectrum analyzer is used, the failing bearings will produce frequencies and multiples of the base frequencies that appear as spikes (Monavar, Ahmadi, & Mohtasebi, 2008). To make it easier to work with the vibration spectrum analyzer, the equations' variables needed to be changed. The four Brüel & Kjær equations are based on revolutions per minute (RPM). Yet cycles per second (Hertz) and cycles per minute (CPM) are used to express frequencies.

The method for converting RPMs into Hertz or into CPM is as follows:

1. Step 1: Multiply the running speed (RPM) by the frequency. This is expressed in Hertz
2. Step 2: Divide the Step 1 result by 60. This is expressed in CPM.

When we are looking for defects in a bearing number 16001 product (see Table 38), that is running at 1,800 RPM, we would expect to see spikes at 92.1 CPM, 147.9 CPM, 11.4 CPM and 61.67 CPM, or up to 8 multiples (the number of balls in the bearings) of these frequencies. If these spikes are present, then we know that a defect is being manifested (Monavar, Ahmadi, & Mohtasebi, 2008). This is assuming that the other parts are perfect and not misaligned. If these factors are present, then the spikes will appear elsewhere (Monavar, Ahmadi, & Mohtasebi, 2008).

A machine is running 1,800 RPM.

BPFO: 3.07 (from Table A.2) * 1,800 = 5,526 Hertz
5,526 Hertz / 60 = 92.1 CPM

BPFI: 4.93 (from Table A.2) * 1,800 = 8,874 Hertz
8,874 Hertz / 60 = 147.9 CPM

FTF: 0.38 (from Table A.2) * 1,800 = 684 Hertz
684 Hertz / 60 = 11.4 CPM

BSF: 2.04 (from Table A.2) * 1,800 = 3,676 Hertz
3,676 Hertz / 60 = 61.67 CPM

Figure 43. Example of Conversion Calculations.

Table 38. Deep Grove Ball Bearing Chart[38]

DEEP GROOVE BALL BEARINGS

| Bearing Number | NB | BD | PD | PHI | BPFO | BPFI | FTF | BSF |
|---|---|---|---|---|---|---|---|---|
| 16001 | 8 | 0.187 | 0.807 | 0 | 3.07 | 4.93 | 0.38 | 2.04 |
| 16002 | 9 | 0.187 | 0.925 | 0 | 3.59 | 5.41 | 0.40 | 2.37 |
| 16003 | 8 | 0.218 | 1.023 | 0 | 3.15 | 4.85 | 0.39 | 2.24 |
| 16004 | 10 | 0.218 | 1.244 | 0 | 4.12 | 5.88 | 0.41 | 2.77 |
| 16005 | 11 | 0.218 | 1.417 | 0 | 4.65 | 6.35 | 0.42 | 3.17 |
| 16006 | 12 | 0.25 | 1.673 | 0 | 5.1 | 6.9 | 0.43 | 3.27 |
| 16007 | 13 | 0.25 | 1.909 | 0 | 5.65 | 7.35 | 0.43 | 3.75 |
| 16008 | 15 | 0.25 | 2.125 | 0 | 6.62 | 8.38 | 0.44 | 4.19 |
| 16009 | 16 | 0.25 | 2.362 | 0 | 7.15 | 8.85 | 0.45 | 4.67 |
| 16010 | 17 | 0.25 | 2.559 | 0 | 7.67 | 9.33 | 0.45 | 5.07 |
| 16011 | 15 | 0.312 | 2.854 | 0 | 6.68 | 8.32 | 0.45 | 4.52 |
| 16012 | 17 | 0.312 | 3.051 | 0 | 7.63 | 9.37 | 0.45 | 4.84 |
| 16013 | 18 | 0.312 | 3.248 | 0 | 8.14 | 9.86 | 0.45 | 5.16 |
| 16014 | 18 | 0.343 | 3.543 | 0 | 8.13 | 9.87 | 0.45 | 5.12 |
| 16015 | 19 | 0.343 | 3.74 | 0 | 8.63 | 10.37 | 0.45 | 5.41 |
| 16016 | 20 | 0.343 | 4.035 | 0 | 9.15 | 10.85 | 0.46 | 5.84 |
| 16017 | 21 | 0.343 | 4.232 | 0 | 9.65 | 11.35 | 0.46 | 6.13 |
| 16018 | 19 | 0.406 | 4.527 | 0 | 8.65 | 10.35 | 0.46 | 5.53 |
| 16019 | 20 | 0.406 | 4.724 | 0 | 9.14 | 10.86 | 0.46 | 5.77 |
| 16020 | 21 | 0.406 | 4.921 | 0 | 9.63 | 11.37 | 0.46 | 6.02 |
| 16021 | 17 | 0.531 | 5.216 | 0 | 7.63 | 9.37 | 0.45 | 4.86 |
| 16022 | 17 | 0.562 | 5.511 | 0 | 7.63 | 9.37 | 0.45 | 4.85 |
| 16024 | 17 | 0.593 | 5.905 | 0 | 7.65 | 9.35 | 0.45 | 4.93 |
| 16026 | 16 | 0.687 | 6.496 | 0 | 7.15 | 8.85 | 0.45 | 4.67 |
| 16028 | 17 | 0.687 | 6.889 | 0 | 7.65 | 9.35 | 0.45 | 4.96 |
| 16030 | 17 | 0.749 | 7.381 | 0 | 7.64 | 9.36 | 0.45 | 4.88 |
| 16032 | 18 | 0.749 | 7.874 | 0 | 8.14 | 9.86 | 0.45 | 5.21 |
| 16034 | 17 | 0.843 | 8.464 | 0 | 7.65 | 9.35 | 0.45 | 4.97 |
| 16036 | 19 | 0.812 | 9.055 | 0 | 8.65 | 10.35 | 0.46 | 5.53 |
| 16038 | 19 | 0.874 | 9.448 | 0 | 8.62 | 10.38 | 0.45 | 5.36 |
| 16040 | 17 | 0.937 | 10.039 | 0 | 7.71 | 9.29 | 0.45 | 5.31 |
| 16044 | 18 | 1.062 | 11.023 | 0 | 8.13 | 9.87 | 0.45 | 5.14 |
| 16048 | 18 | 1.062 | 11.811 | 0 | 8.19 | 9.81 | 0.46 | 5.52 |
| 16052 | 18 | 1.25 | 12.992 | 0 | 8.13 | 9.87 | 0.45 | 5.15 |
| 16056 | 19 | 1.25 | 13.779 | 0 | 8.64 | 10.36 | 0.45 | 5.47 |
| 16060 | 16 | 1.562 | 14.96 | 0 | 7.16 | 8.84 | 0.45 | 4.74 |
| 16064 | 17 | 1.562 | 15.748 | 0 | 7.66 | 9.34 | 0.45 | 4.99 |
| 16068 | 16 | 1.75 | 16.929 | 0 | 7.17 | 8.83 | 0.45 | 4.79 |
| 16072 | 17 | 1.75 | 17.716 | 0 | 7.66 | 9.34 | 0.45 | 5.01 |
| 6000 | 7 | 0.187 | 0.7 | 0 | 2.57 | 4.44 | 0.37 | 1.74 |
| 6001 | 8 | 0.187 | 0.807 | 0 | 3.07 | 4.93 | 0.38 | 2.04 |

[38] Table source:http://www.ntnamericas.com/en/website/documents/brochures-and-literature/tech-sheets-and-supplements/frequencies.pdf

## Vita

Caiqiao Xu was born in Hainan, China. He graduated in 2006 with a Bachelor's degree in Business Administration. He came to The University of Tennessee, Knoxville in 2009 to pursue his Master's degree in the Industrial Engineering. He joined Dr.Rupy Sawhney as a Graduate Research Assistant and worked on more than four different projects over the course of two years. Caiqiao Xu is currently completing his master's degree in Industrial Engineering.